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POLICY BRIDGE

Emissions of NO_x from blending of hydrogen and natural gas in space heating boilers

Madeleine L. Wright[1] and Alastair C. Lewis[2,*]

As part of climate change commitments, the United Kingdom is considering an incremental transition from natural gas to hydrogen for domestic heating, blending up to 20% of hydrogen (by volume) into the national gas network. We consider the possible impacts of this policy on nitrogen oxides (NO_x) emissions, a minor waste by-product from combustion. A meta-analysis of changes in NO_x emissions from hydrogen/natural gas blends used in gas burners is undertaken, with focus on mixtures between 5% and 20% v/v. Literature reports are highly variable: for a 5% hydrogen blend, changes in NO_x emissions, when compared to burning pure natural gas, vary over the range –12% to +39%, with a mean change across 14 studies of +8%. These estimates required an important assumption to be made that, when not explicitly described, all literature data on changes in NO_x emissions and/or concentrations were suitably corrected for the reduced energy density and heat output arising once hydrogen is added. A NO_x increase can be rationalized through the increased adiabatic flame temperature generated from hydrogen combustion. The associated range of plausible damage costs of a 5% hydrogen blend is estimated to fall within the range –117 million GBP to +362 million GBP per year; 20% hydrogen (the maximum that could be accommodated with existing infrastructure) would lead to a change in emissions in the range –50 to +154% with a change in damage costs of between –467 million GBP and +1,146 million GBP per year. The mean change is estimated at 292 million GBP per year. For existing poor performing boilers, an economic case can be made for scrappage and replacement based primarily on NO_x damage costs avoided. The response of older boilers to added hydrogen is a critical evidence gap that needs filling before further decisions on hydrogen as a heating fuel are made.

Keywords: Net zero, Hydrogen, Space heating, Domestic combustion, Nitrogen oxides, Natural gas

Introduction

An ever-growing number of countries have announced net zero greenhouse gas commitments to meet obligations made in the Paris Agreement and broader objectives to limit anthropogenic climate change. The transition away from fossil fuels is complex with many possible technological pathways. One element of a decarbonization strategy may be an increase in the production and use of hydrogen as a fuel.

As an example, the United Kingdom has pledged net zero emissions by 2050, a legal commitment set out in The Climate Act (Climate Change Act, 2008). Its science advisory body, The Committee on Climate Change (CCC), has recognized the potential of hydrogen as a future energy source and as a complementary technology to electrification (Committee on Climate Change, 2018). It emphasizes the need for low-regret options to deploy hydrogen quickly, such that it can be a significant part of the UK's energy mix by 2050. In 2019, the CCC emphasized the need for a "serious plan" for decarbonizing space heating (Stark et al., 2019), one of the most challenging sectors to decarbonize in many high-income countries. Within the United Kingdom, space heating is responsible for 23% of all greenhouse gas emissions and 73% of domestic emissions (Department of Business, Energy and Industrial Strategy [BEIS], 2021a). The UK strategy for decarbonization of homes, set out in the Government's *Ten Point Plan to a Green Industrial Revolution*, was to support infrastructure that would enable up to 20% blending of hydrogen into the existing natural gas distribution network by 2023 (BEIS, 2020). Moving to low-fraction hydrogen-natural gas (H2-NG) blends could offer fast initial deployment of hydrogen with minimal infrastructure change necessary in both distribution and end-use processes. Transitioning to low-fraction H2-NG blends is considered feasible without wholesale reengineering of existing commercial or domestic gas boilers or cookers where natural gas is used (Dadfarnia et al., 2019; Energy Networks Association, 2020; HyDeploy, 2021).

Hydrogen can be deployed as an energy source in two distinct ways: through combustion in boilers and engines or in electrochemical fuel cells. The use of H2-NG blends for domestic combustion deploys hydrogen as a combustion

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fuel, and for at least the 2020s and 2030s, this would be the predominant application in the United Kingdom (National Gird Electricity System Operator, 2019; BEIS, 2020, 2021a). While the major product of hydrogen combustion is water vapor, a disadvantage is that combustion can also lead to the formation of nitrogen oxides (NO_x) when the fuel is burned in air. This occurs via the Zel'dovich mechanism (or sometimes described as thermal NO_x), whereby high temperatures in the flame lead to the splitting of atmospheric N_2 and O_2 into atomic N and O, which then go on to react and form NO. By contrast, electrochemical fuel cells produce only water as a by-product.

In the United Kingdom, most domestic natural gas appliances are combination boilers used for both space heating and hot water. Although the use of gas for space heating is restricted predominantly to cooler winter months, boilers continue to be used in summer for hot water. The annual split in terms of gas usage is approximately 80% for heating and 20% for hot water (Department of Energy and Climate Change, 2013), and as a consequence, boiler emissions of NO_x do also occur during summer months as well. Once emitted, NO quickly reaches equilibrium with NO_2 via reaction with O_3 in air. NO_x in the presence of volatile organic compounds results in the formation of tropospheric ozone, which estimates suggest causes upwards of 1 million premature deaths a year (Malley et al., 2017). NO_2 itself causes a range of direct adverse health and environmental impacts, and direct NO_2 damage costs are the focus in this article (Adamkiewicz et al., 2010; Jonson et al., 2017); however, a long-standing motivation for controlling NO_x emissions has been to limit tropospheric ozone concentrations.

National NO_x emissions have been reducing in many high-income countries over the last 20 years through successful application of emissions control in the energy and transport sectors. However, further reductions in NO_x are necessary, requiring actions beyond a business-as-usual case. The World Health Organization has recently reduced its air quality guidelines for NO_2 by 75% (Defra, 2021b); the most recent annual air quality assessment found that the United Kingdom was noncompliant with annual mean NO_2 concentrations in 5 zones (Defra, 2021a). In addition, international transboundary obligations require the United Kingdom to further reduce NO_x emissions by 18% between 2020 and 2030 (Defra, 2022). Although domestic combustion only accounts for 4.5% of national NO_x emissions, its share can be up to 20% in urban areas (National Atmospheric Emissions Inventory [NAEI], 2019a, 2019b). Although NO_x abatement strategies for road transport are well-established and increasingly effective, NO_x regulations for domestic natural gas boilers were only introduced in 2018 (Commission Regulation [EU], 2013). Hence, there is potential for a shift in the major sources of NO_x in some areas of the United Kingdom unless action is taken to further reduce NO_x emissions from domestic combustion (Lewis, 2021b).

At the high temperatures of natural gas combustion (above 1,600 K), most NO_x is formed as thermal NO, through the Zel'dovich (1946) mechanism. This temperature-dependent NO also forms already during pure natural gas combustion; however, the higher adiabatic flame temperature of hydrogen (Choudhury et al., 2020) could mean H2-NG blends burn under hotter conditions that increase NO_x emissions. A recent engineering review of domestic boilers with potential to run on hydrogen concluded that without individual testing, it was difficult to predict the outcome for NO_x emissions, due to the uncertainty in the effect of the replacement of natural gas with hydrogen on the flame temperature (Frazer-Nash Consultancy, 2018). The uncertainty of outcomes was due to varying flame sizes and temperature distributions from different appliance and burner designs and the effect of hydrogen addition on flame propagation (Schaffert et al., 2020).

Although considerable research and policy attention has been paid to how hydrogen might be produced in a net zero economy (Marbán & Valdés-Solís, 2007; Kothari et al., 2008; Stark et al., 2019; van Renssen, 2020; Ueckerdt et al., 2021), less consideration has been given to effects at point of use. The most "optimistic" technological solution is green hydrogen from renewable energy being used in fuel cells. As can be seen from UK plans however, setting aside the question of production method, combustion appears the likely short-term end use. Lewis (2021a) highlighted that the adoption of hydrogen as a combustion fuel, if applied using only existing appliance emissions regulations, would not deliver optimal air quality cobenefits and could increase air pollution inequalities in cities (Lewis, 2021b).

This article examines in more detail the potential outcomes for NO_x emissions of low-fraction H2-NG blends if applied in residential gas burners. It generates a meta-analysis of existing evidence on NO_x emissions from H2-NG blends when combusted. We estimate that the range of plausible NO_x emissions changes if low-fraction H2-NG blends were applied in the United Kingdom for domestic combustion, using existing appliances without modification or additional regulation on emissions. Based on literature emissions, best, worst, and mean air quality damage costs (and savings) are estimated to indicate the possible scale of impacts in economic terms. Effects of different NO_x scenarios are also considered on both a single household scale and an urban budget. We include data from a range of domestic burner end uses in our meta-analysis, since these would all be affected by hydrogen blending in gas networks. However, discussion is focused on space heating since other appliances, such as gas cookers and gas fires, are more likely to be replaced by electric equivalents. Widespread deployment of electric heat pumps, the electrification alternative to gas boilers, may be constrained in the United Kingdom by available electrical power in winter and high consumer installation costs (Bell et al., 2016; Rendali et al., 2021), so hydrogen remains a plausible approach for homes decarbonation.

Literature review

A literature review was conducted to (1) identify studies and experiments estimating NO_x emissions from combustion systems analogous to those of domestic burners, where the H2-NG composition was varied; and (2) extract data and reported relationships between fractional hydrogen content in the fuel and reported changes in NO_x

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emissions, relative to a 100% natural gas or methane base case.

Aside from hydrogen fraction in the combustion fuel, several other experimental factors are found to affect flame temperature and therefore NO_x. These include equivalence ratio (φ, the ratio of fuel to air), burner geometry, and the degree of fuel and air premixing (Ilbas et al., 2005a; Dutka et al., 2015). Each has a different effect on the temperature of combustion. The higher adiabatic flame temperature of hydrogen is expected to increase thermal NO emissions relative to methane. However, these other factors could act to either diminish or exacerbate this effect. Should hydrogen be blended into existing gas networks, the response of individual appliances will be highly dependent on these factors and are difficult to anticipate in advance.

For nonpremixed flames, most literature indicates that increasing hydrogen fraction leads to increased NO_x emissions. However, there is disagreement regarding which process is responsible. Aside from the Zel'dovich mechanism, the other main route to NO is the Fenimore mechanism. This forms prompt NO and is highly dependent on the concentration of CH radicals in the flame front (Ilbas et al., 2005a; El-Ghafour et al., 2010). Some studies found an augmented Zel'dovich mechanism to be responsible, due to correlation of NO_x and temperature profiles (Choudhuri and Gollahalli, 2000; Cozzi and Coghe, 2006). Others attributed the NO_x increase at low hydrogen compositions (0%–50% v/v) to prompt NO, from correlation of CH and NO radical profiles (Rortveit and Hustad, 2003; El-Ghafour et al., 2010). Although it has been suggested that NO_x emissions can be controlled by fixing the equivalence ratio in nonpremixed flames (Leicher et al., 2022), results from the literature discussed do not find this to be the case.

Other studies found little change or a slight decrease in NO_x emissions. This was often the result when premixed or partially premixed flames were used (Zhao et al., 2019a, 2019b) and/or lack of combustion control meant equivalence ratio was not kept constant (Kim et al., 2009; Kippers et al., 2011; Nitschke-Kowsky and Wessing, 2012). As hydrogen is added to these systems, the increasingly fuel-lean conditions can act to suppress the expected temperature increase. However, this has an inherent effect on the efficiency of an appliance (Lewis, 2021a), and derating has been observed on hydrogen addition (Granville et al., 2022). It is also possible that combustion control in premixed burners does not respond properly to hydrogen addition, such that NO_x emissions are not reduced (Leicher et al., 2022).

A review as part of the Testing Hydrogen admixture for Gas Applications (THyGA) project found that NO_x emissions from boilers burning H2-NG blends were similar to those of natural gas combustion (Schaffert et al., 2020). However, data from recently developed ultra-low-NO_x boilers (yet to be widely installed) predominated in this review and may have steered this conclusion. In addition, not all studies considered had their results corrected for energy equivalence. Hence, this conclusion may not be applicable to evaluating the impacts of hydrogen fuel policy when considering older preexisting boilers. In the recently published intermediate testing report, the THyGA project tested a range of domestic gas combustion appliances (Schweitzer, 2022). Although NO_x emissions generally decreased for 0%–60% hydrogen addition, the observed reduction in heat input resulted in increased time to heat water when testing a cooker. This has been observed by other studies on 3 different boiler designs, who suggest that this reduction in load is enough to significantly increase consumer complaints (Nitschke-Kowsky and Wessing, 2012).

Literature sources come to very different conclusions about the impact of hydrogen fraction in H2-NG blends on NO_x emissions. Since this relationship is complex (Granville et al., 2022), the discrepancy is most likely due to experimental variation between studies. Another consideration is whether the burner studied is designed specifically for research or for domestic end use. It is possible that more research burners see an increase in NO_x than domestic burners, but this is not always the case and other experimental variation obscures this potential result. How the age and year of production of the burner affects the relationship between hydrogen fraction and NO_x also suffers from similar issues.

The testing procedures in many studies do not align with UK Government ambitions of 20% volumetric hydrogen addition, with no data points between 0% and 70% hydrogen in some cases (e.g., Cellek and Pınarbaşı, 2018; Büyükakın and Öztuna, 2020). Some studies do not correct for the reduction in heat input observed on (volumetric) hydrogen addition, which would be necessary for providing consumers with a reliable and efficient energy source. This article aims to provide information that is directly relevant to real-world hydrogen blending, in a UK context.

Here, we consider the range of plausible NO_x emissions outcomes that might occur, accounting for the unpredictable old stocks of gas boilers that may persist for many years. Since so little is known about how preexisting boilers may respond to a change in fuel blend, we use all available literature sources to generate a representative range of possible NO_x impacts. Although some data sets are based on research burners rather than end-use appliances, these are included in further analysis to increase our evidence base. Since there is no detailed information on the number of different domestic burner types in the United Kingdom, we do not consider any result more or less likely but generate these to inform future policymaking and illuminate the potential scale of effects.

Literature containing suitable emissions data was identified as part of the review and is presented in **Table 1**. Papers reporting syngas combustion products were excluded from **Table 1** due to the presence of significant amounts of CO in the fuel (García-Armingol and Ballester, 2015; Brown et al., 2019; Pashchenko, 2020), which could impact NO_x emissions via the prompt formation mechanism. (It is unlikely to influence combustion temperature as both CO and hydrogen have an adiabatic flame temperature of 2,400 K). Data sets with fewer than three different H2-NG blends/compositions were excluded

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Table 1. Summary of literature containing hydrogen-natural gas nitrogen oxides (NO_x) emissions data used in this work. DOI: https://doi.org/10.1525/elementa.2021.00114.t1

Data Set	Authors	Year of Publication	Title	Data Location	Combustion Type	Burner End Use	Range of H_2 (%)	φ[a] (Fuel to Air Ratio)	NO_x With Increasing H_2
1	M. S. Cellek and A. Pinarbasi	2018	Investigations on performance and emission characteristics of an industrial low swirl burner while burning natural gas, methane, hydrogen-enriched natural gas, and hydrogen as fuels	Fig. 12a	N/A	Research	0–100 (mass)	0.833	Increase
2	M. K. Buyukakin and S. Oztuna	2020	Numerical investigation on hydrogen-enriched methane combustion in a domestic back-pressure boiler and nonpremixed burner system from flame structure and pollutants aspect	Fig. 9	Nonpremixed	Domestic boiler	0–75 (mass)	0.833	Increase
3	S. Choudhury, V. McDonell, and S. Samuelsen	2020	Combustion performance of low-NO_x and conventional water heaters operated on hydrogen enriched gas	Fig. 7b [b]	Partially premixed	Water storage heater	0–30 (vol.)	>1	Negligible
4	Y. Zhao, V. McDonell, and S. Samuelsen	2019b	Experimental assessment of the combustion performance of an oven burner operated on pipeline natural gas mixed with hydrogen	Fig. 12a [b]	Partially premixed	Oven burner	0–25 (vol.)	1.55–1.4	Negligible
5	Y. Zhao, V. McDonell, and S. Samuelsen	2019a	Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner	Fig. 12a	Premixed	Cooktop burner	0–50 (vol.)	2–1.5	Decrease
6	S. A. A. El-Ghafour, A. H. E. El-dein, and A. A. R. Aref	2010	Combustion characteristics of natural gas-hydrogen hybrid fuel turbulent diffusion flame	Fig. 5 [c]	Nonpremixed	Research	0–50 (vol.)	N/A	Increase
7	F. Cozzi and A. Coghe	2006	Behavior of hydrogen-enriched nonpremixed swirled natural gas flames	Fig. 9	Nonpremixed	Research	0–100 (vol.)	0.71-0.17	Increase
8a	P. Rajpara, R. Shah, and J. Banerjee	2018	Effect of hydrogen addition on combustion and emission characteristics of methane fueled upward swirl can combustor	Fig. 12a	N/A	Research	0–10 (mass)	0.3	Increase

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8b	P. Rajpara, R. Shah, and J. Banerjee	2018	Effect of hydrogen addition on combustion and emission characteristics of methane fueled upward swirl can combustor	Fig. 12b	N/A	Research	0–80 (vol.)	0.345–0.14	Increase
9	F. H. V. Coppens, J. De Ruyck, and A. A. Konnov	2007	Effects of hydrogen enrichment on adiabatic burning velocity and NO formation in methane + air flames	Fig. 6	N/A	Research	0–35 (mol.)	1.25	Decrease
10	H. S. Kim, V. K. Arghode, and A. K. Gupta	2009	Flame characteristics of hydrogen-enriched methane–air premixed swirling flames	Fig. 9e [d]	Premixed	Research	0–9 (mass)	0.717–0.694	Increase
11a	P. Nitschke-Kowsky and W. Wessing	2012	Impact of hydrogen admixture in installed gas appliances	Fig. 10	Premixed	Domestic boiler	0–30 (vol.)	N/A	Decrease
11b	P. Nitschke-Kowsky and W. Wessing	2012	Impact of hydrogen admixture in installed gas appliances	Fig. 11	Premixed	Domestic boiler	0–30 (vol.)	N/A	Decrease
12	M. J. Kippers, J. C. De Laat, R. J. M. Hermkens, J. J. Overdiep, A. van der Molen, W. C. van Erp, and A. van der Meer	2011	Pilot project on hydrogen injection in natural gas on island Ameland in the Netherlands	Fig. 9	Condensing boiler	Domestic boiler	0–20 (vol.)	N/A	Decrease
13	M. Ilbas, I. Yilmaz, N. Vesiroglu, and Y. Kaplan	2005	Hydrogen as burner fuel: modeling of hydrogen–hydrocarbon composite fuel combustion and NO_x formation in a small burner	Table III	Nonpremixed	Research	0–100 (vol.)	$\asymp 1$	Increase
14	S. Naha and S. K. Aggarwal	2004	Fuel effects on NO_x emissions in partially premixed flames	Fig. 12	Partially premixed	Research	0–90 (vol.)	N/A	Negligible

[a] Ranges are displayed in order of low to high hydrogen fraction.

[b] Correction to 3% O_2 has been chosen as data for use here, as this is most commonly used for stationary combustion. Authors suggest that correction to CO_2 is affected by hydrogen rich fuels and may not be a fair method here.

[c] Data were taken from midburner and radial distance of 7 mm (2dj), as this is where maximum NO_x emissions were measured. This is useful for considering a worst-case scenario.

[d] Data were taken from midswirl strength and 2.5 mm from burner exit, as this is where maximum NO_x emissions were measured. This is useful for considering a worst-case scenario.

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(Schefer et al., 2002; Colorado et al., 2017). H2-NG compositions ranging from 0 to at least 20 vol% were considered necessary for inclusion, so that there was a clear trend within the range being considered in this article. Data sets not covering this were excluded (Choudhuri and Gollahalli, 2000; de Santoli et al., 2020). Data where the temperature is kept constant across H2-NG compositions through the use of a diluent are also excluded as this is not how domestic boilers would operate in the real world (Rortveit and Hustad, 2003). Both old and more recent papers were included in **Table 1**, providing data for a range of appliances, consistent with other current testing programs (Schweitzer, 2022). This will allow us to deduce the full range of outcomes for NO_x emissions, representing different rates of boiler replacement in the United Kingdom.

Method

Literature reports of experiments of hydrogen and natural gas/methane flames can express the blends used in a variety of units. Where necessary, hydrogen fraction was converted from percentage by mass to percentage by volume through Equation 1,

$$f_v = \frac{f_m}{f_m + 0.127(1 - f_m)}, \qquad (1)$$

where f_v and f_m are the volume and mass fractions of hydrogen, respectively, and 0.127 is the ratio of densities of hydrogen to methane at room temperature and pressure. Natural gas is taken as 100% methane in this calculation. An example of natural gas composition was given in Data Set 1 (Cellek and Pınarbaşı, 2018) as over 95% methane, so this is taken to be a reasonable approximation. Fuel composition was expressed as vol.% to be consistent with the policy description of future implementation within the Hydrogen Strategy (BEIS, 2021a) and because it yields data points over a larger range of percentages. Mole fraction data (Coppens et al., 2007) were assumed equivalent to f_v. A *relative* change in NO_x emissions compared to 100% natural gas was calculated for each data set. The *absolute* amount of NO_x emissions in each literature study is not required, since we are considering only the relative change in emissions that may arise from a change in fuel blend. Least squares regression analysis was performed on each data set to give a simple expression of change in NO_x for different hydrogen fractions. Although there is no simple expression that can accurately describe the change in NO_x across a range of appliances, linear expressions were suitable in this case since most R^2 values were above .9 for all data sets in **Table 1** and all were above .75. Combining all relevant literature studies and resulting linear expressions provided the span of possible effects on NO_x emissions as hydrogen fraction is changed.

Interpolation of experimental data from Ilbas et al. (2005b) was carried out using accompanying numerical data from modeling, to produce a more complete data set. Figure S1 shows the calibration curve used.

The lower energy density of hydrogen compared to natural gas means that, without correction for energy equivalence, hydrogen addition results in a reduction in heat output on combustion, which leads to reduced thermal efficiency. Some of the studies accounted for this by keeping the energy input of the fuel constant across the different fuel compositions, but it was unclear in many cases whether this had been accounted for. Due to wide experimental variation across studies, further corrections for energy equivalence were not applied. Hence, it is possible that calculations based on this meta-analysis are an underestimation due this lower output effect.

For 5, 10, 15, and 20 vol.% hydrogen blends, NO_x emissions were evaluated as percentage changes compared to a 100% natural gas base case. The literature evaluated gave a wide range of possible outcomes with increasing hydrogen fraction, from substantially increased NO_x emissions to some studies that reported modest reductions. Three scenarios were considered in more detail:

1. A worst case (Ilbas et al., 2005b), where hydrogen addition causes the greatest increase in NO_x emissions. This would correspond to a scenario, in which current boilers respond poorly to H2-NG blends and are not replaced by lower-NO_x technology.
2. A best case, where hydrogen addition causes the greatest decrease in NO_x emissions (Nitschke-Kowsky and Wessing, 2012). This would relate to a case where the United Kingdom sees widespread adoption of boiler technology that reduces NO_x emissions without a decrease in efficiency, at the time of hydrogen blending.
3. A mean value, corresponding to the average NO_x emissions from all data. The context of this lies between best and worst cases, where a range of burner technologies in homes results in a range of NO_x responses observed across appliances.

These three linear regressions were then considered in further calculations of possible NO_x response to 5%, 10%, 15%, and 20% hydrogen blends if applied in the United Kingdom, a country heavily reliant on natural gas boilers for domestic space heating.

Percentage change in emissions was converted to an annual mass change in NO_x emissions in tons, using the most recent available data for NO_x emissions from domestic combustion of natural gas, provided by the NAEI (2019a). This assumed a full replacement of natural gas with a H2-NG blend right across the United Kingdom. Potential changes in national annual emissions for difference slope scenarios and blends were then converted to damage costs (in GBP) using latest UK Government accounting values. See HM Treasury Green Book damage costs (Birchby et al., 2020).

Damage costs are estimated using a complex methodology that accounts for the health economic impacts of a pollutant via morbidity and mortality changes. Atmospheric emissions are transformed into a change in

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concentration via a model and that change linked to known disease or mortality concentration response functions. Since different emissions lead to different changes in concentrations and exposure, depending on where a pollutant is released, a range of estimates of damage costs exist. For example, 1 ton of road transport emissions in a city center has greater health "cost" than the same from a 50-m high rural power station stack. In the case of NO_2, a cost is attributed to the change in incidence in mortality arising from exposure to an increment in concentration, recently updated in Committee on the Medical Effects of Air Pollution (2018), and the change in incidence in rates of asthma, diabetes, and lung cancer. Cost estimates are then derived from quality-adjusted life years lost, multiplied by a standardized value of a life year lost. A detailed description of the underlying methodologies is provided in Ricardo plc (2019). The values per ton of pollutant are then incorporated into the UK Treasury Green Book of damage costs (Birchby et al., 2020) used for policy value-for-money assessments.

Three sensitivities of damage costs are published for NO_x emissions relevant to a domestic setting, accounting for a range of potential geographies; 48,078 GBP per ton of NO_x, the high sensitivity damage cost, was used since this was most representative value for emissions sources occurring in or close to population centers, which is ultimately where most of the UK population lives (83% urban and 17% rural). In addition, this was the highest damage cost so gives the fullest plausible range of potential changes in NO_x when multiplied by our three scenarios.

To consider the effect on a local scale, lifetime emissions of a boiler were estimated, assuming a boiler is replaced on average every 15 years (Aste et al., 2013; Vignali, 2017) and that 23 million homes in the United Kingdom are connected to natural gas networks.

The NAEI (2019b) interactive map was used to analyze the effect of H2-NG blends to annual NO_x emissions in a small city. A $11 \times 13\ km^2$ section of the city of York was resolved in 1 km × 1 km squares. NO_x emission from "nonindustrial combustion plants" was calculated as an average from 3 screen-grabs of the same $11 \times 13\ km^2$ section. Nonindustrial combustion plants were the most appropriate emission reported sector available in the interactive inventory for translation to domestic combustion. All calculations were also carried out using NAEI 2019 NO_x emissions from domestic combustion, as a comparison to current emissions.

To put NO_x damage cost estimates into broader environmental context, a similar financial accounting approach was applied to carbon savings based on green hydrogen displacement of natural gas. Each H2-NG blend was converted to a natural gas saving, assuming hydrogen is 3.5 times less energy-dense than natural gas (Staffell, 2011; BEIS, 2021b). In 2019, the CO_2 emissions from residential combustion of natural gas were 66.5 Mt and with natural gas responsible for 86% of this (Bell et al., 2016; BEIS, 2021c). The amount of carbon saved relative to this was estimated for each H2-NG blend. Using the UK carbon price for November 2021 of 60 GBP per ton (Ember, 2021), carbon savings in millions of GBP were calculated.

NO_x emission changes for different H2-NG fuel blends — Literature synthesis

The linearized response of NO_x emissions from domestic combustion of H2-NG fuel blends is presented in **Figure 1**. The range of 0%–20% is considered as this is of interest for initial blending policies in the United Kingdom and is the range that is likely safely compatible with existing boilers without any substantial modification. For 5% hydrogen, this analysis suggests that NO_x emissions could change somewhere in the range –12 to +39%. For a 20% hydrogen blend, the span of effects increases, to the range of –50 to +154%.

There is no accurate information available regarding weighted types of domestic boiler/combustion appliances in use in the United Kingdom. The most useful information available is that in 2020, and 76% of homes with boilers have condensing boilers (Department for Levelling Up, Housing and Communities, 2021). Since these are often premixed, it could be implied from inspection **Table 1** that NO_x emissions will follow a case somewhere between the mean and best-case scenario. However, not all studies used account for the reduced energy output resulting from an increase in hydrogen fraction of H2-NG, including the study representing the best-case scenario. We also note the significant number of studies which showed a large increase in NO_x emissions. Hence, we cannot rule out with any certainty any of the given scenarios. The large differences between studies originate from different flame burner designs and experimental conditions used; equally, a wide range of different boilers and designs are likely in use currently in UK homes (Venfield and Brown, 2018). Hence, a mean regression scenario is reasonable to consider, shown in **Figure 1** in dashed red and used in our later analyses. Taking all relevant literature values and weighting equally give a mean NO_x emission increase of 7%–30% for blends of over the range 5%–20% hydrogen by volume. It is possible that this average scenario is a slight overestimation due to the inclusion of research burners in literature, but the inclusion of data from papers that may not have corrected for energy equivalence will balance this out to some degree. The annual UK NO_x emissions damage costs of different H2-NG blends are shown in **Figure 2** and are compared against the current estimated damage cost from natural gas domestic combustion of approximately 940 million GBP per year. Analysis of hydrogen effects is relative to a business-as-usual natural gas scenario to highlight the impact of an H2-NG blending policy in isolation. We do not attempt to account for other parallel policy interventions, such as increased buildings insulation, or the adoption of alternative low carbon technologies, such as heat pumps.

By increasing hydrogen fraction from 0% to 20%, damage costs would almost halve to 470 million GBP per year should emissions follow the best-case scenario (e.g., the most optimistic literature report), suggesting that with the right burner condition, hydrogen addition could be substantially beneficial for NO_x, when compared to natural gas. The mean (and likely most plausible) case indicates an increase in NO_x emissions and associated damage costs, rising by 292 million GBP per year compared to business

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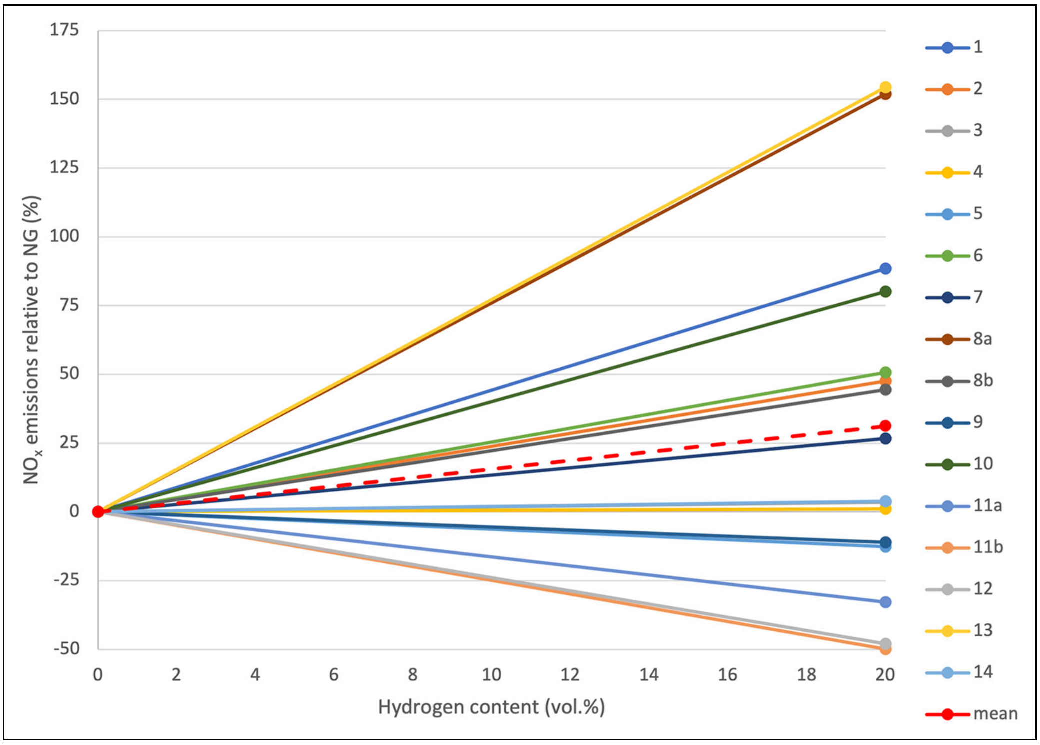

Figure 1. Nitrogen oxide (NO_x) emissions for hydrogen-natural gas fuel blends in domestic burners. Summary of reported effects of adding hydrogen to natural gas in domestic burners and resulting NO_x emissions. Numbers in the legend reference papers in **Table 1**, from which raw data were extracted. Presented here are the linear regression analyses of raw data from each study. NO_x emissions are presented relative to a pure natural gas or methane base case. The mean relationship (red, dashed) of all studies is also presented, weighting all studies equally. DOI: https://doi.org/10.1525/elementa.2021.00114.f1

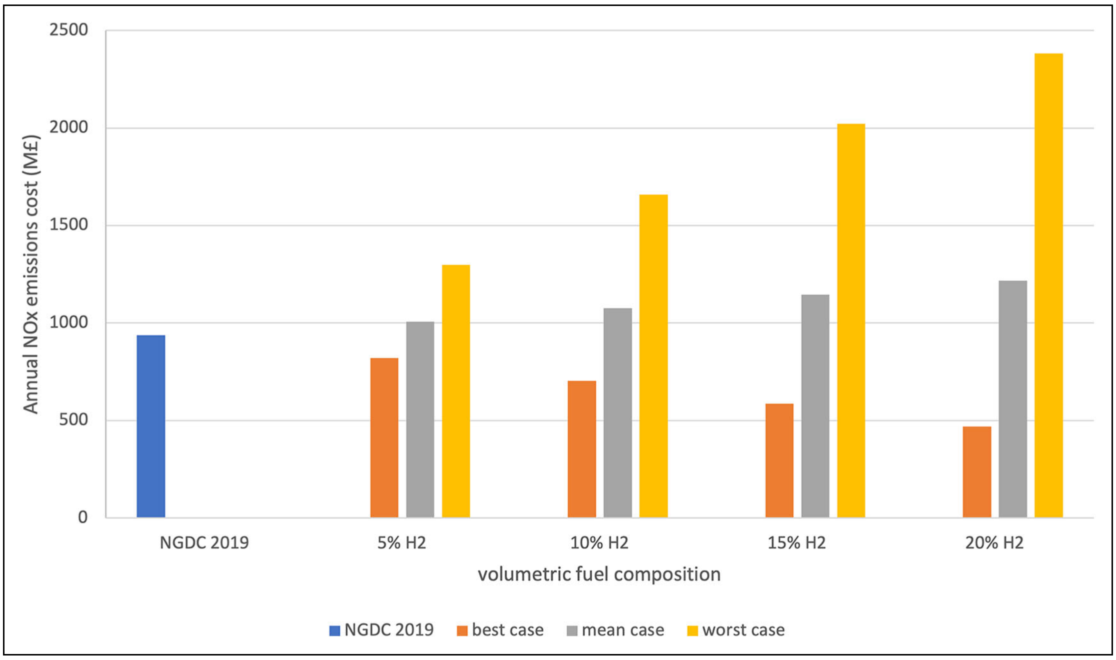

Figure 2. Annual nitrogen oxide (NO_x) emissions damage costs. Calculated for best (orange), mean (gray), and worst-case (yellow) scenarios derived from **Figure 1**. Natural gas domestic combustion 2019 (blue) is the current annual damage cost of NO_x emissions arising from domestic combustion of natural gas in 2019 *(National Atmospheric Emissions Inventory, 2019a)*, presented here for comparison. DOI: https://doi.org/10.1525/elementa.2021.00114.f2

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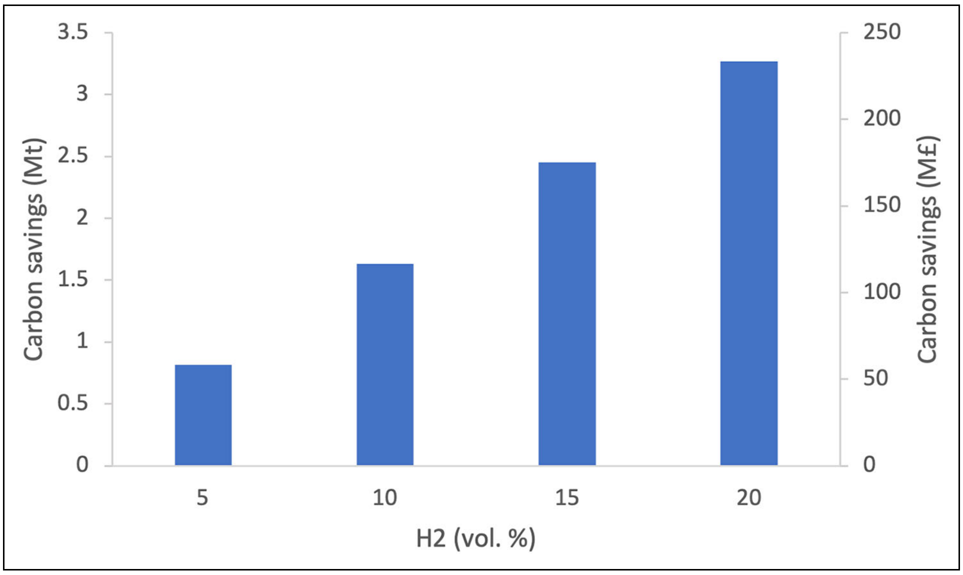

Figure 3. Carbon savings from addition of hydrogen into the United Kingdom natural gas network. Mass-based carbon savings are presented on the left axis. An estimation of carbon savings as an economic metric is presented on the right axis. This is based on a carbon price of 60 GBP/ton (Ember, 2021). DOI: https://doi.org/10.1525/elementa.2021.00114.f3

as usual with 100% natural gas. A significant increase in damage costs of 1,146 million GBP per year is estimated for the worst-case scenario (the least optimistic published raw data). These savings/costs are potentially large; however, the lack of directly relevant data and the sensitivity of outcomes to individual burner designs mean that the impacts are very difficult to predict with any certainty. This work can however provide some informative and evidence-based bounds to the possible scale of effect.

Figure 3 shows mass-based carbon savings from a H2-NG blending policy of up to 20% hydrogen. Due to the lower energy density of hydrogen compared to natural gas, a nationwide blending of 20% hydrogen would only reduce CO_2 emissions by 5.7% (3.3 Mt). If hydrogen blending is to become a mechanism for substantial national carbon emissions reduction, then the transition to higher hydrogen fraction fuels (beyond 20%) would need to occur relatively quickly after the infrastructure for blending is established.

Comparing NO_x damage costs to carbon impacts, expressed in economic terms in **Figure 3**, allows for an accounting-based estimate to be made of the overall environmental damage saving/cost of the policy to be evaluated. We acknowledge that NO_x damage cost and carbon pricing are not directly equivalent scientific metrics, the latter market-derived, the former a fixed value based on expert assessment. However, in policy-making apples versus oranges comparisons are frequently made when placed in an economic context. In addition, possible NO_x or indeed greenhouse gas emissions from the hydrogen production process have not been considered here. However, looking at the problem from an "emissions accounting" perspective may be useful for policy-makers to assess whether hydrogen-specific NO_x standards are needed. For the mean scenario of all H2-NG compositions considered, the economic cost of the small increase in NO_x emissions is offset by about two thirds by the carbon reduction arising from adding hydrogen to natural gas. However, when considering the worst-case NO_x emissions, carbon savings offset less than 16% of additional NO_x damage costs. In the most optimistic scenario, there is a combined benefit of around 650 million GBP per year for a 20% hydrogen fuel. Although the carbon price can fluctuate significantly, this analysis shows that best and worst cases lead to very different net outcomes in environmental economic terms.

Even with a 5% blend, the smallest hydrogen fraction fuel considered, the least optimistic scenario still brings risk. If boilers were to respond poorly to blending, a damage cost in the region of 300 million per year would be plausible. However, should the response in the real world follow the mean scenario then a small increase in NO_x damage cost could be anticipated, but offset to a large degree by carbon savings, a close to neutral policy in economic terms. Correcting for energy density, a 5% blend only saves 1.4 vol.% of natural gas. Hence, it should be considered whether this high risk for low reward is justified as a steppingstone to a long-term goal of full decarbonization of domestic combustion with hydrogen.

Impacts on NO_x emissions from H2-NG blends at appliance scale

The estimated impacts for NO_x emissions from a single boiler are presented in **Figure 4**. This follows the same pattern as annual NO_x emissions damage costs but emphasizes effects on individual households. It is clear from literature that it is feasible to engineer a gas boiler to emit lower NO_x from H2-NG blends, and regulation would ideally require that. Assuming a relatively long service lifetime of 15 years means it will likely be some time until hydrogen boilers, or those specifically designed for

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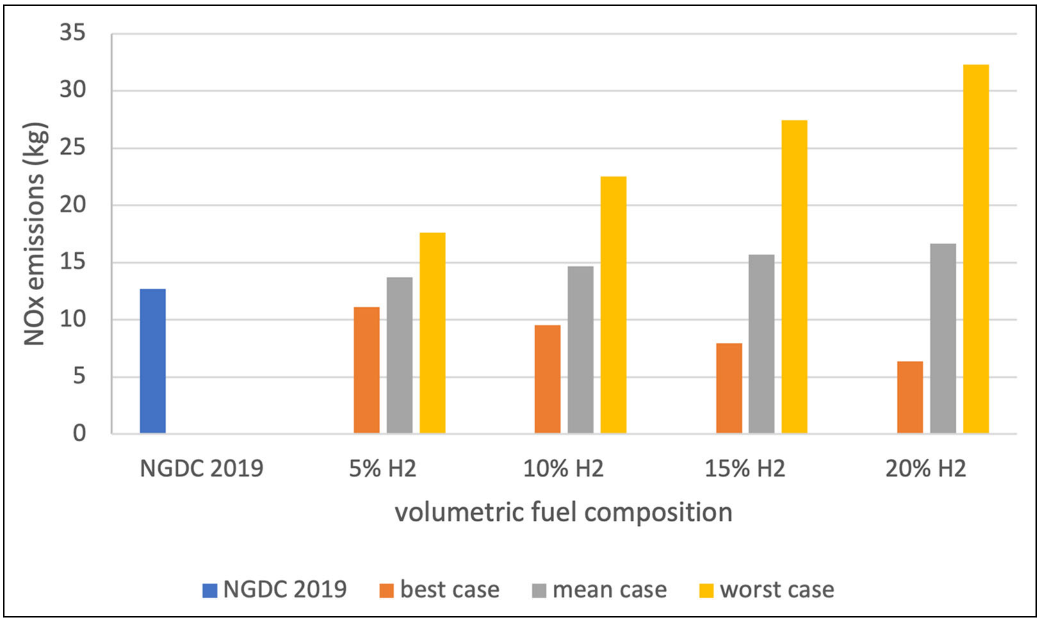

Figure 4. Estimated nitrogen oxide (NO_x) emissions for a single boiler over 15 years for different hydrogen-natural gas fuel compositions. An average 15-year boiler lifetime is assumed. Calculated for best (orange), mean (gray), and worst-case (yellow) scenarios determined from literature data in **Figure 1**. The natural gas domestic combustion (NGDC) value is derived from national emission estimates with a denominator of households connected to the gas network in the United Kingdom, estimated as 23,000,000 *(Bell et al., 2016)*. NGDC 2019 (blue) is the current annual NO_x emissions from domestic combustion of natural gas in 2019 *(National Atmospheric Emissions Inventory, 2019a)*. DOI: https://doi.org/10.1525/elementa.2021.00114.f4

H2-NG blends, are deployed at scale. If hydrogen blending is introduced in 2025, this would mean boilers supplied in 2010 would still be widely in use. Since regulations on NO_x from space heating were not introduced in the United Kingdom until 2018 (Commission Regulation [EU], 2013), these are unlikely to be the low-NO_x boilers that have been recently developed. Undoubtedly over time, the possible negative effects of hydrogen addition would diminish leaving only boilers designed for this fuel. However, that transition could take upwards of 20 years to fully complete, considering that hydrogen boilers are still in prototype stages and natural gas boiler installations in existing homes are not expected to be banned until 2035 (BEIS, 2021d). The effects here therefore represent impacts on "day one" in a hydrogen fuel transition. Mitigation of NO_x emissions effects, for example, through accelerated boiler replacement, would not be necessary in the best-case scenario. Should emissions follow the worst-case scenario, there is potential for emissions per boiler to increase to 32.3 kg in its lifetime if run on 20% hydrogen. Using the high sensitivity damage cost values for emissions in the urban environment, 32.3 kg of NO_x would generate approximately 1,590 GBP in damage costs over the 15-year lifetime of the boiler (5% annual discount rate applied). Accounting for carbon savings (with the same discount rate) reduces the net cost to approximately 750 GBP, suggesting boiler replacement may not be necessary. If carbon savings are not considered, however, assuming a new boiler price approximately 2,000 GBP, this would indicate an approximate 1.25-life cycle payback based solely on NO_x emissions avoided. This suggests that an economic case for accelerated home boiler replacement could be constructed largely around a justification of "NO_x avoided" rather than the perhaps more intuitive "carbon saved."

Significance for an urban NO_x budget

In locations where urban NO_x emissions from road transport are declining due to better regulation and fleet electrification, it is valuable to consider what fraction of urban emissions derive from domestic combustion and how this might change in the future. The impacts on annual NO_x emissions in York, UK (population approximately 210,000, urban area approximately 140 km^2, and total area 270 km^2) have also been considered using the 3 possible hydrogen scenarios. York was chosen to model a small city whose major source of NO_x emissions, aside from transport, is domestic combustion. There are no large industrial sources, energy production facilities, or other sources such as shipping or aviation. Currently, annual NO_x emissions from nonindustrial combustion plants from the 143 km^2 area considered are 175 ton per year or 14% of total city NO_x emissions. Blending of 20% hydrogen into the gas network in the city could see emissions from this sector reduce to 88 ton or 8% of total NO_x in a best-case scenario, to the other extreme increase by 445 ton of NO_x in the worst case, making up almost 30% of total NO_x emissions. Based on current projections, road transport emissions in UK cities are estimated to fall by a further 40% by 2030, which would leave domestic combustion from a H2-NG making up 35% of emissions in 2030. With transport making up only 30% of NO_x

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emissions in this scenario, domestic combustion could become the dominant source of NO_x emissions in the city.

Conclusions

In this article, we have conducted a meta-analysis of existing data on NO_x emissions from the combustion of H2-NG blends in gas boilers. This has allowed us to present the range of possible changes in NO_x emissions if hydrogen was added into the natural gas network, a policy that has significant political support in the United Kingdom (BEIS, 2021a). We consider only the impacts of blends up to 20 vol.% hydrogen, consistent with the short-term aims of the UK Hydrogen Strategy, and a gas mixture that would likely be safely compatible with existing equipment. Despite the rapid development of test case deployments and proposals for scale-up, we find remarkably little in the way of quantitative assessment of how adding hydrogen to natural gas may impact on NO_x emissions, a crucial component of air quality and public health.

A review of literature reveals a huge range of possible changes in NO_x emissions from H2-NG fuel blends, a result of experimental and appliance variation in the original literature. A key issue is the inconsistency regarding whether the difference in energy density of hydrogen and natural gas is accounted for in literature data. Nonetheless, this is the only firm evidence base available from which estimates of effects or at least bounds on effect can be made. Since we do not have information on the specific types of domestic burner systems used in the United Kingdom, we do not propose any of our scenarios to be more likely than another. But we do note that much of the literature data indicates increasing NO_x emissions as hydrogen composition is increased. These limitations deriving from the original literature mean our necessary methodological assumptions are integrated within results but have allowed us to present the full range of potential outcomes for NO_x. The primary aim of hydrogen blending is not to reduce NO_x emissions but to decarbonize domestic combustion through a low-regret option. Analysis indicates that hydrogen blends could indeed be low regret if burned in favorable boilers and would generate a substantial air quality cobenefit in addition to the primary carbon reduction objective. However, our mean and worst-case scenarios show sizable increases in NO_x emissions, where the damage costs begin to significantly outweigh carbon savings. The air quality risk associated with hydrogen blending should be considered, especially since the small hydrogen fractions considered in this study result in carbon savings of less than 6%.

For boilers that perform poorly with H2-NG blends, a positive economic case for investment in accelerated scrappage and replacement can be constructed based on the combined NO_x and carbon reductions that might be delivered from new custom designed boilers. Although undoubtedly any introduction of hydrogen into a national gas network would proceed slowly, and most likely only on a regional basis initially, we estimate that even small % blends could have notable impacts on NO_x emissions and that these may be significant at city scale in the wider context of ever-reducing road transport emissions of NO_x. Our analysis should not be construed as either pro or anti-hydrogen as a fuel. We raise only the issue of limited evidence on the performance of the existing boiler infrastructure and the possible effects on NO_x emissions, something which in turn may alter the economic case for hydrogen as a net zero fuel for domestic combustion. A program of testing of older representative appliances would help resolve this important outstanding evidence gap, as would the inclusion of NO_x monitoring in field trials where H2-NG gas is being deployed. This would allow our range of NO_x outcomes to be narrowed, potentially leading to more certainty on the most likely NO_x scenario as a result of H2-NG blending in the United Kingdom.

Data accessibility statement

All data in this study are derived from the existing literature sources. A compilation of all raw data from each relevant literature study and the linear regression analyses is publicly available as a data set from the University of York: Lewis, Alastair; Wright, Madeleine (2021), [Meta-analysis dataset for hydrogen—natural gas NO_x emissions], University of York, https://doi.org/10.15124/796b46d1-7b61-478e-98d6-6bcd4af274b1.

Supplemental files

The supplemental files for this article can be found as follows:

Figure S1. Calibration curve to expand experimental data from data set 13 (**Table 1**).

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ACL is an associate editor of *Elementa* but has not been involved at any stage in the reviewing or assessment of this article for publication.

Author contributions

Contributed to conception and design: MLW, ACL.

Contributed to acquisition of data: MLW, ACL.

Contributed to analysis and interpretation of data: MLW, ACL.

Drafted and/or revised this article: MLW, ACL.

Approved the submitted version for publication: MLW, ACL.

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