Climate change is undoubtedly a pressing environmental issue affecting the entire world, including all ecosystems and human society. In addition, Rockström’s concept of planetary boundaries suggests that the biogeochemical cycling of nitrogen, due to the loading of reactive nitrogen by human activities, is well beyond the planetary boundaries, as is climate change (Steffen et al 2015). In fact, excessive use of reactive nitrogen causes a variety of environmental problems related to air and water quality and contributes to climate change and stratospheric ozone depletion, thereby threatening health, biodiversity, and livelihoods (Sutton et al 2021).

Various methods for the acquisition of primary and secondary energy, as well as energy-saving technologies, have been proposed to achieve a decarbonized society. The use of hydrogen is one of the methods employed in the area of secondary energy, which represents a major strategy of the countries in the European Union (EU Hydrogen Strategy 2020). Similarly, in Japan, there are plans that use ammonia as a secondary energy source and as an alternative to fossil fuel combustion. The use of ammonia (NH3) fuel was clearly identified in the 6th Basic Energy Plan, which received cabinet approval on 22 October 2021, prior to COP26.

Similar to H2, NH3 could serve as a carbon-free combustor that does not produce CO2 when burned (4NH3 + 3O2 → 4NO + 6H2O + 906 kJ). NH3 is a gas at room temperature and pressure, and it can be co-fired in liquid natural gas power plants with only minor additional equipment. They can also be co-fired in coal-fired power plants. NH3 can be liquefied at room temperature (>8.6 kpa), and its volumetric hydrogen density is higher than that of liquid hydrogen, making it superior in terms of transportation and storage (Valera-Medina et al 2021).

In order to reduce CO2 emissions from thermal power plants, the Japanese roadmap plans the use of 20% NH3 co-firing in coal-fired power plants by 2030 and exclusive use of NH3 (mono-firing) in thermal power plants by 2050. In this roadmap, the Japanese government assumes that domestic demand will be on the scale of 3 million tons (2.4 Tg-N) yr−1 (approximately 0.5 million tons of H2 equivalent) in 2030, and about 30 million tons (24.0 Tg-N) yr−1 (approximately 5 million tons of H2 equivalent) in 2050 (METI 2021). Total electricity consumption in Japan is expected to be 934 billion kWh in 2030, and energy production from NH3 combustion in this year is assumed to be 8.2 billion kWh (METI 2021). If there is no change in the efficiency of power generation, we can estimate 82 billion kWh in 2050. The amount of Japanese NH3 fuel used in 2050 will reach approximately one-fifth of the current global annual use of nitrogen in chemical fertilizers. In comparison with Japanese domestic N consumption, the annual N consumption in 2015 was 0.5 Tg-N for fertilizer and 0.6 Tg-N for industrial use. At 20% co-firing in 2030, NH3 energy use will greatly exceed these demands. In the future, in the shared socio-economic pathways 1 scenario (SSP1), which uses the least amount of chemical fertilizers (Mogollon et al 2018), Japan’s NH3 use alone will account for 25% of the global use of chemical nitrogen fertilizers and about 15% of the total reactive nitrogen use, including industrial applications (figure 1). This estimate does not include the potential for energy use of ammonia outside of Japan, and, of course, it is possible that much more reactive nitrogen could be used for energy purposes in the future.

In order to obtain such a huge amount of carbon-free NH3, the Japanese government is looking for new sales channels. Japan’s current domestic production of NH3 is roughly 1 million tons yr−1 (Hayashi et al 2021), which is only about 1/3 of the amount needed by 2030, and of course not a carbon-neutral NH3. The first step in the plan is to import blue ammonia (NH3 synthesized based on the energy generated by CO2 capture and storage power plant) from the...
current coal- and fossil fuel-producing countries (e.g. Australia and Saudi Arabia) (ICFA 2021) and to establish a new supply chain to avoid a significant impact on the market price of NH₃. By 2050, the Japanese government will gradually shift to green ammonia-based renewable energy use. Regarding the market price, there will also be competition for hydrogen energy use, which is essential for ammonia production, and attention should be paid not only to the production costs of green or blue hydrogen, but also to its impact on prices through market mechanisms. For example, the amount of hydrogen needed to synthesize the amount of NH₃ planned for use in 2030 is half the amount of green hydrogen estimated in the EU hydrogen strategy plans.

What is the environmental impact of reactive nitrogen? The main concern is the release of reactive nitrogen species into the atmosphere and their short- and long-term impact on human health and terrestrial ecosystems. Technologically, most of the fuel NOx could be suppressed by using optimized thermal conditions, although thermal NOx is released (MacFarlane et al 2020). It is expected that thermal NOx could be reduced using exhaust gas denitrification technology to meet the standards for exhaust gas under the emission standards of the Air Pollution Control Law. On the other hand, there is a trade-off relationship between NOx production and the unburned fraction of NH₃. Although some conditions permit suppression of the production of both, some amount of NH₃ slipping is expected to occur when NOx production is suppressed (Kobayashi and Hayakawa 2019). As for short-term negative impacts, NH₃ is one of the PM2.5 precursor gases, and there is concern about its impact on human health (Lu et al 2018). In this paper, the NH₃ emission from the power plant was evaluated using a value of 1 ppm, assuming the condition of 20% NH₃ co-firing. Although this assumption is reasonable for 20% co-firing, it is theoretically known that NH₃ slip increases rapidly when the co-firing rate exceeds 40% (e.g. NH₃ exceeds 100 ppm when the co-firing rate exceeds 80%) (Zhang et al 2020). Therefore, it is clear that further study is needed to evaluate the impacts of NH₃ slip when NH₃ mono-firing or during the transition period. To date, there are no laws regulating the amount of NH₃ emissions from plants in Japan. As for long-term negative impacts, the NH₃ released into the atmosphere is supplied to various ecosystems via nitrogen deposition. In Japan, an increase in nitrate leaching from stream water due to nitrogen deposition has been observed (Chiwa et al 2019), and NH₃ slipping may further contribute to nitrogen leaching. It should also be noted that the additional nitrogen deposition from this energy use may result in the loss of multiplicity of terrestrial and aquatic ecosystems adapted to oligotrophic conditions (Krupa 2003, Bobbink and Hicks 2014). I have not addressed the positive impacts on the environment resulting from the replacement of fossil fuels by NH₃ co-firing (or co-firing) so far; however, partial replacement with NH₃, or mono-firing, may have disadvantages, as well as co-benefits for the environment. VOC and SOx emissions from thermal power plants may be reduced, which are also responsible for secondary PM2.5.
In Japan (and probably worldwide), information sharing is insufficient between engineering scientists and environmental scientists developing the technology for this decade. While there are quite a large number of articles on NH₃ combustion in energy engineering journals (e.g. Valera-Medina et al 2021), there are still few in environmental science journals. To date, evaluations of the environmental impact of NH₃ fuel from the environmental perspective are still very limited (e.g. Lu et al 2018). On 8 November 2021, the first symposium in Japan that brought together Japanese nitrogen experts from engineering and environmental sciences was held to overcome this situation. Since Large-scale NH₃ fuel use is a new technology and policy, it is not well known to the public, and there is no global recognition of it. United Nations Environment Programme (UNEP) aims to halve the amount of nitrogen waste by 2030 (Sutton et al 2021), and the use of NH₃ combustion is completely contrary to the reduction of reactive nitrogen use, so it is necessary to keep a close eye on this issue. Appropriate measures should be taken to maintain an appropriate nitrogen cycle for the next and subsequent generation. Time for decarbonization is limited, and it must be carried out at a rapid pace in parallel with technology and infrastructure development. This year, there have been many skeptical articles about NH₃ combustion, especially in the Japanese press media, but the advantages and disadvantages of using NH₃ fuel have not been sufficiently evaluated, apart from the decarbonization and energy aspects. There is an urgent need for communication, discussion, and validation regarding this technology including various audiences.

Data availability statement

No new data were created or analysed in this study.

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