Proposed Emission Limit Values for Hydrogen and Non-Conventional Fuels

Introduction

Combustion of hydrogen is potentially a significant contributor to reducing reliance on fossil fuels and emissions of CO_2. To date, however, it has been limited to specific industry sectors and has not been considered at any significant scale in regulation of the combustion of natural gas sector. We are now at the point where we must develop emission limit values (ELVs) for hydrogen combustion in order to provide regulatory certainty to operators and OEMs.

This memo outlines emission rates of local air quality pollutants from hydrogen combustion, with comparison to conventional fuels and proposes ELVs for use of hydrogen as a fuel.

Combustion of Hydrogen as a Single Fuel

Combustion of hydrogen has the potential to release significantly more NOx than most conventional fuels, as a result of higher flame temperatures and laminar flame speed. Celek et al, demonstrated experimentally that pure hydrogen combustion using an industrial boiler resulted in an NOx level increase of 659.3% compared to pure natural gas combustion. In another experimental study, Dutka et al. (Dutka et al.2016) showed that using a Partially Premixed Bluff Body (PPBB) burner NOx emissions using hydrogen fuel were double that of natural gas. With theoretical based studies, it is shown that combustion characteristics notwithstanding, exhaust gas volume has an effect on pollutant NO_X emission rates. Douglas et al, completed a study on hydrogen methane fuel blends, using correction curves for 100% hydrogen fuel the NOx concentration is predicted to be up to 37% higher compared to traditional methane combustion. In a separate study Douglas et al, stated that a volume-based measurement approach can indicate higher NOx emissions for hydrogen blended systems and for pure hydrogen required a correction of 36 to 40%. These calculations are derived from the of change to flue gas volume, the absence of CO_2 (relative to combustion of carbonaceous fuels) and correction to dry conditions results in a relatively smaller gas volume hence a more concentrated NO_X component for combustion of hydrogen.

Use of exhaust gas recirculation (EGR) abatement in gas turbines can effectively lower combustion temperature and reduce oxygen concentration in the combustion chamber, effectively reducing NO_X emissions (Ditaranto et al. 2014). Dilarantoa et al, proposed the use of EGR to reduce oxygen content in the fluid entering the combustor, limiting combustion temperature and hence NOx formation ates. The study found by using this method NOx concentration were halved for a EGR rate of 30-40% in comparison with cases without EGR, this is attributed to lower temperatures and less available oxygen. In addition, modifications to existing equipment can aid in reducing NOx emissions with use of hydrogen fuel, including use of swirl burners with gas turbines . Lee et al, investigated hydrogen dosed with carbon monoxide to measure its combustion performance in a gas turbine in comparison to methane. The higher the hydrogen content the more NOx was emitted, with emissions increasing exponentially with heat input. Due to hydrogens high combustibility and diffusivity at 40% hydrogen and higher it achieves effective mixing with air and complete combustion reducing CO emissions to very low or non-existent.

Based on the literature available, it is proposed that new hydrogen ELVs are aligned with the minimum standards (IED and MCPD) for the combustion of natural gas in appliances>1MWth. The definition of new plant will commence at the point of adoption of the regulatory mechanism and all plant permitted prior to that date will be considered as existing plant for the purposes of these ELVs. Table 1 presents NO_X ELVs for natural gas as presented in these directives, along with the proposed ELVs for hydrogen, which are consistent with these existing natural gas ELVs. The difference between the two is down to a correction factor of 1.37, which is applied to account for the lower dry flue gas volume of hydrogen, relative to natural gas.

Table 1: Proposed NOx ELVs for 100% hydrogen combustion

	Natural Gas (mg/Nm^3)	**Hydrogen (mg/Nm^3)**	**Natural Gas (mg/Nm^3)**	**Hydrogen (mg/Nm^3)**
LCPs	**Existing plant**		**New Plant**	
Gas Turbine >50MWth	50	68.5	50	68.5
Boiler>50MWth	100	137	100	137
Gas Engines>50MWth	100	137	75	102.8
MCPs	**Existing Plant**		**New Plant**	
Gas Turbines >5MWth	150	205.5	50	68.5
Boilers>5MWth	200	274	100	137
Gas Engines>5MWth	190	260.3	95	130.2
Gas Turbines >1<=5MWth	150	205.5	50	68.5
Boilers>1<=5MWth	250	342.5	100	137
Gas Engines>1<=5MWth	190	260.3	95	130.2

Note Reference conditions are 273.15K, 101.3kPa, dry, 3% oxygen for boilers and 15% oxygen for gas turbines and engines.

As more data become available in coming years, Best Available Technique (BAT) for use of hydrogen as a fuel will be developed and this would then be applied in addition to the minimum standards. As hydrogen combustion technology is not available (in terms of the definition of BAT) at an industrial scale at present we will develop guidance under the new UK approach to determining BAT. Abatement technology is well established and available, though the effectiveness of abatement where hydrogen is used is of key interest. Questions in the final section of this document are included to explore this further.

Combustion of Hydrogen Blended with Natural Gas

As presented previously, experimental studies generally show where a blended fuel of hydrogen and natural gas is used NO_X emissions are greater as the component of hydrogen is increased. Celek et al, have shown experimentally using an industrial boiler that 100% natural gas and the addition of 25%, 50% and 75% hydrogen, resulting in NOx increases of 92.81%, 219.72% and 360% respectively. Wright and Lewis collated experimentally determined NOx emissions from hydrogen blends of up to 20% hydrogen in domestic boilers finding that NO_X emissions varied from a decrease in 50% to an increase in 154% relative to natural gas. Valera-Medina et al. (2015) show experimentally that NO_X emissions can be improved using a swirl burner with a gas turbine, this is further supported by Vigueras-Zuniga et al. (Vigueras-Zuniga et al. 2020) who also inlet temperature, pressure, fuel flowrate in combination with a fuel blend of hydrogen and ammonia affects NO_X emissions from a gas turbine. Schroder et al., found raw NOx emissions in a marine engine with hydrogen combustion in excess air to be comparable to those with natural gas with SCR . As mentioned previously, these experimental based studies can demonstrate changes in emissions of NO_X as a result of combustion characteristics. Douglas et al, calculated correction factors for the hydrogen blended combustion system NOx emissions when using a volume-based measurement approach due to lower emission volumes for hydrogen blends. These correction factors are 7% for a 50% hydrogen and methane bend, 17% for 80% hydrogen and 37% for 100% hydrogen. Meziane et al. demonstrated using numerical simulation that actual emission rates of NO were decreased by 14% where a 10% hydrogen fuel addition was made.

It is proposed that for blended fuels, ELVs are linearly interpolated, between those for natural gas and hydrogen (as single fuels) set out in Table 1. Thes values are set out in Table 2 for existing plant and Table 3 for new plant.

Table 2: Proposed NOx ELVs for blended natural gas and hydrogen fuel in existing plant

	100% Natural Gas (mg/Nm^3)	75 % Natural Gas with 25% Hydrogen (mg/Nm^3)	50 % Natural Gas with 50% Hydrogen (mg/Nm^3)	25 % Natural Gas with 75% Hydrogen (mg/Nm^3)	100% Hydrogen (mg/Nm^3)
LCPs					
Gas Turbine >50MWth	50.0	54.6	59.3	63.9	68.5
Boiler >50MWth	100.0	109.3	118.5	127.8	137.0
Gas Engines >50MWth	100.0	109.3	118.5	127.8	137.0
MCPs					
Gas Turbines >5MWth	150	163.9	177.8	191.6	205.5
Boilers >5MWth	200	218.5	237.0	255.5	274.0
Gas Engines >5MWth	190	207.6	225.2	242.7	260.3
Gas Turbines >1 <=5MWth	150	163.9	177.8	191.6	205.5
Boilers >1 <=5MWth	250	273.1	296.3	319.4	342.5
Gas Engines > 1<=5MWth	190	207.6	225.2	242.7	260.3

Note Reference conditions are 273.15K, 101.3kPa, dry, 3% oxygen for boilers and 15% oxygen for gas turbines and engines.

Table 3: Proposed NOx ELVs for blended natural gas and hydrogen fuel in new plant

	100% Natural Gas (mg/Nm^3)	75 % Natural Gas with 25% Hydrogen (mg/Nm^3)	50 % Natural Gas with 50% Hydrogen (mg/Nm^3)	25 % Natural Gas with 75% Hydrogen (mg/Nm^3)	100% Hydrogen (mg/Nm^3)
LCPs					
Gas Turbine >50MWth	50	54.6	59.3	63.9	68.5
Boiler >50MWth	100	109.3	118.5	127.8	137.0
Gas Engines >50MWth	75	82.0	88.9	95.9	102.8
MCPs					
Gas Turbines >5MWth	50	54.625	59.25	63.875	68.5
Boilers >5MWth	100	109.25	118.5	127.75	137
Gas Engines >5MWth	95	103.8	112.6	121.4	130.2
Gas Turbines >1 <=5MWth	50	54.625	59.25	63.875	68.5
Boilers >1 <=5MWth	100	109.25	118.5	127.75	137
Gas Engines >1 <=5MWth	95	103.8	112.6	121.4	130.2

Note Reference conditions are 273.15K, 101.3kPa, dry, 3% oxygen for boilers and 15% oxygen for gas turbines and engines.

Combustion of Ammonia as a Single Fuel

The combustion of ammonia has the potential to release more NOx that traditional fuel combustion systems due to its proficiency in fuel NOx production, which is formed through nitrogen chemically bonding with the fuel, intermediate products, and further oxidation . Numerous process conditions have been reported to significantly impact the release of NOx from ammonia and ammonia blend combustion systems including the combustor inlet temperature and equivalence ratio. Lower combustor inlet temperatures and equivalence ratios close to 1 have been reported to reduce NOx emissions .

Traditional fuels and hydrogen often use a lean combustion to reduce flame temperature leading to less thermal oxidation in gas turbines, however for ammonia-based fuel systems lean combustion seems to generate greater NOx emissions . A fuel rich approach or a rich/lean approach has been concluded to produce lower NO emissions

The use of end of pipe abatement technologies is suggested by Kurata et al, in the development of a low-NOx, ammonia combustor for a gas turbine system. To achieve the required efficiency and power output the combustor inlet temperature was increased to reduce unburnt NH_3 emissions, the consequence of this included increase NOx levels therefore a large-size selective catalytic reduction (SCR) was selected decrease the high NOx levels.

Kurata et al, and Valera-Medina et al, both reported on ammonia combustion efficiencies. Kurata et al, found a decrease in efficiency in comparison with methane, the ammonia-air mix achieved efficiencies of 89-96% of methane combustion. Valera-Medina et al, reported low efficiencies were measured that could not compete with current dry low NOX (DLN) technologies.

Combustion of Ammonia Blended with Natural Gas

Where ammonia is mixed with natural gas or hydrogen the emissions of NO are highest with low ammonia content blends and depend on the combustion conditions and the fuel ratios. Kurata et al, compared ammonia combustion to an ammonia methane combustion mixture. Increasing the ammonia fuel ratio in the ammonia methane mix significantly increased NO emissions for a fuel ratio up to 0.65, above which unburnt ammonia increases and NO decreases. For low ammonia fuel ratios (close to zero) the NO conversion ratio is reported as 57% whereas for an ammonia fuel ratio of 1 the NO conversion ratio decreases to 1,7%. Additionally, Kurata et al, found a decrease in efficiency in comparison with methane, the ammonia methane fuel mix operated at 93-100% of methane combustion.

Valera-Medina, et al. investigated emissions from gaseous ammonia blended with methane or hydrogen in gas turbines. High levels of NOx were measuring during efficient combustion of methane and less efficient ammonia combustion downstream, however it was concluded unburnt ammonia was being converted and measured as NOx by the analyser. The investigated ammonia methane mixture experiences flame blow off at 100% and 90% ammonia before reaching stable conditions and therefore could not provide any results.

Valera-Medina, et al investigated at 70/30 ammonia hydrogen blend for swirl combustion in gas turbine operation, NOx was the dominant pollutant from the ammonia based fuel reaction. However numerical analysis suggests hot unburnt ammonia was available to further react with existing NOx to decompose into NHx radicals reducing NOx pollutant levels.

Mashruk et al, observes a combustion mixture of ammonia, methane and hydrogen in different proportions, concluding NO emissions were highest at high methane concentrations due to increased temperature and increased thermal NOx.

Questions for the Technical Working Group

1. For new plant, What, if any, primary combustion measures would be necessary to achieve these ELVs?
2. With respect to existing plant running on conventional fuels, what impact will using hydrogen as a fuel have on existing emissions for plant using natural gas, namely?
    a. Can existing plant be used without modification and meet proposed ELVs?
    b. Can existing plant be used with modification to meet proposed ELVs, and if necessary, please outline potential modifications?
    c. Will abatement plant have to be added or modified to meet proposed ELVs?
3. With respect to all plant running on conventional fuels, what impact will using hydrogen as a fuel have on monitoring (e.g. CEMS)?
4. Are there any additional limitations in retrofitting boilers/turbines/engines for combustion of hydrogen?
5. Are the ELVs for combustion of hydrogen which are set out in Tables 1-3 achievable for the operator(s) you represent?
6. Are the ELVs for combustion of hydrogen which are set out in Tables 1-3 achievable for the sector as a whole?

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