Why using ammonia in power generation is risky for the climate

Supporting information

Methods

We looked at CO_2, CH_4, and H_2 emissions per unit of energy from ammonia production, using both low and high methane/hydrogen leakage rates and considering both near-term (20-year) and long-term (100-year) impacts. We compared the emissions from ammonia production to those from a coal-fired power plant.

The ammonia production scenarios include 1) gray ammonia produced with natural gas-based H_2 and powered by natural gas (NG); 2-3) blue ammonia produced with natural gas-based H_2, with 60 or 90% carbon capture efficiency, and powered by NG; 4) ammonia produced with green (renewably-based electrolytic) H_2 and the Haber-Bosch process powered by NG, 5) electro-ammonia (e-ammonia) produced with green H_2 and powered by additional wind-based energy, 6) e-ammonia produced with green H_2 and powered by a grid projected for 2050, assuming this electricity is not replaced; 7) e-ammonia produced with green H_2 and powered by grid electricity projected for 2050, which has to be replaced with coal; and 8) e-ammonia produced with green H_2 and powered by grid electricity projected for 2050, which has to be replaced with natural gas.

The emissions sources considered are shown in the **Figure 1** legend. Climate pollutant emissions from ammonia (from steam methane reforming (SMR) (hydrogen production from natural gas), Haber-Bosch (HB) process (ammonia production from hydrogen and atmospheric nitrogen), and carbon capture (CC)) were estimated through mass balance calculations using the following equations and the assumptions and values summarized in **Figure 2** and **Table 1**.

SMR: $CH_4 + 2\ H_2O = CO_2 + 4\ H_2$

Electrolysis: $2\ H_2O = 2\ H_2 + O_2$

H-B: $3\ H_2 + N_2 = 2\ NH_3$

Combustion: $CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$

Limitations

The analysis presented here does not consider the following:

- Climate pollutant emissions from the transportation of ammonia nor its feedstock, given that these will depend on the distance between the hydrogen and ammonia production plants and the power plant. Life cycle emissions from coal-fired power plants are considered (Alvarez et al., 2012).
- H_2 emissions from the Haber-Bosch process because there are no published estimates.
- Ammonia (NH_3) leakage rates and indirect nitrous oxide (N_2O) emissions (GWP_{100} =273) from the biological and chemical transformation of ammonia in the environment.
- Nitrogen oxides (NO_x) and N_2O emissions from ammonia combustion
- Co-emitted cooling aerosol precursors associated with both coal plants and ammonia processes.
    - This includes sulfur dioxide (SO_2) emissions from coal plants that lead to a temporary cooling from sulfate formation, which is a cooling aerosol.
    - NH_3 leakage can lead to nitrate aerosol formation, which is a cooling aerosol.

Thus, future works should incorporate these factors for a more comprehensive understanding of the climate and air quality impacts of using ammonia to generate electricity.

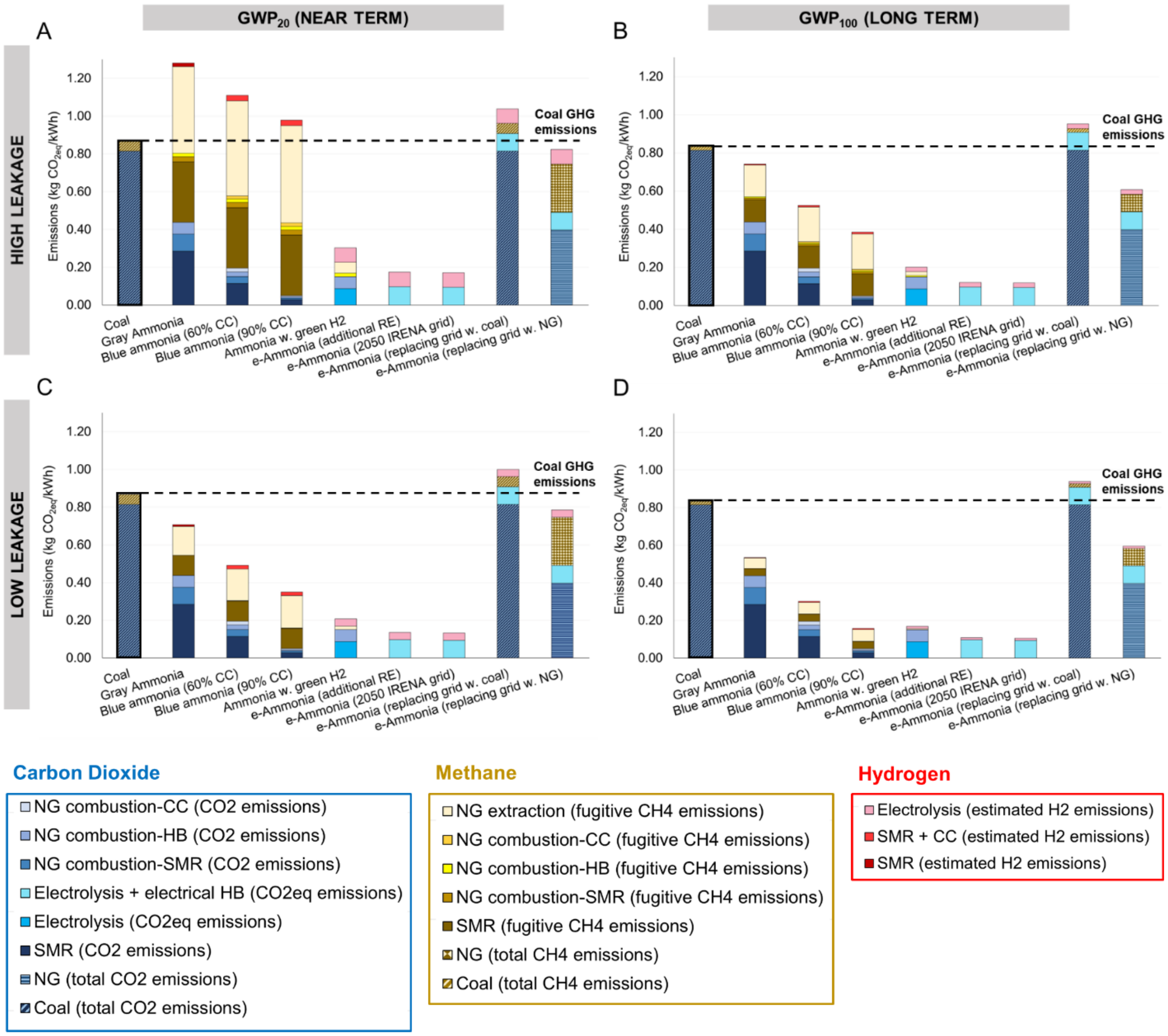

Figure 1. CO_2, CH_4, and H_2 emissions from different ammonia-production scenarios compared to CO_2 and CH_4 emissions from a coal-fired power plant. A-B) Emissions estimations using high leakage rates[a] for CH_4 and H_2 using the metrics GWP_{20} (A) and GWP_{100} (B) to estimate CO_{2eq} emissions. **C-D)** Emissions estimations using low leakage rates[b] for CH_4 and H_2 using the metrics GWP_{20} (C) and GWP_{100} (D) to estimate CO_{2eq} emissions. Shades of blue depict CO_2 emissions, shades of gold-yellow depict CH_4 emissions and shades of red depict H_2 emissions.

[a] **High CH_4 leakage**: 3% for natural gas extraction for ammonia production and for SMR; 1% for combustion processes for SMR, HB, and CC. **High H_2 leakage**: 1.0% for SMR (gray hydrogen), 1.5% for blue hydrogen, and 4.0% for electrolysis.

[b] **Low CH_4 leakage**: 1.0% for natural gas extraction for ammonia production and for SMR; 0.01% for combustion processes for SMR, HB, and CC. **Low H_2 leakage**: 0.5% for SMR (gray hydrogen), 1.0% for blue hydrogen, and 2.0% for electrolysis.

The coal and natural gas emission factors used in the coal reference scenario and the scenarios where the electricity is replaced with coal or natural gas were obtained from Alvarez et al., 2012.
CC: carbon capture; GWP_{20}: global warming potential over a 20-year time horizon; GWP_{100}: global warming potential over a 100-year time horizon; HB: Haber-Bosch process; NG: natural gas; SMR: steam methane reforming.

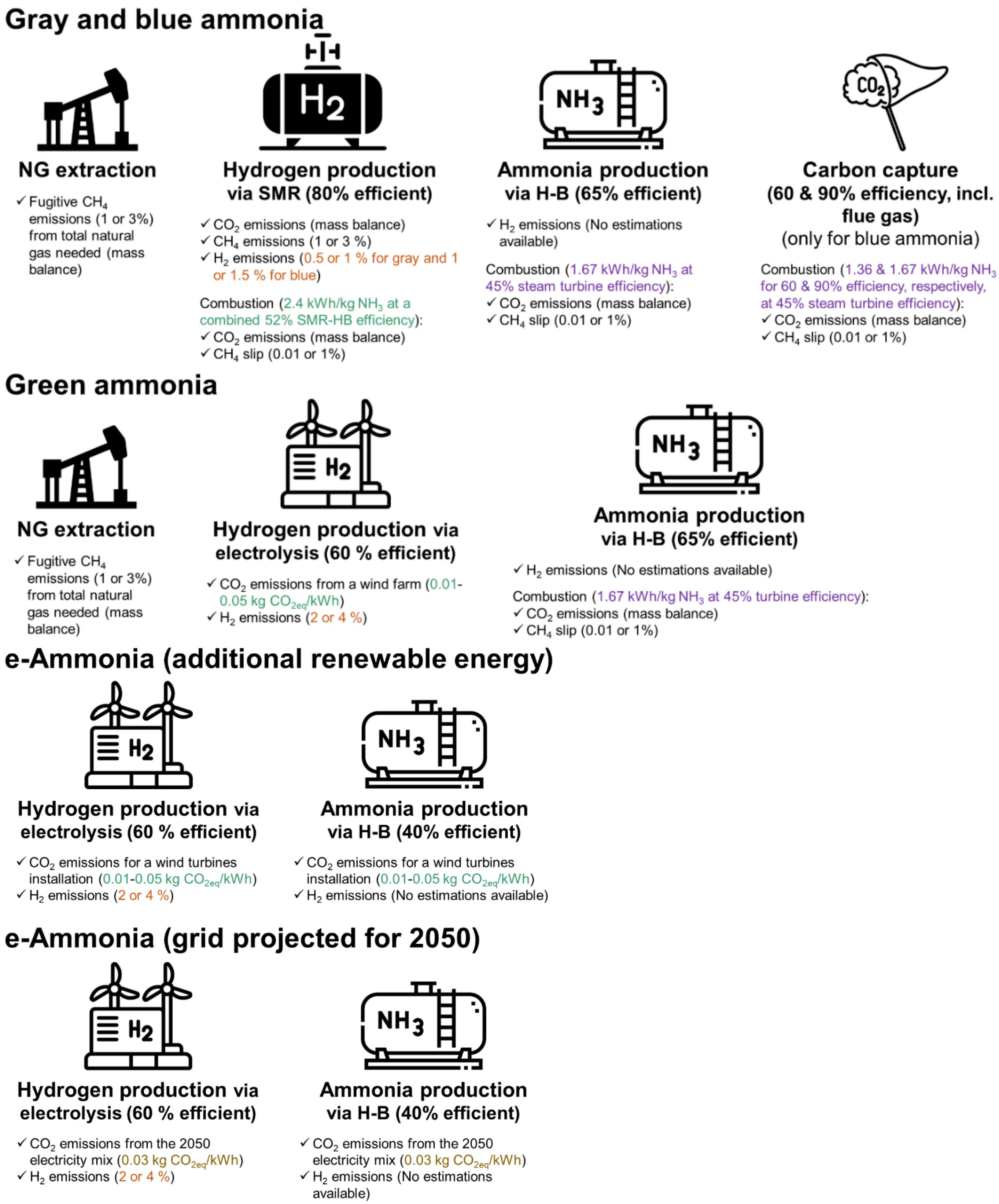

Figure 2. Values considered in the methodology.

References: (Smith et al., 2020);(Fan et al., 2022); (Stocks et al., 2022); (Renewable Energy Agency, 2022). Icons from www.flaticon.com

Table 1. Global warming potential (GWP) values used for 20- and 100-year time horizons.

	GWP_{20}	GWP_{100}
H_2 (Sand et al., 2023)	37.3	11.6
CH_4 (IPCC AR6 2021)	82.5	29.8

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