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Contents

1 Overview

1.1 Hydrogen-production in a low/decarbonised economy

In an effort to combat rising greenhouse gas emissions, decarbonisation efforts aim to shift away from fossil fuel dependence. Along with electrification, hydrogen is potential alternatives to fossil fuels. Although hydrogen has no carbon emissions associated with it's combustion, historical production of hydrogen has been based on natural gas. Rather than typical production of "grey" hydrogen, "green" hydrogen is produced from renewable energy sources and "blue" hydrogen using natural gas with carbon capture. This "green" or "blue" hydrogen can then be used with no associated carbon emissions and can therefore contribute to decarbonisation. Fuel cell technology allows the chemical energy from hydrogen to be extracted at high efficiency with no NOx formation in hydrogen fuel cells (Jeerh et al., 2021; Staffell et al., 2019).

1.2 NOx and PM emissions

Compared to natural gas, combustion of hydrogen is associated with greater NOx emissions due to increased burn temperatures (Lewis, 2021), but there is a reduction in primary PM from hydrogen combustion (Laursen et al., 2022; Miller et al., 2007).

Although NOx emissions may be higher from hydrogen combustion than current sources, there are widely used aftertreatment strategies that could be applied to hydrogen combustion alternatives (Lewis, 2021). In this short report, information is presented that could be incorporated into international guidance, such as the EMEP/EEA Air Pollutant Emissions Inventory Guidebook for hydrogen combustion in aviation, and domestic and commercial boilers. These source sectors have been identified as having more limited aftertreatment options (Lewis, 2021). Other sectors could be assumed to be similar to current natural gas use due to emissions regulations.

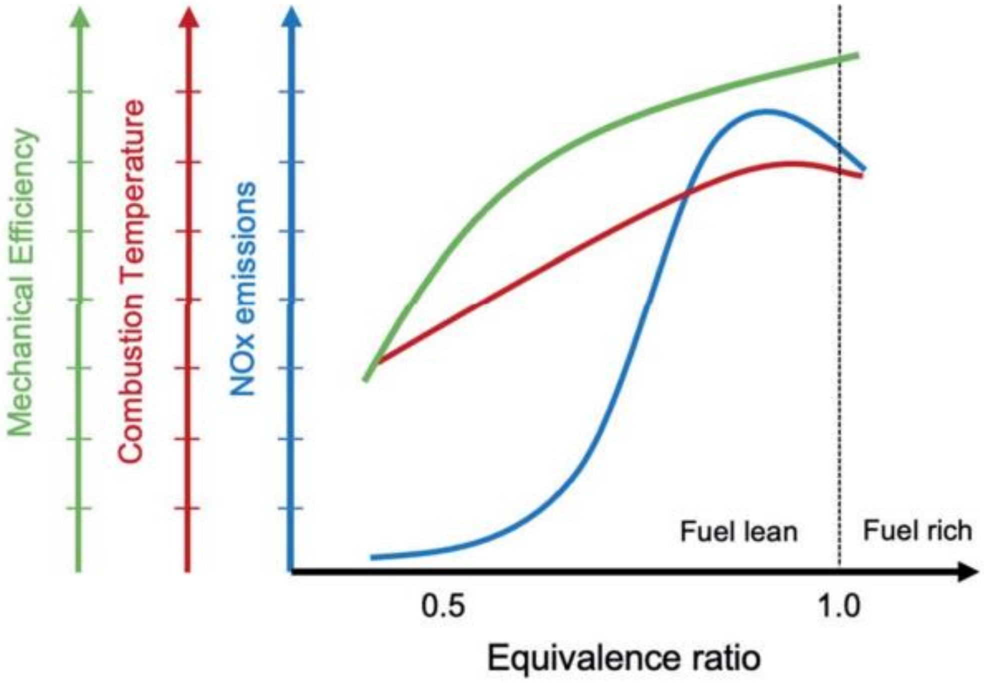
2 Gas turbines in power hydrogen

2.1 Combustion conditions for hydrogen

It is generally thought that there is limited scope for the use of hydrogen as a fuel in large point sources. But it is considered here for completeness.

Using hydrogen in a natural gas turbine engine at full power requires higher equivalence ratios (i.e. "fuel rich" combustion conditions) than natural gas, and this results in greater NO formation (Therkelsen et al., 2009). It was found that even at lower equivalence ratios, the NO emissions were greater for hydrogen than for natural gas. As shown in Figure 2-1, low equivalence ratios are associated with lower mechanical efficiency, so would be undesirable. Therefore, burner design is likely to be very important in reducing NOx emissions, and current natural gas burners are unlikely to be sufficient without changes that are specific to hydrogen combustion.

Figure 2-1 "The variation of mechanical efficiency, combustion temperature and NOx emissions as a function of the equivalence ratio. The equivalence ratio is a measure of the amount of fuel relative to the amount of air. A ratio of 1 means that the amount of oxygen supplied in the air exactly matches the amount of fuel available for all the fuel to be burned with no excess. 'Fuel lean' means there is more oxygen available than there is fuel to burn, and 'fuel rich' more fuel than oxygen to completely combust it." (Lewis, 2021)



2.2 Emissions and emissions control

There is the potential for NOx emission control strategies to be applied to hydrogen fuelled gas turbine combustion systems. For example, Dry Low Emission (DLE) gas turbine combustion systems were developed to reduce NOx emissions (usually below 25 ppmv) and are widely used (Faqih et al., 2022). However, DLE hydrogen combustion cannot directly use DLE gas turbine combustion systems as hydrogen has different physical properties to natural gas and similar fuels (Tekin et al., 2019). Instead, the Micro-Mix DLE combustion chamber was developed for hydrogen using cross-flow mixing of air and gaseous hydrogen so that combustion occurs in multiple smaller “diffusion-type” flames. This results in low NOx emissions due to a short residence time of the reactants in the hot flame region. Furthermore, this low NOx gas turbine combustion system can switch between burning natural gas, natural gas/hydrogen mixtures, and 100% hydrogen.

As there are extensive aftertreatment possibilities for gas turbines in power plants (Lewis, 2021), it is recommended that NOx emission factors for hydrogen combustion are assumed to be similar to current values for natural gas combustion currently reported in the EMEP/EEA Guidebook.

3 Internal combustion engines

The introduction of hydrogen to the road transport vehicle fleet is broadly considered to unlikely on a large scale, unless it is produced from hydrogen fuel cells. As with other applications, simply replacing current fuels with hydrogen in internal combustion engines is likely to result in an increase in NOx emissions (Guo et al., 2020) due to factors such as higher combustion temperatures. In internal combustion engines, NOx emissions depend on the engine load and hydrogen-air ratio (Verhelst and Wallner, 2009). Exhaust gas recirculation (EGR), currently used in diesel engines, reintroduces cooled exhaust gas into the combustion chamber to lower the combustion temperature by decreasing oxygen content (Guo et al., 2020). There are also aftertreatment options to significantly reduce NOx emissions (Stępień, 2021) in internal combustion engines.

No information has been obtained that reliably quantifies NOx or PM emission factors for hydrogen combustion in internal combustion engines, but emissions will be highly dependent on emission control technologies. So, it is recommended that NOx and PM emission factors for hydrogen combustion are assumed to be the same as those already in the EMEP/EEA Guidebook for compressed natural gas (CNG).

4 Heavy goods vehicles

4.1 Introduction

For the decarbonisation of transport, electric batteries in heavy goods vehicles (HGVs) are unlikely to be used extensively in the near future, due to feasibility issues such as recharging time (Cunanan et al., 2021). However, hydrogen fuel cells (H2FC) and hydrogen internal combustion engines (H2ICE) may be used as decarbonisation options for HGVs.

4.2 Emissions and emissions control

With aftertreatment, the use of H2ICE in HGVs is unlikely to have greater NOx emissions than diesel HGVs (Lewis, 2021). For example, companies with prototypes for 100% hydrogen combustion report NOx emissions that are lower than comparable diesel combustion (Wright & Lewis, 2022). Another pilot hydrogen combustion trial found that NOx emissions were reduced to near-zero by EGR, water injection and aftertreatment (Atkins et al., 2021). Although there is potential to greatly reduce NOx emissions in hydrogen internal combustion engines, it may be that legislation aims to implement regulations that reduce emissions to similar levels to those of current diesel emissions (Lewis, 2021). So, the NOx reduction potential in H2ICE is likely to depend on government policies

5 Aircraft

5.1 Introduction

Decarbonising aviation is a challenge due to the high energy content of liquid jet fuel per unit mass and per unit volume (Mukhopadhaya and Rutherford, 2022). Hydrogen (142 MJ/kg) has low energy density when considered on a per unit volume basis, but it has around 3 times the energy density of kerosene (46.2 MJ/kg) when considered on a mass basis. So, it is an appealing option for the aviation sector, although it would require storage in cryogenic tanks.

5.2 Emissions and emissions control

Aftertreatment in aircraft engines, such as selective catalytic reduction (SCR), has not been feasible due to high mass flow rates in the engine core (Prashanth et al., 2021). This might make aftertreatment of NOx in hydrogen combustion engines difficult, although there is on-going research into aftertreatments that could be used in aircraft engines.

A study modelling NOx emissions from an aircraft with 160 passengers over 3000 nautical miles found hydrogen cruise emissions an order of magnitude lower than for kerosene, but slightly higher landing and take-off (LTO) emissions (Khan et al., 2022). However, given that this was a modelling study, actual NOx emissions from hydrogen combustion in aircrafts may differ significantly. Water vapour emissions were found to be over 4 times greater than for kerosene fuel, but PM levels were negligible. This is expected to result in increased contrails, but with lower radiative forcing.

Based on the research currently available, it is recommended that the NOx scaling factors for hydrogen relative to kerosene in turbine-powered aircraft shown in Table 5-1 are used.

Table 5-1 Suggested NOx scaling factors for hydrogen relative to kerosene in turbine-powered aircrafts based on a modelling study by Khan et al., 2022

	Hydrogen fuel NOx scaling factor
Cruise emissions	0.1
LTO Cycle emissions	1.2

6 Maritime shipping

Use of hydrogen as a maritime fuel may require some aftertreatment to reduce NOx emissions (ABS, 2021). However, an analysis of the use of hydrogen and ammonia in shipping suggests that ammonia may be a better option than hydrogen (Inal et al., 2022). Whilst a literature review has been undertaken for emissions arising from the use of NH3 as a maritime fuel, it has been concluded that there is currently insufficient information to provide emission factors.

7 Residential domestic boilers

7.1 Introduction

Currently, there are economic and design limitations to aftertreatment in domestic boilers (Lewis, 2021) which is important when considering hydrogen as a fuel due to its association with increased NOx emissions. This may lead to NOx emissions being highest in areas with high population densities often home to more disadvantaged communities. For hydrogen combustion in domestic boilers, there are uncertainties in the distribution of the temperature within the flame, the flame size, and how long molecules remain at a temperature high enough for NOx formation (Frazer-Nash Consultancy, 2018). Although retrofitting and designing boilers for hydrogen combustion is possible as outlined below, the feasibility of this on a large scale is uncertain, given the current lack of aftertreatment employed in domestic boilers.

7.2 Emissions and emissions control

The retrofit and development of two condensing natural gas boilers for hydrogen resulted in lower NOx emissions than the natural gas equivalent while maintaining a high efficiency (Gersen et al., 2020a). This was due to the flue gas being maintained at lower temperatures through flue gas recirculation (FGR) than in conventional boilers. After retrofitting, one boiler had greater NOx emissions at certain thermal loads (around 75 mg/kWh) than the current EU Ecodesign emission limit for NOx emissions from gaseous fuel boilers (56 mg/kWh)[1]. However, when applying strategies such as FGR and optimising the combustion air flow pattern, NOx emissions as low as 5 mg/kWh at lower thermal loads were recorded. The difference between the maximum and minimum value for a certain thermal load was around a factor of 3 for a given thermal load.

The second boiler had lower NOx emissions than the EU limit for small gaseous boilers. This retrofitted boiler was also tested with methane, and hydrogen was found to give NOx values 3 to 7 times lower than for methane. The hydrogen domestic boilers used in the study were based on condensing boilers, which generally have better NOx performance than conventional boilers due to lower combustion temperatures (Bălănescu and Homutescu, 2018).

It is recommended that NOx emission factors for hydrogen domestic boilers used in emission inventories are a factor of 3 times higher than the current emission factors for natural gas in the EMEP/EEA Guidebook. This is based on the increase found before aftertreatment strategies are implemented by Gersen et al., 2020a, so it is important that any reporting of this new emission factors clearly indicates that it represents an emission factor without aftertreatment.

This first estimate should be revised following any new research, and if the widespread use of aftertreatment and NOx reducing strategies is deemed viable.

8 Commercial heating boilers

8.1 Introduction

Compared with domestic boilers, aftertreatment is more feasible in commercial heating boilers (Lewis, 2021). Although the use of hydrogen as a fuel may result in more NOx production than other fuels such as natural gas, this can potentially be mitigated with aftertreatment technologies.

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[1] *Commission Regulation (EU) No 813/2013*, 2013

8.2 Emissions and emissions control

A study looking at the NOx emissions from burning natural gas, natural gas/hydrogen mixtures and pure hydrogen in a 475kW industrial boiler found that the greater NOx emissions associated with hydrogen could be reduced significantly with FGR (Gersen et al., 2020b). For pure hydrogen, the NOx emissions were a factor of three greater than natural gas in the same conditions but were reduced by more than a factor of 10 when using FGR.

It is recommended that the NOx emission factor for hydrogen combustion is assumed to be the same as that for gaseous fuels reported in the EMEP/EEA Guidebook, as aftertreatment strategies are available for commercial heating boilers. However, the upper confidence interval could be increased by a factor of 3 (as shown in Table 8-1 for medium size boilers) to represent the greater potential for NOx emissions from hydrogen combustion. It is recommended that the lower confidence interval is kept the same, as although NOx reductions (compared to natural gas) have been observed using FGR, the wider use of these strategies has yet to be assessed for hydrogen. Similar to domestic boilers, this should be reviewed in future years to capture results from relevant research studies.

Table 8-1 NOx emission values and 95% confidence interval for gaseous fuels in medium (>50 kWth to <=1 MWth) boilers (EMEP/EEA Guidebook. Section 1.A.4 (Small combustion), Table 3.26), and proposed changes for hydrogen.

	NOx value	95% confidence interval	
		Lower	Upper
Gaseous fuels	73 g/GJ	44 g/GJ	103 g/GJ
Hydrogen	73 g/GJ	44 g/GJ	309 g/GJ

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