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Navigating the challenges of global NO_x emissions throughout the energy transition: state of play and outlook

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Global nitrogen oxide (NO_x) emissions have surged over the past fifty years, contributing to pollution problems such as surface-level smog. Primarily produced during the combustion of fuels, NO_x emissions are challenging to fully mitigate across various industries due to regulatory gaps and inefficient, costly abatement technologies. This perspective provides an overview of NO_x emissions, and details the significant increase in emissions that could occur with the shift to renewable fuels such as hydrogen and ammonia. A summary of key incumbent and emerging post-combustion NO_x abatement technologies is provided, with costs of treatment in the range of \$2–8 per kg NO_x. Finally, the existing NO_x regulatory landscape is reviewed, underscoring the critical need for stringent and global emission limits, particularly when certifying and regulating renewable and low-carbon fuels. To attain net-zero emission targets, regulations must evolve alongside innovative NO_x abatement technologies that address the shortcomings of current solutions.

1 Introduction

Nitrogen oxides (NO_x), primarily referring to nitric oxide (NO) and nitrogen dioxide (NO_2), are a class of toxic, highly reactive gases produced during the high-temperature ignition of fuels, either from the fixation of nitrogen in the combusting air (such as in the combustion of diesel, known as thermal NO_x) or from the fuel itself (such as in the combustion of coal or ammonia, known as fuel NO_x).[1] Nitrogen oxides are primarily emitted from the exhaust of motor vehicles and stationary engines such as electricity generators, as a byproduct of manufacturing and refining plants, and from agriculture and waste. NO_x emissions can lead to global cooling effects (through the destruction of methane) or warming effects similar to those of other greenhouse gases (GHGs), depending on the chemical and physical characteristics of the local atmosphere.[2] For example, at altitudes of 5–14 km, the global warming potential, GWP (the potential to warm the planet compared to an equivalent mass of carbon dioxide) of NO_x is positive, peaking at a considerable GWP of ~70 at an altitude of 10 km, highlighting the importance of abating NO_x emissions from the aviation sector.[3] NO_x emissions can also lead to ground-level ozone formation through reactions with volatile organic compounds (VOCs), which form smog in major cities around the world, causing damage to the human respiratory tract and increasing vulnerability and severity of asthma and respiratory illnesses.[4] NO_x emissions also result in acid rain, causing the acidification of soil and waterways, damaging agricultural crops and natural environments.[5]

Nitrous oxide (N_2O) is occasionally included under the NO_x umbrella; around 75% of N_2O emissions occur from soils and agriculture, with only minor contributions from industry (including from the production of adipic acid and nitric acid) and stationary combustion (typically from large coal-fired power plants).[6] N_2O is a potent GHG, with a significant GWP of 265.[7] Notably, excess use of ammonium and nitrate-based fertilizers leads to the production of N_2O by soil microbes, highlighting the importance of abating aqueous NO_2^- and NO_3^- waste emissions.[8] Moreover, N_2O can be formed as a byproduct of industrial NO_x abatement processes such as selective catalytic reduction (SCR), requiring significant research in order to optimize abatement systems to meet future emission legislations.[9]

Global NO_x emissions have risen from 70 to over 100 megatonnes per annum (Mtpa), peaking at ~114 Mtpa in 2011 (Fig. 1a). Of the total 5.2 gigatonnes of NO_x emitted since 1970, the largest emitters include the USA (18.7%), China (14.2%), and the international maritime sector (11.5%).[10] Whilst emissions have significantly reduced in many countries (for example, NO_x emissions in the USA have decreased from 23.6 to 9.3 Mtpa since 1990), emissions in emerging and middle income economies such as China (emissions have increased from 8.8 to 21.5 Mtpa since 1990) and India (emissions have

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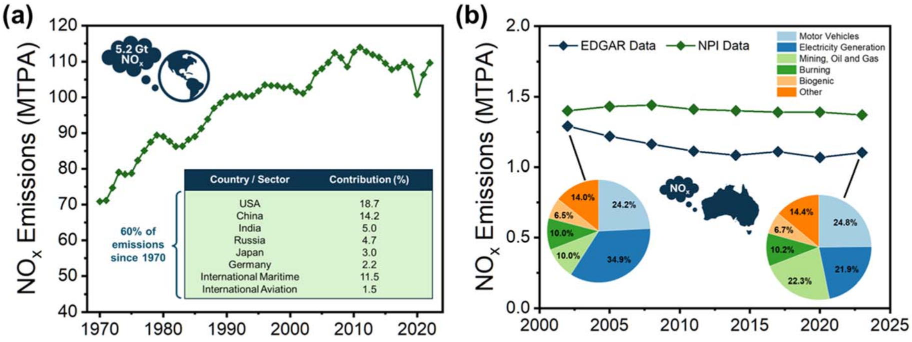

Fig. 1 (a) Global NO_x emissions since 1970.[10] Top emitting nations, as well as international aviation and shipping, comprise around 60% of total emissions. (b) Twenty-year NO_x emission profile in Australia.[10,12] Note: EDGAR – Emissions Database for Global Atmospheric Research; NPI – National Pollutant Inventory.

increased from 3.4 to 10.1 Mtpa since 1990) are continuing to prop up global emissions.[11] In Australia (Fig. 1b), transportation and power generation contribute to around half of the annual NO_x emissions of ~1.3 Mtpa, whilst contributions from the mining sector have more than doubled over the past two decades, currently comprising over 20% of emissions.[12]

To reduce NO_x emissions and their impacts, various regulations and abatement technologies have been implemented worldwide. Selective catalytic reduction (SCR) and flue gas recirculation (FGR) systems are incumbent treatment technologies typically employed for vehicles and industrial exhausts, resulting in a reduction in NO_x of up to 95%.[13,14] Emission regulations mandate strict emission limits for different sectors, with non-compliance resulting in stiff penalties.[15] Despite this, several challenges persist in closing regulatory gaps and in addressing emissions from sectors that are more difficult to decarbonize, including aviation, mining, construction, and shipping, which remain problematic due to (i) difficulties in developing efficient and cost-effective NO_x control measures, and (ii) challenges with NO_x that will be exacerbated by the transition to renewable hydrogen and derivative fuels including ammonia (NH_3).

As shown in Table 1, the use of renewable fuels can reduce NO_x in some applications (for example, the use of methanol in shipping is expected to reduce emissions by over 50%), however in other applications, the emissions of NO_x will remain consistent (such as the replacement of fossil-derived jet fuels with SAF), or may significantly increase (for example, combusting hydrogen will produce over three times the NO_x emissions compared to natural gas, whilst the use of ammonia as a shipping fuel will produce twice the NO_x emissions and over 60 times the N_2O emissions compared to heavy fuel oil).

Considering the projected role of renewable fuels and the expected increase in shipping activity by 2050, the shift to these fuels in the maritime sector would lead to a 2.5-fold increase in NO_x emissions (from 19 to 47 Mtpa) and an almost 60-fold increase in N_2O emissions, respectively (Fig. 2). Similarly, 80% blending of hydrogen into natural gas power plants and 100% replacement of coal power plants with ammonia fuel will be required in the power generation sector by 2050, which will result in increased NO_x emissions in both these applications.[20] As such, there are questions on how these emissions can be effectively dealt with, given the limitations of current abatement technologies.

This perspective aims to provide an understanding and critique of the current regulatory and technical landscape, including issues and challenges relating to the abatement of NO_x emissions, as well as introduce an outlook for formulating future policies and technologies for addressing these emissions.

Table 1 Tank-to-wake NO_x emissions from future renewable fuels compared to current fossil fuel equivalents[16–19]

Renewable fuel	Emissions[a] (g kW h^{-1})	Emissions[b] (g MJ^{-1})	Current fuel	Change in emissions[c]
Hydrogen	4.0 NO_x	0.58 NO_x	HFO/MGO [d]	0.3× NO_x
			Natural gas	3.4× NO_x
Ammonia	28.2 NO_x	3.91 NO_x	HFO/MGO	2.0× NO_x
	1.95 N_2O	0.27 N_2O		64× N_2O
				4600× NH_3
	10 NH_3	1.39 NH_3	Natural gas	24× NO_x
				92× N_2O
Methanol	6.5 NO_x	0.74 NO_x	HFO/MGO	0.45× NO_x
SAF	0.9 NO_x	0.12 NO_x	Jet A-1	0.90–1.0× NO_x

[a] g of pollutant per kW h of engine output. [b] g of pollutant per MJ of fuel. [c] Increase or decrease in emissions per kW h of engine output, when combusting the renewable fuel *vs.* the current fuel. [d] HFO: heavy fuel oil. MGO: marine gas oil.

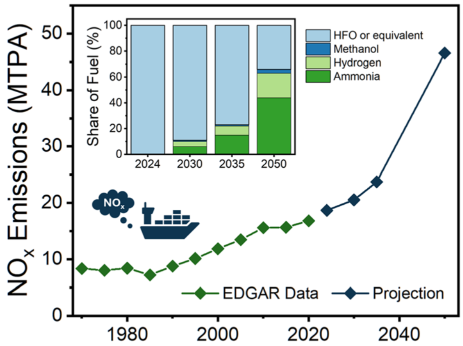

Fig. 2 Global NO_x emissions from international shipping to date, and projected emissions based on fuel mix and activity increase.[10,17,21]

2 State of technologies for NO_x treatment

This section focuses on the state of key current and emerging methods of NO_x emission abatement (Fig. 3), describing their operating principles and primary advantages and disadvantages.

2.1 Key current NO_x abatement technologies

2.1.1 Pre-combustion technologies. Flue (or exhaust) gas recirculation (FGR) is a technology typically used in both small-scale diesel engines and large-scale oil and gas-fired boilers. FGR recycles a portion of the exhaust gas back into the combustion chamber, where it combines with the fresh intake air. This reduces the oxygen content and the peak combustion temperature, effectively reducing NO_x production by 50–60%.[22] However, this can result in less complete combustion in diesel engines, leading to an increase in CO and hydrocarbon emissions and a reduction of peak cylinder pressure and fuel conversion efficiency, especially at high loads. For example, with 10% of exhaust being recirculated *via* FGR, fuel conversion efficiency decreases by around 6%, CO emissions increase by around 42%, whilst NO_x emissions reduce by up to 30%. An FGR rate of 40% achieves low levels of NO_x emissions (1–2 g kW^{-1} h^{-1}), but with increased emissions of PM, fuel consumption, and engine noise.[23,24]

Using less excess air (LEA) is another pre-combustion technique that reduces oxygen availability; however, this approach does not significantly reduce NO_x emissions.[1] Alternatively, oxy-fuel combustion can produce no NO_x emissions when fuels with no N content are combusted in either pure oxygen or in a gas mixture containing no N.[25]

Other pre-combustion techniques include reducing the peak temperature and/or the residence time at the peak temperature, such as by the injection of water or steam; however, these approaches incur energy and efficiency penalties.[1]

2.1.2 Post-combustion physical technologies. Activated carbon can be used to adsorb NO_x; NO can be oxidized to NO_2 on the carbon surface, where NO_2 is then adsorbed on the high surface area carbon. However, there is a low capacity for NO_x removal, and the carbon must either be replaced or regenerated.[26,27] There are also emerging physical methods of NO_x capture, such as *via* metal–organic frameworks (MOFs), where NO_x is adsorbed similarly to activated carbon, and through membrane separation, where membranes can selectively remove undesirable components of an exhaust stream. However, these approaches display shortcomings that may be difficult to overcome. For example, MOFs struggle to attain high structural stability and reusability, which are key prerequisites for the application of MOFs for NO_x removal.[28] Similarly, membrane separation, although technically viable, has yet to be shown as commercially viable.[29] As such, this perspective focuses on chemical approaches due to their more widespread use and applicability.

2.1.3 Selective catalytic reduction. Selective catalytic reduction (SCR) systems are typically employed for large-scale NO_x removal, such as from waste incineration and energy generation plants, as well as the removal of tailpipe emissions from diesel-powered vehicles and equipment. SCR is a post-combustion technology involving the reduction of NO_x to N_2 and H_2O, requiring ammonia or urea as a reducing agent in the presence of a catalyst of vanadium/tungsten oxides on a titanium substrate. Eqn (1)–(3) describes possible chemical reactions for the reduction of NO and NO_2 using NH_3 as the reducing agent:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \tag{1}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \tag{2}$$

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \tag{3}$$

The removal efficiency of SCR is typically around 60–95% and can lower the NO_x concentration to less than 20 ppm.[30] The SCR unit can be either placed directly after the combustion process (known as high-dust switching) or after filters and scrubbing units (known as low-dust switching).[31] SCR is a mature and commercially available technology and yields higher NO_x removal compared to selective non-catalytic reduction (SNCR). However, SCR requires a higher investment cost than SNCR, and the catalyst can be poisoned by SO_x and can suffer degradation. Furthermore, SCR leads to NH_3 emissions (known as NH_3 slip) in high-dust switching or requires the heating of flue gases to 300–500 °C in low-dust switching, significantly increasing the operating costs. At lower temperatures, the NO_x reduction activity is significantly reduced.[31] Furthermore, these systems cannot be operated effectively when ramping the emitting process up or down. SCR systems can also produce small amounts of N_2O emissions.[9,32]

2.1.4 Selective non-catalytic reduction. SNCR systems are also typically employed for large-scale NO_x removal, such as from waste incineration and energy generation plants. SNCR involves the injection of a NO_x-reducing agent such as ammonia or urea into the exhaust gas at temperatures of around 700–1000 °C in the absence of a catalyst (eqn (1)–(3)).[30] The reducing agent breaks down NO_x into N_2 and H_2O. SNCR units typically achieve 25–75% NO_x removal efficiency, and under ideal

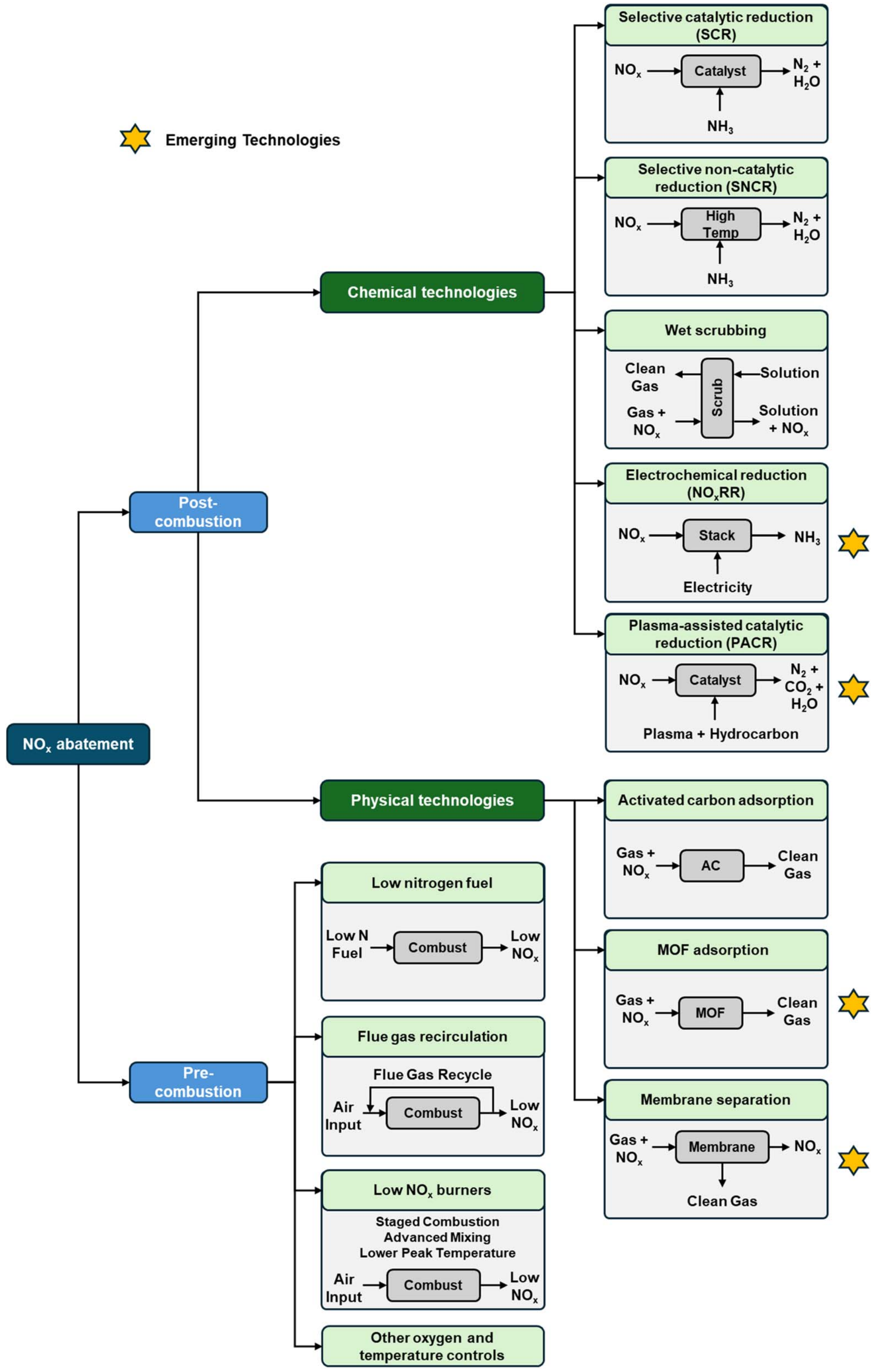

Fig. 3 Simplified schematics for current and emerging NO_x abatement technologies.

conditions, are an effective technology for NO_x reduction. Compared to SCR, SNCR has lower investment costs and energy usage. However, high temperatures are required, and there is a small range of optimal temperatures, outside of which either ammonia or NO_x is emitted.[33] SNCR can also release up to 200 ppm N_2O when using urea or cyanuric acid in the process.[34]

2.1.5 Wet scrubbing. Wet scrubbers employ a liquid solution to remove NO_x from an exhaust stream, typically from large-scale energy generation facilities. Solvents can include iron ethylenediaminetetraacetate (Fe-EDTA), sodium hydroxide (NaOH), sodium hydrosulfide (NaHS), or chlorine dioxide (ClO_2).[35,36] For example, eqn (4) and (5) detail the scrubbing of NO and NO_2 using chlorine dioxide.[37]

$$5NO + 2ClO_2 + H_2O \rightarrow 5NO_2 + 2HCl \quad (4)$$

$$5NO_2 + ClO_2 + 3H_2O \rightarrow 5HNO_3 + HCl \quad (5)$$

Wet scrubbers are effective at removing both NO_x (generally around 60–80% efficiency) and other pollutants such as SO_x and particulate matter, however, the process produces a waste stream that must be treated for disposal. Furthermore, the solvent is costly and corrosive, requiring durable materials for process equipment. Scrubber systems can also require a large footprint, and the removal process is generally slow.[35]

2.2 Key emerging NO_x abatement technologies

2.2.1 Plasma-assisted catalytic NO_x reduction. Plasma-assisted catalytic NO_x reduction (PACR) aims to address the shortcomings of SCR, namely the catalyst durability in the presence of soot, SO_x, and water vapor, the requirement for a reducing agent such as ammonia, and the high operational temperatures. PACR consists of two steps: the plasma-assisted oxidation of NO to NO_2 in the presence of a hydrocarbon (eqn (6)), and the reduction of NO_2 to N_2 in the presence of the catalyst and the hydrocarbon (eqn (7)).[38]

$$\text{Plasma} + NO + \text{hydrocarbon} + O_2 \rightarrow NO_2 + \text{hydrocarbon products} \quad (6)$$

$$NO_2 + \text{hydrocarbon} \rightarrow N_2 + CO_2 + H_2O \quad (7)$$

Oxidizing NO to NO_2 in the plasma allows the function of the catalyst to be devoted exclusively to the selective reduction of NO_2, improving activity and durability.[38,39] PACR can also employ catalysts that require little or no precious metals, reducing costs. Despite these advantages, PACR requires a high energy input for the oxidation of NO_x using plasma, which is a significant challenge when integrating into real-world exhaust systems. Exposure to high-temperature water vapor is a major cause of catalyst degradation, which will occur under typical operating conditions.[38] Additionally, the reduction of hydrocarbons leads to CO_2 emissions, with some studies noting that unregulated emissions such as aldehydes increased in the plasma environment, whilst ozone can also be emitted.[1,40]

2.2.2 Electrochemical NO_x reduction. The electrochemical NO_x reduction reaction (NO_xRR) represents a promising pathway for NO_x abatement, utilizing electricity for the conversion of waste NO_x (both gaseous NO_x and aqueous NO_x^-) to products such as NH_3.[41–43] In generating a value-added chemical commodity, the NO_xRR promotes circularity, sustainability, and green chemistry whilst effectively abating NO_x emissions. For example, eqn (8) and (9) detail the electrochemical reduction of gaseous NO and aqueous NO_3^- to NH_3 under acidic conditions.

$$NO + 5H^+ + 5e^- \rightarrow NH_3 + H_2O \quad (8)$$

$$NO_3^- + 9H^+ + 8e^- \rightarrow NH_3 + 3H_2O \quad (9)$$

The process can be advantageously performed at ambient temperature and pressure, can demonstrate high activity and selectivity towards NH_3 production, can be scaled to a wide range of industrial applications, and can be powered by renewable electricity, simultaneously abating waste NO_x emissions whilst converting intermittent renewable electricity to a stable chemical fuel.[44] Unlike SCR and SNCR, the NO_xRR avoids the use of ammonia or urea as a reducing agent, lowering operational costs and reducing storage and handling risks.

However, several technological, economic, and regulatory hurdles must be addressed before commercial implementation.[44,45] On the technical side, this includes the development of highly active and stable electrocatalysts, the translation of current research into industrially applicable technologies, and the development of NO_xRR systems that can effectively deal with (i) waste streams exhibiting very low NO_x concentrations, and (ii) both gaseous and aqueous NO_x/NO_x^- waste emissions. From an economic and implementation perspective, the energy consumption of the NO_xRR will be in competition with the economic cost of abatement technologies such as SCR, with feasibility strongly reliant on the energy consumption (*i.e.*, kW h per kg NO_x), as well as the electricity pricing. Regulations will also play a key role; the production of ammonia as a hazardous substance will be regulated, and the product will be subject to certification and quality standards if used as a fuel or a fertilizer precursor. Additionally, the use and discharge of water or salts used as the electrolyte must comply with all relevant environmental regulations.

2.3 Technology comparison

A technical and economic comparison of these technologies is detailed in Table 2, employing data derived from available literature and technoeconomic models (for example, the US EPA's cost analyzer for costing SCR, SNCR, and wet scrubbing[46]). It is seen that the levelized cost of NO_x abatement lies in the range of \$2–8 kg^{-1} NO_x for large-scale incumbent technologies. Employing currently available benchmark literature for the NORR in electrolyzer systems[43] and using the published performance data as inputs into the technoeconomic model (the model is detailed further in our previous work[47]), a highly favorable capital expense (~\$90 kW_{boiler}^{-1}) and levelized cost (~\$1.4 kg NO_x^{-1}) could be achieved, highlighting the potential of electrochemical pathways to more effectively abate waste NO_x emissions at a lower project cost.

2.4 Technology challenges and future pathways

Incumbent control technologies for NO_x emissions present challenges that must be addressed to ensure maximum NO_x abatement in hard-to-abate industrial sectors. These include

Table 2 Technical and economic comparison of selected abatement technologies. Values are in 2024 USD

Technology	Typical capacity (MW)	Capex ($ per kW)	OPEX ($ per kW)	NO_x removal (kg NO_x MW h^{-1})	Levelized cost ($ kg NO_x^{-1})	Removal efficiency (%)	Ref.
FGR	50–1000[a] 0.1–1.0[c]	2.0–20[b] 1.4–6.7[c]	—	—	1.4–19[b] 12–200[c]	25–60	1 and 48–51
SCR	100–1000[a]	390–580[d] 140–240[e]	~40[d] ~8.0[e]	~7.7[d] ~4.7[e]	2.0–2.6[d] 2.5–3.9[e]	60–95	46 and 52
SNCR	100–1000[a]	26–93[d] 20–71[e]	~28[d] ~7.6[e]	~2.3 [d] ~1.4[e]	3.2–4.3[d] 3.3–5.9[e]	25–75	46 and 52
Scrubbing	100–1000[a]	600–1100[d]	32–50[d]	~3.7[d]	4.1–7.9[d]	60–80	46 and 53
NO_xRR	0.1–10[f]	350–4300[g] 350–1000[h] ~90[i]	~1300[g] ~1000[h] ~93[i]	~100[g] ~60[h] ~8.6[i]	~1.4[g,h,i]	Approaching 100%	43, 47, 54 and 55

[a] Boiler capacity. [b] General utility boiler. [c] Diesel engine capacity for road vehicles. [d] Coal-fired boiler. [e] Natural gas-fired boiler. [f] Electrolyzer capacity expected for a similar scale of NO_x abatement to existing technologies. [g] NO_3^-RR to NH_3, electrolyzer capacity. [h] NORR to NH_3, electrolyzer capacity. [i] NORR to NH_3, coal-fired boiler capacity basis.

the large footprint required and lack of physical space available for abatement technologies, high capital and/or operational expense, including chemical input, high energy usage, catalyst deactivation, slow reaction times, and secondary pollution.

Such drawbacks could be mitigated by emerging technologies such as the NO_xRR, which operates at ambient temperatures, requires no chemical input, has a low footprint, and can draw from the global experience gained in deploying electrolyzer systems, such as for hydrogen generation. With renewable energy carriers, including hydrogen and ammonia, coming into play over the next decades, the NO_xRR presents a further advantage with the ability to recycle produced ammonia to the engine, reducing emissions whilst improving overall efficiency.

Future work should focus on improving the technology readiness level (TRL) of the NO_xRR, including developing more active and stable catalysts, and developing systems that can effectively deal with exhaust streams exhibiting low (less than 200 ppm) NO_x composition.

3 Regulatory landscape and outlook

3.1 Road transport

Emission standards, such as the US EPA Tier I–V and Euro 1–6 standards, mandate limits on NO_x emissions from road vehicles. Each iteration of these standards has led to stricter limits,[56] with non-compliance leading to significant penalties for the manufacturer.[57] The Euro 7 standards (planned to be introduced in 2025) were amended to be less stringent following resistance from industry and some EU countries concerned with the high vehicle production costs and engineering resources required to achieve these limits. For example, it is estimated that the cost of emission control technologies for a diesel engine has increased by around five times from the Euro III to Euro VI limits, highlighting the technological and cost barriers that are preventing complete abatement of NO_x emissions from sources such as motor vehicles.[58,59] The EU also plans to mostly ban the sales of new petrol and diesel cars by 2035, with traditional petrol and diesel engines allowed to use synthetic fuels to meet the stringent emission targets.[60] However, these fuels will still release NO_x upon combustion, requiring effective abatement technologies. With the limited potential use of hydrogen as a transport fuel source (for example for captive fleets such as forklift trucks), more demanding hydrogen-specific NO_x emissions standards should still be implemented in parallel with more promising uses of hydrogen (such as in petrochemicals, fertilizers, and steelmaking) to ensure that NO_x emissions are reduced and air quality is improved as a co-benefit of net zero commitments and low carbon investment.[61,62]

3.2 Maritime

In the maritime sector, Tier III engine regulations (applying to ships built after 2016 operating within NO_x emission control areas) mandate NO_x emissions of 2.0–3.4 g kW^{-1} h^{-1} of engine output (g kW h^{-1}).[63] Typically, SCR systems are deployed on ships where adherence to these regulations is required. These emissions control areas are updated regularly, with the Canadian Arctic ECA (in effect as of January 2025), the Norwegian Sea ECA (in effect as of March 2026), and the North-East Atlantic ECA.[64,65] Additionally, in April 2025, the International Maritime Organization (IMO) introduced a global fuel standard that mandates a gradual reduction in the GHG intensity of marine fuels, as well as a pricing mechanism for GHG emissions. This framework will encourage carbon-free fuels such as ammonia, which will however exacerbate NO_x emissions.

To address these challenges, the IMO should establish NO_x, N_2O, and NH_3 emission standards specific to the use of fuels, including ammonia, requiring technologies that can reduce NO_x emissions by up to 90%. It is critical that future regulations consider alternative fuels such as ammonia; studies have shown that increased formation of N_2O as a result of ammonia combustion could completely offset the GHG emissions benefit of switching from fossil fuels, highlighting the importance of ensuring total abatement of NO_x emissions from ammonia-fuelled engines.[66] For example, the Maersk Centre for Zero Carbon Shipping suggests N_2O and NH_3 emission limits of 0.06 g kW h^{-1} and 10–30 ppm, respectively.[67]

Governments should also collectively agree on a consistent global regulation framework to manage marine emissions while incentivizing the use of innovative emission control technologies and alternative fuels. As strict NO_x regulations only apply to newer ships and in relatively small ECAs, the total NO_x emitted from the shipping sector will not decrease, and in fact is more likely to significantly increase with the projected growth in shipped goods over the next decades. A study by MIT has found that the development and enforcement of ammonia fuel emission regulations is critical to provide a positive impact on air quality and prevent negative impacts from excessive nitrogen (in the form of NO_x and N_2O) leakage.[68] By addressing these key areas, the marine shipping industry can effectively contribute to lowering NO_x and greenhouse gas emissions as it transitions to more sustainable fuel options.

3.3 Industry

NO_x emissions from existing large-scale (>50 MW) coal-fired power generation are limited to 150–175 mg m^{-3} of total exhaust flow (mg m^{-3}) (EU), 640 mg m^{-3} (USA), 856 mg m^{-3} (Australia), and 50–100 mg m^{-3} (China). For new plants, limits are typically lower, including 85, 100, and 50 mg m^{-3} in the EU, USA, and China, respectively.[69]

Industrial sectors such as mining are responsible for significant NO_x emissions. From 2008–2018, over 10% of NO_x emissions in Australia were attributed to coal mining, whilst mining, oil, and gas were responsible for over 20% of emissions in 2023.[12,70] The enforcement of emission regulations within mining sites is challenging due to remote locations and a lack of specific emission standards for mining equipment. For instance, diesel vehicles such as trucks and bulldozers used at Australian mine sites are often US EPA tier 1–4 compliant.[71] However, other specialized equipment such as drilling rigs, generators, and cranes may lack the proper certification.

Whilst developed nations tend to employ strict and transparent emission standards with better enforcement mechanisms, many developing nations are less regulated or have no standards in place. This inconsistency can make it challenging for industries and companies to manage their emissions effectively across different regions. International collaboration between governing bodies and industry can facilitate a consistent regulatory framework in different regions. In addition, a "green premium" that could include NO and N_2O amongst the GHGs released should be employed, such that the sectors such as mining are incentivized to reduce NO_x emissions.[72]

3.4 Market-based instruments

The US Environmental Protection Agency's (EPA) Cross-State Air Pollution Rule (CSAPR) NO_x cap-and-trade program was established in 2015 and is a market-based scheme to reduce NO_x emissions.[73] The EPA sets a pollution limit (known as a budget) for each of the states covered by CSAPR. Authorization to emit (known as an allowance) is then allocated based on the state emissions budget, which takes into consideration factors such as historical emission data, plant capacity, and previous contributions. In 2022, the NO_x price for group 3 emissions (the most stringent market) peaked at over \$50 000 ton_{NOx}^{-1}, dropping to ~\$15 000 $\text{ton}_{NO_x}^{-1}$ by mid-2023.[74,75]

The EU Emissions Trading Scheme (ETS) is a cap-and-trade system that sets a limit on the total volume of GHGs that can be emitted by all participants, which is reduced annually in line with the EU's climate targets.[76] The EU ETS covers emissions of CO_2, methane, and N_2O; however, methane and N_2O are only covered from 2026 onwards. From 2024 and 2025, respectively, the maritime and aviation sectors will need to incorporate N_2O emissions into the relevant Monitoring, Reporting and Verification (MRV) frameworks, which refer to the multi-step process to measure GHG emissions.[77]

In Norway, the NO_x Fund aims to reduce emissions by financing NO_x reduction methods.[78] Rather than pay the government fiscal rate of ~\$2300 $\text{ton}_{NO_x}^{-1}$, enterprises can pay ~\$1600 $\text{ton}_{NO_x}^{-1}$ (for the oil and gas industry) or ~\$1000 $\text{ton}_{NO_x}^{-1}$ (for other industries including shipping, land-based industry, and aviation). These funds are then paid back to emitters for implementing of NO_x reduction measures. Since 2008, the fund has granted over \$1.2 B for such technologies, primarily in the maritime sector. In Denmark, a NO_x tax of ~\$780 $\text{ton}_{NO_x}^{-1}$ is mainly targeted towards the energy and industry sectors.[79]

In Sweden, a NO_x charge of ~\$4800 $\text{ton}_{NO_x}^{-1}$ aims to reduce emissions from large power plants (typically oil boilers) that generate over 25 GW h of useful energy per year, whilst emitters from industries such as cement and lime, mining, and refining are exempt due to concerns around high treatment costs.[79] Collected revenue is returned to the participating plants in an inverse proportion to the NO_x emitted per unit of energy production, to incentivize low emissions and to allow emitters to decide themselves how best to reduce emissions. This scheme has resulted in a reduction in emissions intensity from taxed emitters of 0.4 to 0.2 g kW^{-1} h^{-1}, with an annual revenue of over \$70 M.[80] However, the scheme only applies to a small portion of the total emitters in the country. Additionally, it was noted that measures to abate NO_x emissions can increase emissions of other pollutants, including CO, VOC, N_2O, and NH_3, which is an important consideration when employing NO_x abatement technologies.[81]

A global NO_x price could assist in incentivizing and expediting the development of improved technologies for emission abatement. For example, studies have found a correlation between the EU ETS carbon price and the patenting rate in low emission technologies, indicating that a \$1 increase in carbon price expectations corresponds to a 1.4% increase in the number of patents for low carbon technologies after two years.[82] Such a pricing scheme for NO_x emissions would provide the greatest benefit if taken up by the majority of emitting nations and sectors.

3.5 Summary

In summary, we outline the challenges associated with NO_x emissions from key sectors and propose a detailed deployment roadmap for advanced abatement technologies. Additionally, we present a holistic strategy for managing NO_x emissions

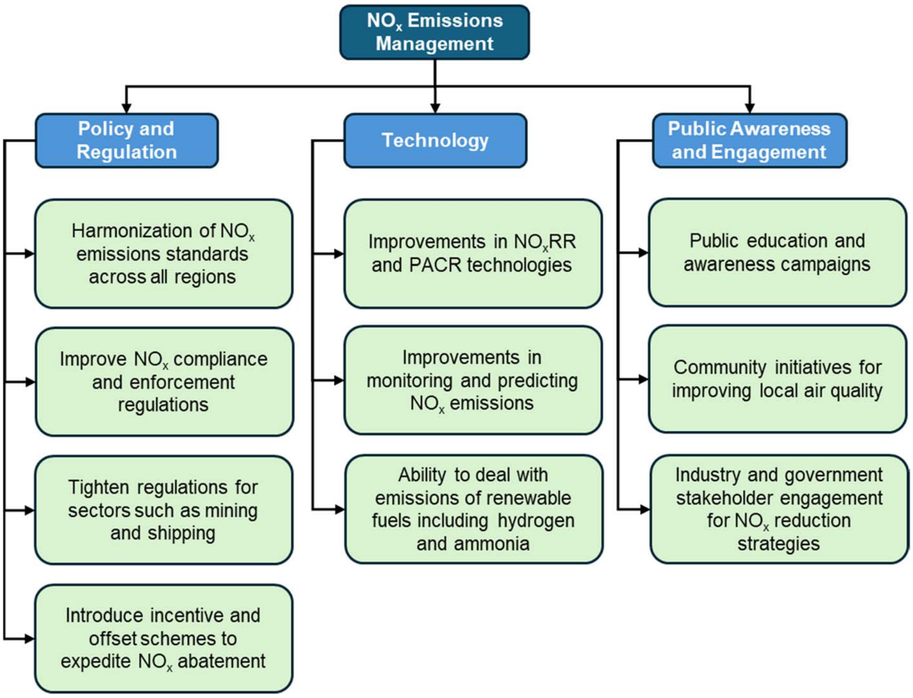

Fig. 4 Key areas that must be addressed to curb global NO$_x$ emissions.

through regulatory, technical, and community-based initiatives, as illustrated in our schematic overview (Fig. 4).

Critically, harmonized policies and strengthened emission regulations targeting key sectors such as mining and shipping must be implemented, alongside the introduction of incentives or offset schemes to accelerate emission abatement. In addition, the best available technologies (BAT) in emitting industries should be mandated. Learnings from currently enforced regulations such as the Swedish NO$_x$ tax, where emitters are refunded the tax based on their abated NO$_x$, can inform suitable policies worldwide.

Abatement technologies must also be improved in the face of challenges with tightening regulations and the use of fuels such as ammonia. There must be increased focus on advancing and commercializing promising technologies such as PACR and NO$_x$RR. Furthermore, improvements in monitoring and predictive technologies for NO$_x$ emissions are also vital. Engaging the community through increased awareness and participation is crucial for enhancing local air quality, while collaborative efforts between the government and industry are necessary to develop further NO$_x$ reduction strategies.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

Conflicts of interest

There are no conflicts to declare.

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