AIR QUALITY EXPERT GROUP

Air pollution arising from hydrogen combustion.

Prepared for:

Department for Environment, Food and Rural Affairs;
Scottish Government; Welsh Government;
and Department of Agriculture, Environment and Rural Affairs in Northern Ireland

This is a short advice note from the Air Quality Expert Group to the Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of Agriculture, Environment and Rural Affairs in Northern Ireland, on the scientific and technical issues associated with the combustion of hydrogen gas that may be relevant to air quality. The information contained within this report represents a review of the understanding and evidence available at the time of writing.

Front cover image credit: Hydrogen flame in air (Shutterstock, 2023)

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Summary

Expanding the use of hydrogen as a zero carbon fuel has some potential implications for air quality if it is used as a combustion fuel. Using hydrogen to power fuel cells that directly generate electricity does not create any air pollution at point-of-use. When hydrogen is burned in engines, boilers, cookers and furnaces the very high temperature of the flames can split apart nitrogen (N_2) in the air leading to the formation of nitrogen oxides (NO_x), an important class of air pollutant. Hydrogen burns with a hotter flame than most fossil fuels and has the potential to emit more NO_x per unit of heat that is generated. On the other hand burning hydrogen gas instead of hydrocarbon fuels (e.g. gasoline, diesel, or bioderived fuels such as ethanol) can bring benefits for air quality, producing lower emissions of particulate matter and eliminating carbon monoxide. Reducing emissions of NO_x from the combustion of hydrogen can be achieved in many situations using existing exhaust aftertreatment technologies, by lowering the temperature at which the hydrogen is burned and by optimising the ratio of fuel to air. This can sometimes leads to additional cost and/or a reduction in energy efficiency. There are few commercially available examples of engines or boilers that have been specifically designed to burn hydrogen and real-world data on emissions performance is very limited. To ensure hydrogen fulfils its potential to be a substantially cleaner fuel from an air quality perspective requires effective NO_x emission controls (both technical and regulatory) to be in place.

Background and introduction

Hydrogen has been identified by the Department for Energy Security and Net Zero as a potentially important future energy source that will support UK net zero ambitions, with possible uses spanning from industry and energy generation to the home. This short advice note summarises some issues related to the impacts on air pollution emissions, concentrations and exposure from using hydrogen as a fuel. The focus of the advice note is the use of hydrogen in combustion systems, including boilers, furnaces, internal combustion engines and turbines. Hydrogen can also be used as a fuel in electrochemical fuel cells, however since this technology only generates water as a by-product it is not described in detail here.

The technology, climate impacts and economics of hydrogen production have been subject to significant academic and policy debate. Our focus is on the air pollution implications from use of hydrogen as a fuel, rather than air pollution emissions from production and leakage. Some production routes for making hydrogen seem likely to also generate air pollution emissions. Supply chain impacts on air pollution are not covered in this note, although ultimately they would need to be reflected in industrial emissions accounting and control. There has previously been some consideration of the atmospheric impacts of leakage of hydrogen to the atmosphere (e.g. Schultz et al., 2003; Derwent, 2018, Sand et al. 2023) which include increased stratospheric water content and climate impacts via perturbation of global methane and ozone cycles. Whilst the effects of hydrogen leaks on ozone are arguably also air quality effects, they are likely modest compared to the direct effects arising from combustion.

The implications of using hydrogen for combustion and the effects that might occur at point-of-use were highlighted in earlier work by AQEG on the impacts of net zero actions on air quality (AQEG, 2020) and this note explores that aspect of net zero in more detail. In AQEG’s report on air quality and net zero hydrogen combustion was identified as being potentially highly beneficial for reducing PM, CO, SO_2 and VOC emissions, but that there was the potential for continued emission of NO_x. In 2020 AQEG noted that the use of hydrogen as a mainstream fuel was still in its infancy and in many end-use sectors there were very few datasets to provide quantitative insight into real-world emissions. That position is little changed in 2023 and a more quantitative exploration of the effects of using hydrogen at large scale in different sectors remains hampered by lack of basic emissions and performance data.

A key limitation in evidence is that data in peer reviewed literature that reports emissions of pollutants such as NO_x and PM is generated frequently using appliances that have been converted in the lab from fuels such as natural gas, gasoline or diesel to burn hydrogen instead. Whilst this data can be highly instructive it is potentially not reflective of how appliances that are designed from first principles to burn hydrogen would perform.

The advice note provides short answers to a set of questions agreed with Defra.

1. How do the combustion properties of hydrogen and hydrogen-fossil fuel blends differ from fossil fuels when used in a) boilers and b) internal combustion engines?

The only major air pollution emission arising from the combustion of hydrogen is NO_x. The high temperature combustion of hydrogen leads to NO_x formation via the Zeldovich mechanism (Zeldovich, 1946), also referred to as 'thermal NO_x'.

The key reactions steps are:

$$N_2 + O \rightleftharpoons NO + N \qquad (k_1)$$
$$N + O_2 \rightleftharpoons NO + O \qquad (k_2)$$
$$N + OH \rightleftharpoons NO + H \qquad (k_3)$$

In most combustion circumstances the first forward reaction rate constant (k_{1f}) is the rate determining step since it involves breaking the very strong 'triple' bond in molecular N_2. High temperatures in the flame lead to the decomposition of atmospheric N_2 and O_2 into atomic N and O, which then go on to react and form NO. NO production *via* this mechanism occurs in all fuel-air mixed flames burning hotter than around 1300 °C regardless of whether the fuel is hydrogen, fossil hydrocarbons such as gasoline or diesel, or bio-derived fuels such as ethanol or Hydrotreated Vegetable Oil (HVO).

Combustion of hydrocarbon fuels (e.g. natural gas, gasoline etc) can also lead to the formation of NO *via* other mechanisms: 'prompt NO_x' via reaction of $CH + N_2 \rightarrow HCN + N \rightarrow \rightarrow NO$, and 'fuel NO_x' derived from traces of organic nitrogen in both liquid and solid fuels. Whilst pure hydrogen combustion is not impacted by these two effects, hydrogen-natural gas (or hydrogen-diesel) blends generate additional prompt NO_x derived from the methane in the fuel mixture.

A key property of hydrogen combustion is that it can generate hotter flames than hydrocarbon equivalents both in open flame boilers and in the cylinders of internal combustion engines. The production of thermal NO_x is sensitive to temperature and the amount of NO_x emitted increases as flame temperature increases. Plotting the reaction rate constant (k_{1f}) as a function of temperature illustrates that there are different NO_x formation rates for natural gas compared to hydrogen (Figure 1).

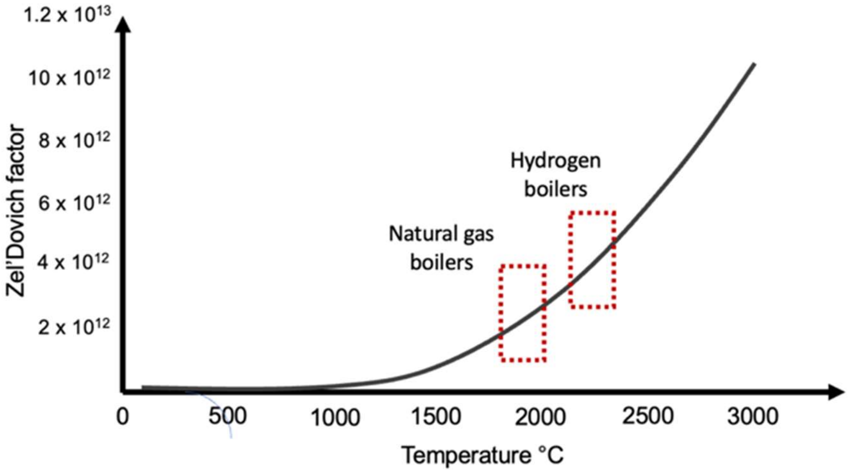

Figure 1. Likelihood of formation of a NO product represented as Zeldovich factor (which has units cm^3 mole^{-1} s^{-1}) for reaction rate constant (k_{1f}) as a function of temperature. Red boxes show typical flame temperatures for natural gas and hydrogen fuelled boilers.

Whilst the basic physical chemistry of hydrogen combustion is one that tends towards hotter flames and thus greater production of thermal NO_x technical interventions including optimising burner conditions and adding exhaust aftertreatments can manage the effect and reduce emissions. The NO_x emissions released from hydrogen-fuelled systems are therefore to a large degree defined by the degree of abatement that is applied to them, as for hydrocarbon-fuelled appliances. Often studies of emissions from the burning of hydrogen use converted boilers or engines originally designed for other fuels.

An important benefit of using hydrogen fuel from an air quality perspective is that combustion does not generate substantial quantities of particulate matter (PM) directly or lead to emissions of combustion by-products such as SO_2, VOCs or CO. The use of hydrogen for heating and cooking and the elimination of CO emissions from faulty domestic gas combustion appliances is potentially a substantial benefit for indoor air quality. In some use-cases such as hydrogen internal combustion engines, small amounts of PM for example may be generated from lubricants in the cylinders. It is to a degree semantics whether these should be categorised as ‘hydrogen emissions’. If used as a fuel in aircraft turbines at high altitude the water vapour released in exhaust would continue to lead to contrail formation.

Answers to Defra’s questions in this advice note will focus primarily on the most prominent issue to consider from a regulatory perspective which is related to NO_x emissions, rather than PM / CO reductions and pollution avoided. However, these benefits do need to be kept in mind and for some applications burning hydrogen may be advantageous from an air quality and climate perspective where the counterfactual is continued use of fossil fuels.

Gas boilers

Hydrogen can be added to natural gas to fractionally reduce fossil carbon emissions or used on its own as a pure gas. The industry consensus is that up to 20% v/v hydrogen can be safely blended into the natural gas network before any changes to pre-existing pipework and gas boilers would be needed. The evidence related to NO_x emissions arising from blends of small amounts of hydrogen (5 - 20% v/v) with natural gas was recently reviewed in Wright and Lewis (2022a). This indicated a mixed set of results from across the literature with some laboratory studies indicating higher NO_x when hydrogen was added (compared to pure natural gas, and on an energy equivalency basis) and others lower (range of -12% to +39% NO_x with a mean change across 14 studies of +8%).

Data on NO_x emissions from contemporary gas boilers that are designed to burn blends or pure hydrogen is not available in the open literature and this is a major data gap. There are currently no peer-reviewed field trials at the domestic scale, although some test installations in homes are planned in the UK. Reports from manufacturers or government provide little insight into likely real-world emissions.

Most recently in the 2022 Chief Medical Officer’s Annual Report on Air Pollution, BEIS reported that “*Hydrogen policy teams [are] developing standards for domestic and industrial appliances for hydrogen combustion, to ensure that the NO_x emissions are no higher than from the current natural gas appliances*”. This would suggest that the NO_x emissions from pure hydrogen burning boilers should be assumed at this stage of technical development to be broadly similar to current natural gas appliances. This would deliver compliance with Ecodesign Directive limits on emissions of NO_x and other pollutants. It is notable that UK proposals for future product standards for energy-related products (BEIS, 2021) is framed only around energy efficiency and makes no reference to non-CO_2 emissions.

Internal combustion engines

Hydrogen can be used as a pure fuel or in a blend with hydrocarbons in both spark ignition and compression ignition engines, indeed the world’s first internal combustion engine in 1804 ran on a hydrogen / oxygen blend. There is extensive literature on air pollution emissions from hydrogen-fuelled spark ignition engines from the 1980s and 1990s notably from Japan where for a time hydrogen-fuelled Internal Combustion Engine (ICE) passenger vehicles appeared to have some technological advantages (Wright and Lewis 2022b). It now seems very unlikely that ICE hydrogen passenger cars will emerge as a mainstream product although fuel cell vehicles remain a possibility. Fuel cell passenger cars emit no NO_x at point-of-use but still generate non-exhaust PM emissions, similar to battery electric vehicles (AQEG, Non-exhaust emissions report, 2019). It is worth noting that fuel cells more generally require hydrogen gas of considerably higher purity than can be used for combustion.

Hydrogen is however considered a serious option for either pure fuel or co-fuelling in larger compression and spark ignition engines, notably as a route to decarbonising larger diesel applications. These include off-road machinery and static engines. The demanding energy requirements of off-road machinery, coupled to high asset utilisation rates (high value construction equipment may be used up to 20 hours per day), and sometimes limited access to grid energy, may make hydrogen engines the only near-term viable decarbonisation route.

Broadly speaking the amount of NO_x that is produced in an ICE is a function of the temperature of that combustion. Temperature is determined by engine design but is universally a function of the fuel-to-air mixture used (the equivalence ratio ϕ). Varying ϕ leads to changes in mechanical and fuel efficiency. In combination this results in the engine-out amount of NO_x being controllable to a degree, but sometimes being traded off against efficiency (Figure 2).

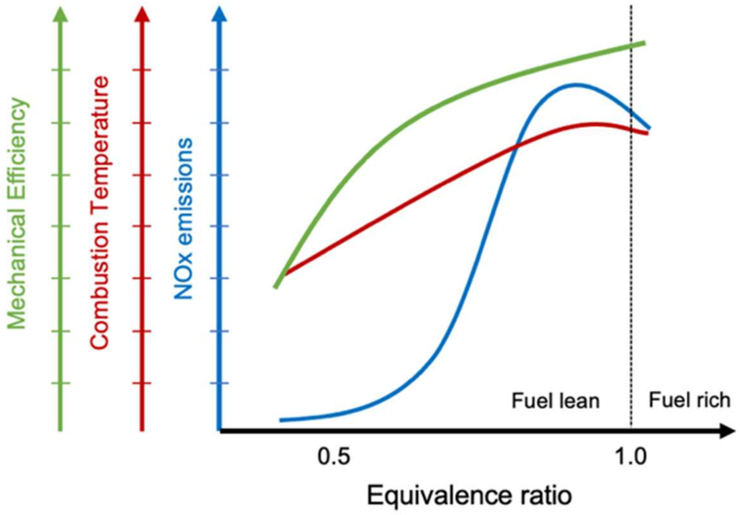

Figure 2. The stylised variation of mechanical efficiency, combustion temperature and NO_x emissions as a function of the equivalence ratio ϕ in an internal combustion engine converted from gasoline to hydrogen. The equivalence ratio is a measure of the amount of fuel relative to the amount of air. A 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. Reproduced from Lewis, Env. Sci: Atmos., 2021.

For all ICE engines the potentially hot combustion of hydrogen creates potential for NO_x formation, but well-understood mitigations such as burning very lean, fuel pre-mixing, exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) aftertreatment can all be applied. Whilst modern Euro 6/VI SCR systems are generally effective for abatement of NOx, it is notable that some evidence has emerged that their widespread use in the vehicles fleet has led to urban increases in ammonia (Reche et al. 2022). A recent review by Wright and Lewis (2022b) highlighted that hydrogen fuel as a replacement for diesel fuel could be beneficial for NO_x emissions in automotive sectors where extended periods of idling or low loads were commonplace, such as construction equipment. However, using hydrogen could be potentially detrimental for NO_x in continuous high-load applications such as capacity market power. Whilst NO_x emissions from hydrogen-fuelled ICE requires suitable controls its use does bring other clear air quality benefits. Hydrogen engines have reduced tailpipe PM emissions (although some still arise from lubricants) and they eliminate emissions of volatile organic compounds from the tailpipe or evaporative loses from the fuel system.

There is little evidence on emission performance from purpose-designed hydrogen engines, a consequence of the huge cost associated with designing and building a new engine from scratch. One example that is instructive however is from JCB who have developed a very lean burning four-cylinder 4.6 L swap-in spark ignition hydrogen engine for medium-sized off-road equipment such as backhoe loaders[1]. Portable Emission Measurement System (PEMS) testing on standard non-road mobile machinery (NRMM) cycles indicated that emissions of NO_x would easily meet current Stage V limits for NO_x (measured: 0.3 g kWh^{-1}, vs limit of 0.4 g kWh^{-1}) with very little or no exhaust aftertreatment. When a classical SCR system was added as aftertreatment this reduced tailpipe NO_x emissions close to zero (0.02 g kWh^{-1} for the NRMM cycle). PM emissions were also very substantially reduced. Under the current regulatory regime for NRMM there is no specific emissions class for hydrogen fuelled engines, instead such vehicles would need to meet only Stage V standards designed for diesel fuel.

Whilst this is only one commercial example it provides significant encouragement that purpose-designed hydrogen appliances have the potential to be engineered to deliver substantial improvements in NO_x emissions performance when compared to the diesel engines they would directly replace.

2. How can hydrogen and hydrogen-blend emissions be regulated and abated to ensure no additional NO_x emissions (“no back sliding”) in real-world applications, compared with current fossil fuels?

The production of NO_x from the combustion of hydrogen can be abated in many applications using the same technologies that are currently used for fossil fuels. There are trade-offs between overall energy efficiency, production cost and NO_x emissions, as there are with fossil fuels. Lewis (2021) reviewed the potential range of uses for hydrogen and identified that in many cases the NO_x emissions arising from burning hydrogen would not be fundamentally limited by available technologies. Instead, they would be largely defined by the regulatory standards that were applied.

Currently, when used as a combustion fuel, hydrogen is treated from an air quality emissions perspective as if it was a fossil fuel. A hydrogen-burning domestic space heating boiler for example would be subject to existing NO_x, CO, PM etc emission limits per kWh defined in the Ecodesign Directive. Prevailing EURO standards would apply in the automotive sector. Stage V standards would apply to NRMM. Noting that NO_x emissions are often a trade-off with energy efficiency and abatement aftertreatment adds cost, it seems reasonable to conclude that in most cases hydrogen combustion appliances would be designed to maximise energy efficiency as a first priority. They would undoubtedly meet their regulatory air quality obligations on NOx emissions but may not greatly exceed them, if doing so brought a fuel inefficiency, heat / work, or manufacturing cost penalty.

It is notable that domestic natural gas boilers that are being brought into service today under-emit compared with the regulatory limits for NO_x emissions of 56 mg kWh^{-1} (Greater

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[1] https://www.jcb.com/en-gb/campaigns/hydrogen

London Authority, 2018). Manufacturer reported nominal emission rates can be half the regulated limit. This creates the possibility that future use of hydrogen may lead to higher emissions in real-world use while remaining within permitted Eco-design Directive limits. This would be an important deterioration in emissions without back-sliding from a regulatory point of view.

The regulatory system for point sources of air pollution is to a degree adaptive through installation-specific permitting by the Environment Agency and parallel responsible agencies in the Devolved Administrations. A new medium-sized combustion plant (MCP) that burned hydrogen – for example an ICE generator plant to provide electrical power at peak demand – would be initially subject to existing fossil fuel NO_x (and other pollutant) emission limits within the MCP Directive. Should evidence for enhanced performance and lower emissions from hydrogen installations emerge then limits on emissions from individual installations can theoretically be tightened to reflect Best Available Techniques (BAT). Therefore *de facto* hydrogen-specific limits on air pollution emissions via BAT could potentially emerge from within the existing regulatory framework.

Local planning policies often drive the adoption of technologies with emissions that are lower than national regulations. For example, the Greater London Authority has set emissions standards for natural gas boilers and Combined Heat and Power plant which are more stringent than those set nationally (Greater London Authority, 2014). Small gas boilers in new building developments in London must emit less than 40 mg kWh^{-1} NO_x, rather than the national limit of 56 mg kWh^{-1}. Furthermore, planning requirements to demonstrate 'better by design' (Moorcroft and Barrowcliffe, 2017) or 'air quality positive' (Greater London Authority, 2023b) encourage moving beyond minimum standards. There are thus opportunities to encourage techniques with demonstrably lower emissions regardless of the overarching regulatory standards applied.

Emissions from construction equipment can also be intertwined with the planning and permitting of developments. For example, the use of equipment that meets certain standards can be a condition of planning approval. Given the potentially large reductions in NO_x and PM emissions that might be delivered by hydrogen ICE NRMM (should the data from JCB be replicated in general use and by others), then the development of hydrogen-specific standards would likely be influential in accelerating adoption (assuming hydrogen fuel was available and cost-competitive). Placing hydrogen NRMM within the existing framework of Stage V controls designed for diesel engines may limit the extent to which planners can differentiate between diesel and potentially cleaner hydrogen.

Whilst the focus in this note is on plausible near-term uses of hydrogen in engines and boilers, it is also possible that hydrogen may be used longer-term in other sectors like long-haul aviation and for international maritime. These sectors have regulations on emissions of air pollutants set often at the international level by ICAO and MARPOL, respectively. In aviation the use of hydrogen in gas turbines has been explored since the 1980s (Brewer, 1982), although it brings formidable technical challenges to use in practice, not least requiring cryogenically liquified hydrogen rather than compressed gas. Rolls Royce and Airbus have hydrogen-fuelled gas turbines under development for aviation[2,3]. There is some

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[2] https://www.rolls-royce.com/innovation/net-zero/decarbonising-complex-critical-systems/hydrogen.aspx

[3] https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

trade reporting that future hydrogen jet aircraft engines would likely deliver lower NO_x than current kerosene fuelled ones[4]. They would also be anticipated to have lower ultrafine particle and black carbon emissions, and no SO_2 emissions (Beyersdorf et al., 2013).

In maritime it seems possible that ammonia, rather than hydrogen, may be used as a low carbon fuel[5]. Combustion of ammonia also generates NO_x emissions and probably some PM. Large marine power-plant installations typically use substantial aftertreatment systems to clean exhaust gases and releases to air are likely to be determined largely by the aftertreatment and standards that are applied.

Existing air pollution emissions standards that were designed for fossil fuels provide therefore an immediate regulatory backstop that limits potential NO_x emissions from new and emerging hydrogen-fuelled appliances to being no worse than current fossil fuels. However, the concept of no regulatory back-sliding may not prevent emissions that are worse than current fossil fuel use. There is however likely to be value in exploring whether ambitious hydrogen-specific standards that deliver lower NO_x and PM emissions than existing fossil fuel equivalents (eg Euro 6d, Stage V, Ecodesign etc) would accelerate adoption and air quality benefits.

3. *Are there gaps in emissions regulations for boilers and combustion engines that could lead to increased NO_x emissions when hydrogen and hydrogen blends are combusted?*

Although Ecodesign and the MCP provide regulatory backstops in many applications they do not apply to all combustion scenarios. A regulatory gap exists between the two regimes for plant between 500 kW and 1 MW, although most electrical generators of this size are regulated, depending on their usage. This is the type of combustion plant that might heat a large commercial or public building for example. The 2019 Air Quality Strategy highlighted this regulatory gap. The Emissions Reduction (Local Authorities in London) Bill introduced in the House of Lords in 2021 contained provisions for the Secretary of State to specify emission limits for plant of less than 1 MW. There is also a risk that manufacturers and the market may favour plant that is sized to fit in this regulatory gap rather than bear the cost of abatement. Hydrogen fuel may be well-matched to many applications in this 500 kW to 1 MW band of installations and so the current regulatory gap becomes relevant to future fuels as well as existing ones.

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[4] https://www.aerospacetestinginternational.com/features/why-hydrogen-as-an-aviation-fuel-is-in-for-the-long-haul.html

[5] https://www.ammoniaenergy.org/topics/ammonia-internal-combustion-engine/

4. How would the combustion of hydrogen and hydrogen blends affect the attainment of current limit values for NO_2 in ambient air and pathways to the attainment of World Health Organisation guidelines in the future?

Emissions of NO_x have fallen dramatically in the UK over the last 30 years (with over a 70% decline relative to 1990 in 2021) particularly from the energy generation and transport sectors. It is a very rapidly changing picture with road transport emissions falling substantially year-on-year as newer (and now often hybrid/electrified) vehicles enter the transport fleet displacing older more polluting ones. At the same time however evidence on the health impacts of NO_2 has also evolved; the latest WHO air quality guidelines recommend exposure to an annual average of no greater than 10 $\mu g\ m^{-3}$. This is significantly lower than the previous guideline of 40 $\mu g\ m^{-3}$, which is also the current UK and EU annual average limit value. The retention of emissions from relatively modest NO_x sources (by historical standards) becomes more significant in the light of these new health evidence and guidelines.

COMEAP (2022) stated they regarded the WHO's revised air quality guidelines (WHO, 2021) as suitable long-term targets to inform policy development in the UK. The Committee commented that guideline values should not be regarded as thresholds below which there are no impacts on health: continued reductions in pollutant concentrations, even where levels are below the AQGs, are also likely to be beneficial to health.

WHO (2021) note that the existing evidence generally supports a linear, or supralinear, no-threshold relationship for the various pollutants examined in the systematic reviews, which underpin the guidelines. They explain that the concentrations used as the starting points for guideline development are not equivalent to thresholds of no effect; rather, they are levels below which there is less certainty about the existence of an effect.

The potential role and uptake of hydrogen is of course highly uncertain and indeed it may not ultimately emerge as a competitive technology at all in the long term. Nonetheless it is useful to gain a sense of scale around how significant possible emissions of NO_x might be from future combustion of hydrogen, using current and future emissions of NO_x from road transport as a broadly understood comparator.

Figure 3 draws on data from the National Atmospheric Emissions Inventory for UK NO_x emissions from road transport (segmented by passenger cars, LGV and HDV), from commercial combustion of natural gas and from domestic combustion of natural gas (for both water and space heating). Future projections for 2025, 2030 and 2040 from the NAEI are included on the same plot. The fraction of NO_x emissions assigned to gas arising from domestic and commercial combustion is based on the spilt between energy sources for the NAEI year 2021 and projected into the past and future as a first approximation. In the very recent past, road transport was clearly a much larger source of NO_x in the UK than natural gas combustion in homes and businesses, but that position is changing rapidly.

There is spatial variation in the proportion of heating (both domestic and commercial) and transport. In central London, NO_x emissions from heating have been greater than those from transport for the last ten years (Greater London Authority, 2023). In 2019, industrial, commercial and domestic heating and power was estimated to produced 56% of total emissions. In inner and outer London, it is projected that heating will be the largest source of NO_x by 2030. London is not unique in this respect. For the City of York, Wright and Lewis (2021a) predicted that domestic heating will also be a larger emitter of NO_x than road transport by 2030.

A very simplistic scenario is to imagine that current consumption of natural gas for domestic and commercial combustion is simply swapped for an energy-equivalent amount of hydrogen gas over time, that demand remains constant and NO_x emissions are identical per kWh delivered. Would this retained emission create a barrier to the attainment of WHO NO_2 guidelines in the future? Arguably consumption of natural gas might well be reduced faster than projections and replaced with electrification, making this an overestimate. Conversely laboratory evidence suggests that real-world NO_x emissions from hydrogen in boilers per kWh might be higher than current natural gas (but still within regulatory limits).

By the mid-2030s retained gas combustion (whether hydrogen or natural gas) would be a larger source of NO_x than all of UK road transport combined. There are of course many approximations and uncertainties in this very simple illustration, but it provides a sense of scale of the issue. Swapping hydrogen for natural gas for space heating and hot water retains NO_x emissions into the future, whereas a shift to electrification or to use hydrogen in fuel cells would eliminate them. It is important to note that NO_x generated from space and water heating and cooking is released near to people, and so has an amplification to its effects similar to road transport (Lewis, Nature, 2021).

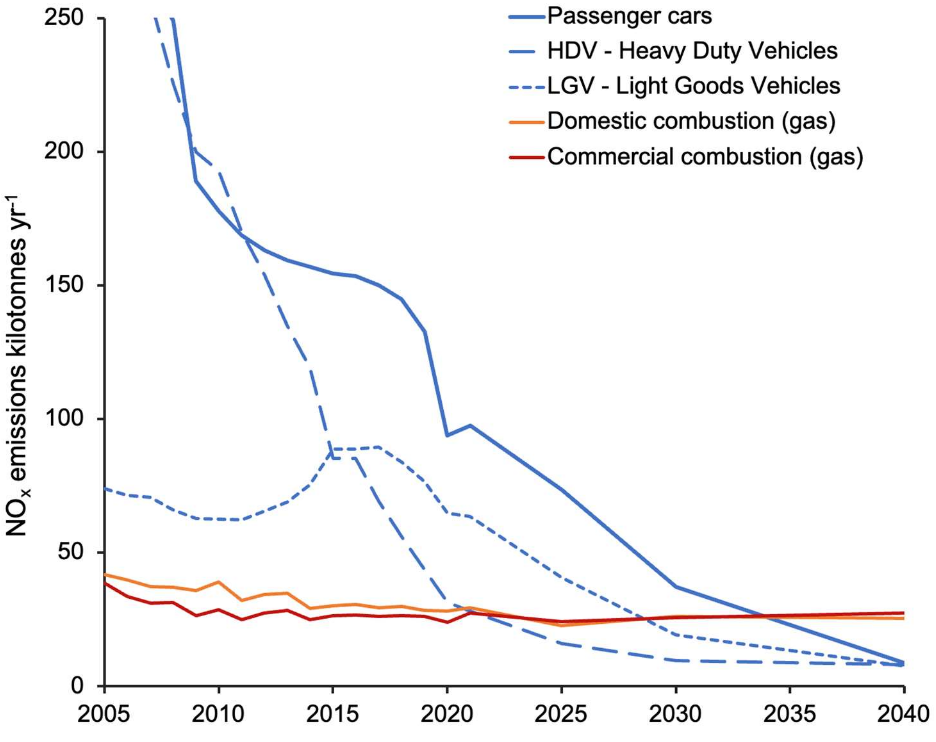

Figure 3. Past and estimated future UK NO_x emissions for Passenger cars (long blue dashes), LGVs (short blue dashes), HDVs (long blue dashes), domestic (orange line) and commercial (red line) combustion of natural gas. (naei.beis.gov.uk)

Converting emissions to potential ambient concentrations requires a model. In Figure 4 the CMAQ 2 km x 2 km air pollution model (2019 data) is used to estimate annual average NO_2 concentrations in the UK, should the only remaining source of NO_x be domestic and commercial use of gas. If one assumes that hydrogen and natural gas heating systems were to emit equivalent amounts of NOx, then Figure 4 provides a guide to the annual NO_2 arising from a full conversion to hydrogen for heating. The distribution of NO_2 becomes closely linked to population centres with some urban locations exceeding the 10 $\mu g\ m^{-3}$ WHO guideline from these heating sources alone. In practice the elimination of all other sources of NO_x is highly implausible, so heating contributions more reasonably would sit on top of remaining NO_2 from other sources such as energy, NRMM and so on. It does however provide an indication of scale of the difference that taking plausible alternative decarbonisation pathways might have on air quality – up to 10 $\mu g\ m^{-3}$ in NO_2. As identified earlier, the focus in the note is the potential disbenefit arising from remaining NO_x emissions, and undoubtedly scenarios can be envisaged where improvements in $PM_{2.5}$ would be generated should hydrogen displace fossil fuels in other sectors.

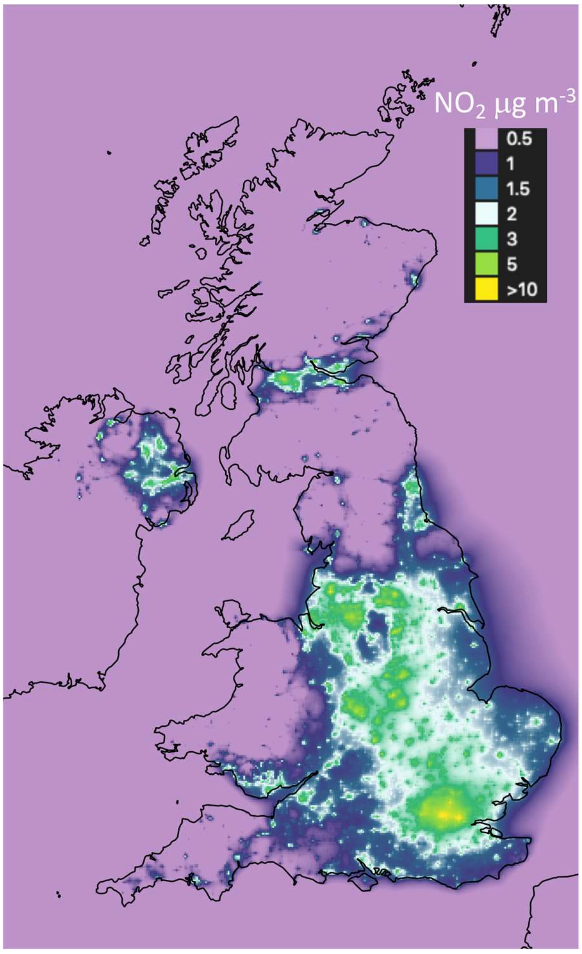

Figure 4. CMAQ modelled concentrations of NO_2 ($\mu g\ m^{-3}$) in 2019 from a combination of SNAP 2, 3 and 4 emissions sources (SNAP 2 - Non-industrial combustion plants, SNAP 3 - Industrial combustion plants, SNAP 4 - Industrial processes without combustion). All other UK NO_x sources set to zero emissions. This map forms part of a study funded by the National Institute for Health Research (NIHR) PHR Project: NIHR129406 "The air quality health and economic costs and benefits of a zero carbon UK".

5. What are the differences between emissions, concentrations and exposure and what are the implications for technology-neutral approaches to the use of hydrogen and hydrogen blends?

Technology choices and location of use will play a defining role in determining the potential scale of impact on air quality from using hydrogen in the UK. Whether hydrogen use leads to air pollution emissions is linked directly to which technology it is used in. Most simply, using hydrogen to directly generate electricity in an electrochemical fuel cell creates no atmospheric emissions, and can be considered pollution-free at the point of use. Using hydrogen as a combustion fuel to generate heat or mechanical work can create NO_x, as described in earlier sections, but emissions are not inevitable and likely can be abated successfully. There is the potential for NH_3 slip from SCR systems that may be used to control the NO_x. Emissions of other pollutants are avoided by when pure hydrogen combustion is used.

Energy policy in the UK typically advocates for a technology-neutral approach to new energy sources and fuels, using cost and greenhouse gas emissions as a primary drivers. From an air quality perspective however, technological pathways make a profound difference to outcomes. Technology pathways adopting hydrogen will influence total overall NO_x emissions, of relevance to future UK level of ambition and subsequent attainment of National Emission Ceilings and ambient concentrations that are subject to limits through Air Quality standards.

A technological choice between hydrogen fuel cells or hydrogen combustion may emerge in several sectors (including primary power and aviation), but most immediately in the use of hydrogen as a replacement for larger diesel engines, in off-road vehicles, construction equipment and HDVs. For these applications fuel cells and hydrogen engine alternatives are already commercially available and essentially may compete against each other. Whilst there are government damage costs for NO_x (Defra, 2023) and these are used to inform air pollution policies, there is no practical marketplace for NO_x emissions reductions analogous to carbon trading. Decisions on technological pathways are likely to be based largely on economics of the underlying fuel / efficiency and the cost of the equipment itself.

Where geographically hydrogen is used, and hence where point-of-use emissions occur, can influence the effects arising. Whilst all NO_x molecules are considered equal from the perspective of national emissions ceiling limits and transboundary obligations, different locations of sources have different impacts on people. Emissions from high level stacks in rural locations often lead to little direct exposure to NO_2 whereas vehicle tailpipe NO_x in cities is released close to large populations. Hence the disproportionate public health impacts of NO_x from road transport. This geographic differential may make use of hydrogen more or less impactful depending on which sectors it is used in. For example, using hydrogen in domestic gas boilers locates a NO_x source inevitably close to where people live and will be exposed. Using hydrogen for long-haul aviation may result in most of the emissions occurring away from people. This is not to underplay the negative effects that NO_x has on the wider atmosphere and ecosystems, on secondary PM and ozone, and on acid deposition and eutrophication, but there is a significant localisation of effects that should be considered. Conversely reduced PM emissions from hydrogen burning in place of fossil fuel may be an opportunity to localise benefits and improvements in certain areas.

6. Will indoor air pollution be affected by the combustion of hydrogen and hydrogen blends for cooking?

The use of natural gas for cooking is commonplace in the UK and is a source of NO_x and PM that occurs directly inside homes. Whilst perhaps only 5% of all domestic natural gas consumption is for cooking (AQEG Indoor Air Quality report, 2022) since all those emissions arising occur in a confined space it has a disproportionate effect on NO_2 exposure. Replacing current fossil fuels (mostly natural gas, but also some LPG) used for cooking is one component part of the wider set of measures needed to decarbonise UK homes for net zero. Hydrogen has been proposed as possibly playing a role here, as part of either blending into the natural gas grid or full conversion of the domestic gas grid to pure hydrogen. A hydrogen-fuelled cooker and hob would behave very similarly to a natural gas one, but visibly burn with a yellow-coloured flame.

Although emissions of NO_x from cooking with natural gas usage are significantly lower than for space heating, representing around 1.3 kt NO_x yr^{-1} (compared to >15 kt yr^{-1} for space heating and ~12 kt yr^{-1} for hot water) attention is now being paid to this source as a cause of harm (Lebel, et al. 2022; Blair et al. 2023). A recent study testing emissions of NO_x from blending H_2 with natural gas in six typical home gas cooker hobs found highly variable results (TNO, 2022). No clear pattern emerged using H_2 blends up to 40% with blended fuels broadly releasing similar amounts of NO_x on average to 100% natural gas, when corrected on an energy-released basis. Use of hydrogen blends typically resulted in higher direct NO_2 emissions compared to 100% natural gas. A modest reduction in particle number was observed for hydrogen blends.

A strategy of using hydrogen as a low carbon energy source for indoor cooking inevitably retains some indoor NO_x emissions for the long-term and there are few technical options for abatement beyond ventilation. The use of pure hydrogen (but not blends) for cooking would however eliminate the indoor air quality risk of CO emissions that can occur from poorly optimised burners. The impact of particle emissions from use of hydrogen for cooking is uncertain, but typically it is the PM derived from cooking activities (e.g. from oils, fats etc) rather than the flame that dominate emissions in literature studies, and these will remain irrespective of cookers using fuel combustion or electric hobs.

A note on comparing emission measurements.

Most sectors where hydrogen may be used as a fuel have limits placed on NO_x emissions, typically referenced to a unit of useful output, for example NO_x (g) per kWh. In this regard, comparing hydrogen emissions with other fuels is relatively straightforward and on that basis use of H_2 as a fuel falls within existing emissions standards and regulations. It is noteworthy however that these output-based emission factors are not directly measured quantities. Rather measurements of NO_x in exhaust gases are made as a mole fraction (for example in ppm (part per million)). These are frequently normalised for a dried sample with water removed. Dried mole fraction data are then often corrected to give a NO_x mole fraction for a standardised oxygen content (e.g. 15%). This final measure of NO_x, for a dry sample and O_2 corrected, is then related to the amount of useful heat or work generated. This provides a level playing field between appliances that may use different equivalence ratios in combustion and hence have differing amounts of H_2O and O_2 in their exhaust gases.

Comparing NO_x in exhaust gases arising from hydrogen combustion vs combustion of a hydrocarbon requires some important corrections, not least because the stoichiometry is different. Simply put, burning H_2 produces more water which is later removed in the drying step in the analyser, leaving less gas for dilution of the exhaust, relative to a hydrocarbon. The combustion of H_2 also consumes less O_2 per molecule of fuel compared to burning CH_4 (or other fuels) and does not create CO_2. Taken as a whole, the stoichiometry of H_2 combustion produces exhaust gases in which NO_x is 'less diluted' than would be the case if the fuel was a hydrocarbon. A system burning H_2 that was producing exactly the same amount of NO_x per kWh heat output would generate exhaust flue gas with an 'observed' NO_x mole fraction ~40% higher than one burning CH_4. Further (albeit somewhat smaller) corrections can then be made to create equivalence for energy input and mechanical outputs. The latter is significant for burning H_2 in gas turbines where the higher H_2O content in the exhaust gas leads to a higher specific heat capacity allowing the exhaust gases to hold more enthalpy for a given temperature. The result may be a more efficient turbine cycle for H_2 gas, and a reduction of NO_x emissions, per unit of gas turbine work (often reported as shaft work). For a review of this issue see Douglas *et al.* 2022.

Care is needed therefore when comparing NO_x emissions between appliances using hydrocarbon fuels and hydrogen, and it is essential that all necessary corrections to point-of-emission measurement data have been made to ensure NO_x is being compared on a like-for-like basis. Whether such corrections have been made is often not clear in much of the literature related to hydrogen combustion.

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