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ZERO CARBON ENERGY FOR THE ASIA-PACIFIC

Global emissions implications from co-burning ammonia in coal fired power stations: an analysis of the Japan-Australia supply chain

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Abstract

We study the greenhouse gas emissions of different technology choices for ammonia production for power generation. We adopt a global supply chain approach, considering emissions generated at the point of manufacture in addition to consumption for ammonia co-combustion in coal fired power stations using a range of ammonia production technologies. These include: standard Haber-Bosch ammonia production with hydrogen generated from steam methane reforming using natural gas, with and without carbon capture and storage; Haber-Bosch ammonia production with hydrogen generated from renewable sources; and fully renewable electricity generated ammonia. The empirical setting of the study is an ammonia supply chain encompassing Japan and Australia. Our findings show co-burning of ammonia produced with the current Best Available Technology (BAT) of steam methane reforming and the Haber-Bosch process provide no net benefit for global emissions. In contrast, ammonia, with the hydrogen and ammonia manufactured from renewable energy would reduce global emissions by more than a factor of 10 compared to coal combustion, and between 4-10 times compared to co-combustion of ammonia produced using SMR-HB processes with varying levels of carbon capture and storage. Based on this, we suggest different policy options for managing the life-cycle emissions associated with a Japan-Australia ammonia supply chain.

Keywords:
Ammonia; global supply chain; co-combustion; greenhouse gas emissions; Japan; Australia

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The Australian National University Grand Challenge: *Zero-Carbon Energy for the Asia-Pacific* transdisciplinary research project is a $10m investment between 2019 and 2023 that aims to help transform the way Australia trades with the world. It comprises five interrelated projects: Renewable Electricity Systems, Hydrogen Fuels, Energy Policy and Governance in the Asia-Pacific, Renewable Refining of Metal Ores, and Indigenous Community Engagement. The Grand Challenge's goals include developing zero-carbon export industries, creating new paradigms in benefit-sharing, and developing technologies, polices and approaches which can be applied in the Asia-Pacific and beyond.

1. Introduction

Green industry policies are used by governments globally to support the transition to technologies with low Greenhouse Gas (GHG) emissions (REN21, 2020). Industry policies implemented by governments are highly interdependent. Policies designed to stimulate domestic demand for a low embedded emissions product, for example, induce producers in other countries to increase production of that product. Production for many low emissions technologies are organized by Global Supply Chains (GSC), in which different stages of production are broken into discrete steps that can be produced in different locations, and by different companies (Bush *et al.*, 2015; Meckling and Hughes, 2018).

Where the production of low carbon technologies is governed by GSCs, a key question is how to account for the (GHG) emissions from different stages of production, and in different jurisdictions (Nabernegg *et al.*, 2019). The issue of accounting for emissions is acute for hydrogen and associated vectors, which emit no carbon emissions at point of use but can account for significant carbon emissions during production and transportation (White *et al.*, 2020).

Ammonia is an attractive hydrogen vector as it retains around 90% of the energy embedded in the hydrogen feedstock and is significantly easier to liquefy and store than hydrogen. Critically, there is already a sizeable global ammonia supply chain developed for the manufacture of fertilizers.

Ammonia does not directly contribute to GHG emissions at the point of combustion and can be used in place of fossil fuels in power stations to reduce emissions. However, approaches to ammonia manufacture have different GHG emission intensities, and low emission technologies are less mature and more expensive than high emission ones. Because of this, the total emissions of an ammonia supply chain are affected by how the ammonia is made. In cases where the ammonia is produced in one country and used in another, there is no incentive for the consumer to purchase expensive ammonia with low embedded GHG emissions, as these emissions will be occurring in another jurisdiction for carbon accounting purposes.

In this paper we examine the implications of different technology choices for GHG emissions from the use of ammonia. We adopt a GSC approach, considering emissions generated at the point of manufacture in addition to consumption. Specifically, we examine the emissions implications of ammonia co-combustion in coal fired power stations using a range of ammonia production technologies, including standard Haber-Bosch ammonia production with hydrogen generated from steam methane reforming using natural gas, with and without carbon capture and storage; Haber-Bosch ammonia production with hydrogen generated from renewable sources; and 100% renewable electricity generated ammonia.

We consider carbon capture and storage (CCS) to capture CO_2 emissions from the steam methane reforming process, which are then compressed, transported and pumped underground in suitable geological formations for permanent storage. Carbon capture is a relatively mature technology and there are currently 21 large-scale operating plants around the world (Global CCS Institute, 2020). However, over three quarters of these installations subsequently use the captured CO_2 for enhanced oil recovery. Unlike CCS, carbon capture and use, also known as CCU, can result in significant re-emission of the CO_2 into the atmosphere. In particular, enhanced oil recovery can have retention rates of below 30% (Olea, 2015). For this reason, we do not consider CCU further in the paper.

The empirical setting of the study is an ammonia GSC encompassing Japan and Australia. Japan is pursuing the import of low carbon fuels as part of its national decarbonization strategy (Government of Japan, 2018a). Trials in experimental reactors have demonstrated that 20% ammonia heat fractions can be combusted with pulverized coal in a combustor retrofit to reduce GHG emissions (Crolius, 2018). The 2014 Japanese Strategic Energy Plan states the Japanese government should enable the importation and use of ammonia by the latter half of the 2020s, produced using an array of technologies, including with renewable energy, and with carbon capture and storage applied to standard processes (Government of Japan, 2017a). Australia is identified as a partner for the development of a hydrogen supply chain (Government of Japan, 2017b). Japan and Australia are collaborating on a pilot project designed to demonstrate an integrated supply chain through the Hydrogen Energy Supply Chain (HESC), with a decision about whether to proceed with commercialization made in the 2030s. In September 2020 Japan imported a cargo of ammonia from Saudi Arabia manufactured through methane reforming with carbon capture use and storage (Chemicals Technology, 2020).

Our findings show that the co-burning of ammonia produced with the current Best Available Technology (BAT) of steam methane reforming (SMR) and the Haber-Bosch (HB) process would reduce emissions at the point of combustion, but emissions across the supply chain would be similar to the continued direct combustion of coal*.* This means that there would be no net benefit for global GHG emissions reductions. In contrast, “zero emission” ammonia, with both the hydrogen and ammonia manufactured from renewable energy, would reduce global emissions by more than a factor of 10 compared to coal combustion, and between 5-10 times compared to co-combustion of ammonia produced using SMR-HB processes with varying levels of CCS.

Currently, zero-carbon ammonia production is more expensive than ammonia produced with fossil-fuel based BAT. Policy is thus needed to account for emissions across the supply chain in order to reduce emissions globally. Given this, we suggest different policy options for managing the life-cycle emissions associated with a Japan-Australia ammonia supply chain.

2. Background and Literature Review

Along with 189 other countries, Japan has ratified the Paris Agreement on Climate Change. Japan's first nationally determined contribution (NDC) post-2020 committed it to reduce GHG emissions by 26% by 2030 relative to 2013 (Government of Japan, 2015). As approximately 90% of Japan's total emissions are energy-related, this requires a 25% reduction in energy related carbon dioxide equivalent (CO_2-e) emissions. Japan's Agency of Natural Resources and Energy (ANRE) estimates that this equates to a reduction of 310 million tons of CO_2-e to meet its NDC obligations.

The ability of Japan to meet its NDC commitments is dependent on the rate of economic growth (Kuriyama, Tamura and Kuramochi, 2019). Nevertheless, more than 190MT (60%) of the required reduction must be accounted for by the power sector, which contributes 40% of total national CO_2-e emissions (Government of Japan, 2017a). Japan is reliant on fossil fuel based power and faces challenges decarbonizing its electricity supply. In 2019 natural gas was the largest share of power generation at 339 Terawatt Hours (TWh; 35%), followed by 316 TWh (32%) from coal, and 48 TWh (5%) from oil. The balance of the electricity supply comprised low emissions sources. Total electricity generation in Japan in 2019 was 1036 TWh, and has been decreasing over the last five years at 0.5% per annum.

The government has established a target of achieving 44 percent of its electricity generation from 'zero emissions' sources by 2030, predominantly nuclear power and renewable energy (International Energy Agency, 2019). Historically, the largest source of low emissions power in Japan was nuclear energy, producing 29% (288 TWh) of total electricity in 2010 (IEA, 2019). The 3rd Strategic Energy Plan of 2010 projected nuclear power to provide between 30 and 40 percent of total electricity in 2030. However, as a result of the Fukushima Daiichi power plant accident in 2011, nuclear power only contributed about 6% (64 TWh) of electricity in Japan in 2019. The 5th Strategic Energy Plan now expects this to increase up to only 20-22% by 2030 (Government of Japan, 2018b).

Countries adopt different strategies in promoting energy transition (Cherp *et al.*, 2017). As part of its long-term decarbonization strategy, Japan is exploring importing low embodied carbon fuels, including hydrogen in its liquified form or carried via another vector. While the third phase of Japan's Strategic Roadmap for Hydrogen and Fuel Cells is the establishment of a CO_2-free hydrogen supply chain by around 2040, early phases are less prescriptive regarding emission intensity (Government of Japan, 2017a).

One approach under consideration to enable international trade in hydrogen is the use of ammonia. Ammonia is attractive as an energy vector since there is already well-established international trade, primarily for fertilizers, with some US$7.0 billion traded internationally in 2018 (OEC, 2020). Led by Japan, the Green Ammonia Consortium was established in April 2019 to support the global development of an ammonia supply chain. In contrast, there is little existing international trade in hydrogen, and no standardised method for large-scale transport and storage.

The use of ammonia in Japan's coal-fired power industry is also well established, as it is used to manage NO_x emissions. High combustion temperatures in coal fired plants result in the formation of nitrogen oxides (NO and NO_2) due to the presence of atmospheric nitrogen in air. Nitrogen oxides are considered a pollutant as they can react with moisture in the air to form nitric acid, and these emissions are regulated (Ministry of the Environment, 2020). To reduce NO_x concentrations, Japanese coal plants routinely inject ammonia gas into the post combustion flue gases to trigger the selective catalytic reduction of nitrogen oxides, reducing them to nitrogen and water vapour (Sorrels *et al.*, 2016). Therefore, the required infrastructure for handling ammonia already exists at Japanese coal plants.

As a fuel, however, ammonia is not ideal. Ammonia has relatively poor properties for combustion relative to hydrocarbons with otherwise similar properties (Kobayashi *et al.*, 2019). Ammonia has poor flammability with high ignition temperatures and relatively low heat of combustion, flame velocity and flame temperature. Recognizing this, the Japanese government and industries are exploring the possibility of co-firing ammonia in Japan's fleet of thermal coal power plants (Nikkei Asia, 2017). In this process, pulverised coal is introduced into the burner along with a supply of air. Ammonia is then evaporated and introduced into center of the burner as a pure gas stream, and mixed around by a circulating flow of pre-heated air. This enables a stable flame and reduces NO_x concentrations. Measurements of exhaust gas concentrations show that the burner design delivers similar NO_x emissions to a pure pulverized coal system (Tamura *et al.*, 2020)

Chugoku Electric Power has trialed small additions of ammonia to an operating coal powered thermal plant (Chugoku Electric Power). A 155MW power plant had ammonia added at rates equivalent to contributing 1MW of output power (0.6% at 155MW and 0.8% at 120MW). There was no change in the concentration of the NOx in the exhaust stream within the natural variability of the plant. Choguku Electric assumed that the reduction in carbon dioxide emissions was proportional to the fuel ammonia energy contribution, although carbon emission changes were not reported. The most advanced results have been demonstrated by IHI Corporation, with 20% ammonia (i.e. 20% by energy on a lower heating value basis) combusted with pulverized coal in a test (Ishii *et al.*, 2020)). IHI has demonstrated ammonia co-firing with 20% ammonia by heat content in a large scale (10MW thermal) combustion test facility (IHI, 2018). Suitable choice of combustion conditions enabled NO_x levels similar to that of the coal combustion in the absence of ammonia, and the expected 20% decrease in carbon emissions. The potent greenhouse gas nitrous oxide (N_2O) was also below detection limits. IHI subsequently reported intent to design an ammonia co-firing system for a 1000MW coal fired power plant.

As the combustion of ammonia releases no carbon emissions, the co-burning of ammonia within Japan's existing fleet of coal-fired power plants implies a theoretical reduction in emissions. The emissions implications from ammonia co-burning across the supply chain depend, however, on the processes used to produce the ammonia. In the next section we discussion ammonia co-burning in the context of emission accounting boundaries.

2.1. Emission boundaries

The emissions associated with the supply chain of ammonia for use in co-burning, and the fact that these emissions can vary substantially with different production methods, raises an important question about the boundaries of carbon accounting. Under national accounting for CO_2-e, importing countries receive the full benefit of emission reductions associated with ammonia-co-burning. Given this, there is no incentive to choose a low emission source; rather, consuming countries are likely to be motivated towards using the lowest cost source of ammonia.

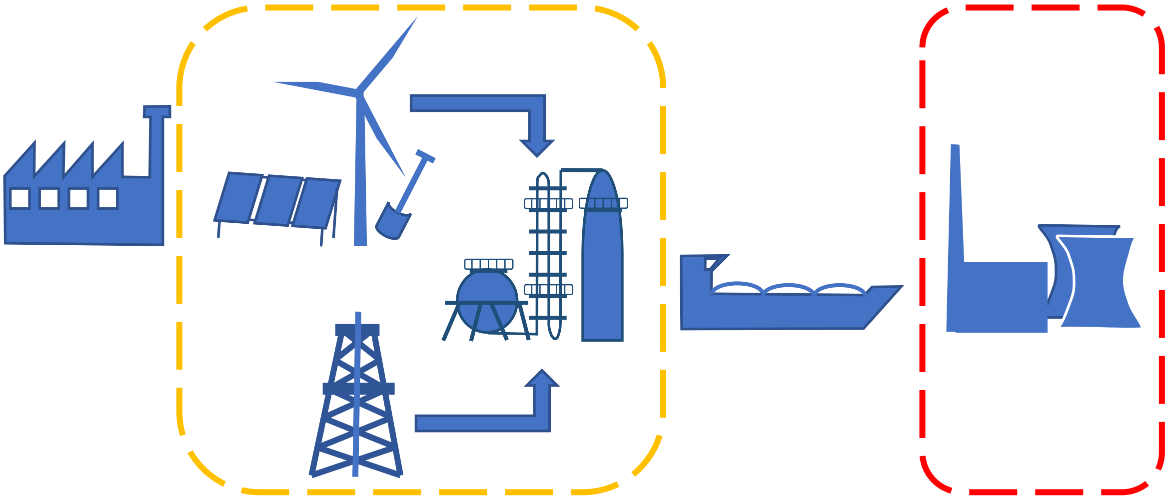

Figure 1. Boundaries for emissions accounting under Japan and Australia's national accounting frameworks in the ammonia energy supply chain. Japan (red) is responsible for emissions associated with power generation while Australia (orange) accounts for emissions associated with ammonia manufacture and the emissions associated with methane extraction and renewable energy facility construction. Emissions associated with international shipping and manufacture of renewable energy components fall outside Japan and Australia accounting frameworks.

In contrast, under a national emissions accounting framework encompassing a supply chain between Australia and Japan, Australia would increase its national emissions regardless of the manufacturing process, assuming ammonia production for exports are an increase in economic activity relative to baseline. Emissions may increase substantially, however, when deploying technologies other than renewable energy and electrolysis to generate the hydrogen used in green ammonia. Australia and other potential suppliers thus face conflicting motivations between supplying the lowest cost ammonia in order to maximize sales, against the need to minimize emissions.

Further, without the appropriate incentives in place to ensure emissions are accounted for across the supply chain, co-burning of ammonia could result in little to no benefit in reducing global CO_2-e emissions. Quantifying the global emissions impact for emissions involved in ammonia production thus warrants attention.

In the next section we describe the CO_2-e emissions from Japan's coal power fleet, and estimate the potential emission reductions that could be achieved in Japan by co-burning ammonia. In order to understand the global emissions benefit of ammonia-co-firing we also analyze the emissions that occur at the point of production for different technology options. We then summarize the theoretical supply chain emissions implications of ammonia co-burning for Japan.

3. Methodology

This section describes the methodology used to consider the emissions implications of co-burning ammonia with coal. First, we examine the current emissions intensity of coal combustion in Japan, and estimate the likely emissions profile of Japan's coal fleet in 2030 given stated policy change. Then we consider the emissions intensity of ammonia production using different technologies, beginning with steam methane reforming of hydrogen and Haber-Bosch with and without carbon capture and storage, and then considering processes where renewable electricity is used to produce hydrogen for the Haber-Bosch, and finally, a fully renewable, electrically driven Haber Bosch process. We then use these calculations to identify the total emissions implications of co-burning 20% ammonia in Japan's 2030 coal power generation fleet.

3.1. Coal Generation in Japan

Japan had 140 operating thermal coal generation units as of July 2020, with a total capacity of 47.3GW (Government of Japan, 2020a). Significant retirement of the coal generation fleet is unlikely by 2030 in the absence of policy or major fuel cost change drivers. The average age of retirement of the coal plants globally is 40 years, however the average age of retirement in Japan is longer, at 49 years (Parra *et al.*, 2018). Based on 8.3 GW of plant announcement and construction, 'business as usual' retirements would result in similar fleet capacities of 45.6 and 51.7 GW in 2030 for each of these respective retirement ages.

In 2018 Japan's coal generator fleet had an average emissions intensity of 0.864 kg CO_2 per kilowatt hour (kWh) (METI, 2018). The largest proportion of the fleet (48% of power capacity) are ultra-supercritical (USC) generation units, with an average emissions intensity of 0.795 kg CO_2 per kWh. Most of the remaining units are supercritical (28%) and subcritical (22%) generators which operate at lower efficiency with an average emissions intensity of 0.93 kg CO_2 per kWh. Assuming that the new build is all ultra-supercritical, and given that the retirements are all from the lower efficiency fleet, the 'business as usual' retirements would result in a 1.9% to 3.2% decrease in the average emissions intensity of Japan's coal generation fleet by 2030.

Japan is also developing lower emission coal generation plants. Joban Kyodo Power Company, for example, constructed a 250MW integrated coal gas combined cycle (IGCC) plant which commenced commercial operations in 2013. In an IGCC plant, coal is gasified in the presence of oxygen and water to produce syngas: a mixture of hydrogen and carbon monoxide. This gas mixture is then used as a fuel for a combined cycle gas generation plant. The resulting improvement in efficiency with high turbine combustion temperatures delivers an emission intensity around 0.71 kg per kWh. There are currently two 540MW IGCC plants under construction (Amamo*to et al*>, 2019).

Japan's Agency of Natural Resources and Energy (ANRE) projects Japan's total power generation to be 1065 TWh in 2030, with coal contributing 26% of total power generated. Assuming no changes in the capacity factors of the coal power plants, and similar level of self-generation by industrial companies using coal in 2019, the required capacity of coal power plants in 2030 is estimated to be 41.5 GW, 4.1-10.2 GW lower than the 'business as usual' fleet capacity estimated above.

ANRE has drafted a plan to provide an incentive to companies to retire sub-critical and supercritical plants, replacing these with high efficiency plants (Government of Japan 2020). If these proceeds, it will lead to the retirement of almost all existing sub-critical and supercritical plants, and their replacement with USC and IGCC plants.

In our analysis, we define the baseline emission intensity of the coal fleet in Japan, assuming a capacity of 41.5 GW in 2030, and that the fleet will consist of mostly USC and IGCC plants. The ratio of replacement plants mix (USC:IGCC) was taken from the current announced/under construction build ratio according to ANRE data (Government of Japan, 2020b). Adjustments were made due to the limited capacity in regional interconnects and the 50/60Hz issue, meaning that the subcritical plant in Okinawa will likely be preserved for reliability reasons. There is also a 300 MW sub-critical plant that is expected to be operational in 2022 in the Chūgoku region which was incorporated into the analysis (Government of Japan, 2020a) . Without the effect of ammonia-co-firing, the proposed plan would decrease the emissions intensity of the power sector to 0.796 kg CO_2 per KWh, 7.5% less than current fleet, and would reduce the power generation by 12% and total GHG emissions from coal power plants by 19% by 2030, as shown by the line in Figure 2.

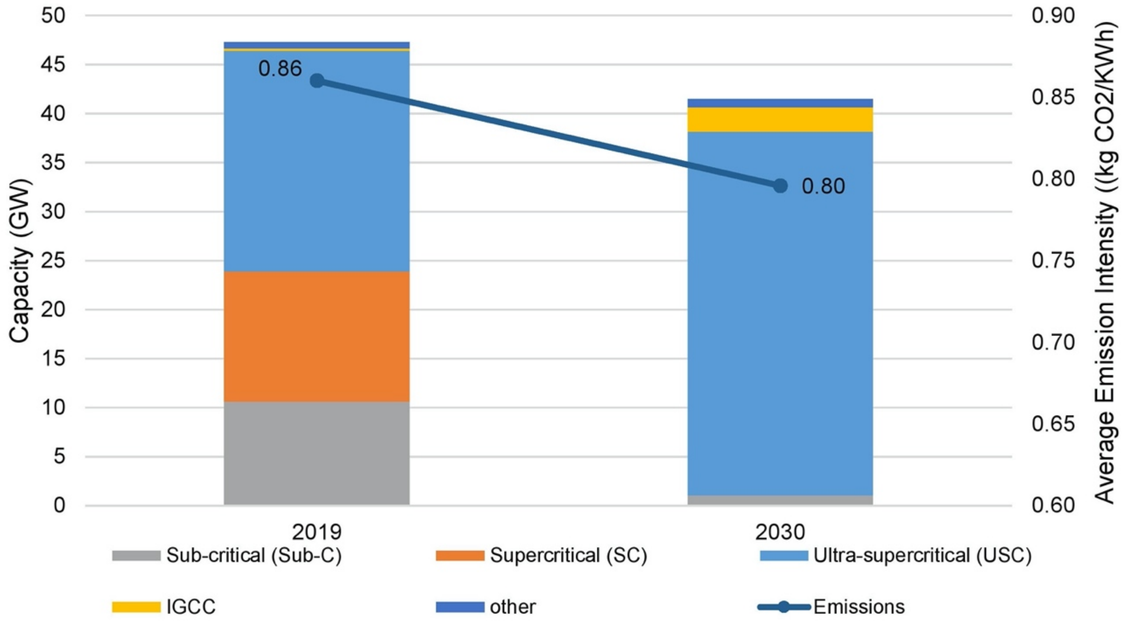

Figure 2. Capacity mix of thermal coal generation technology for 2019 and ANRE 2030 proposal and percentage reduction in energy generated and emissions in 2030 relative to 2019.

3.2. Technology Options and Emission Intensities for Ammonia Production

Despite ANRE's attempts to shift to the coal fleet to low emissions plants, the projected reductions in emissions calculated above are not sufficient to meet Japan's NDC obligations. Given this, it is unsurprising the Japanese government is exploring the use of ammonia co-firing to displace emissions from thermal coal.

From a supply chain perspective, a key question when considering the benefit of co-firing with ammonia is the emissions intensity of ammonia production. Global ammonia production is at an appropriate scale, producing 159 million tons in 2018, equivalent to 17% of Japan's total primary energy consumption on a lower heating value basis. The bulk of this production is delivered via steam reforming of methane to produce hydrogen, which is fed with air captured nitrogen into the Haber-Bosch process. The Haber-Bosch process has been improved over the last 100 years with a switch from coal gasification to methane reforming, and reductions in thermal losses have reduced the input energy requirements by more than half (Smith, Hill and Torrente-murciano, 2020).

Despite these technological improvements, the ammonia production process is a major source of emissions. The International Energy Agency reports the global emissions from ammonia as 406MT with an average intensity of 2.33 tonnes of CO_2 per tonne of ammonia (IEA, 2020). The International Fertilizer Industry Association reports the direct emissions for Best Available Technology (BAT) of 1.6 tonnes of CO_2 per tonne of ammonia produced with steam methane reforming, increasing to 3.8 tonnes of CO_2 for coal partial oxidation processes (International Fertiliser Industry Association, 2009). The emissions intensity of ammonia production in all regions has historically exceeded 2.0 tonnes of CO_2 per tonne, with the lower limit approached in regions, such as Oceania, dominated by methane as the energy source. (Institute for Industrial Productivity, no date)

The values reported above are the direct emissions associated with ammonia production. The production of methane also has significant fugitive emissions associated with it. The amount of methane released during gas extraction can vary with the type of gas field and the particular site. The IEA estimated an international fugitive emission intensity of 12.8kg/GJ (World Energy Outlook 2017, 2017) Australian gas has a relatively low average equivalent intensity of 5.8kg/GJ, based on analysis of Australian gas production and reported emissions for 2017-18 (Australian Government, 2019a). This increases the effective emissions intensity of ammonia production from methane by 11 per cent. The production of ammonia from methane is a highly optimized process with significant energy flows between processes. The bulk of the energy input is required for the endothermic steam methane reforming reaction to convert methane to hydrogen and carbon monoxide. Energy is released during the exothermic water shift reaction, which converts steam and the carbon monoxide to hydrogen and carbon dioxide, but at temperatures too low for the steam methane reforming process. Excess energy from hydrogen production, often in the form of steam, is used to drive the nitrogen air separation and the compressors for the Haber-Bosch process.

The steam methane reforming process for hydrogen production produces a carbon dioxide rich waste stream which needs to be separated from the hydrogen. Approximately 0.97 kg of CO_2 results from the stoichiometric reduction of hydrogen from methane which is 64% of the BAT emissions. The ammonia industry already captures 36% of this CO_2 for other use with approximately one third used for the production of urea from ammonia and the remainder sold for use in other industries (IFA, 2009).

A second technology option is to deploy carbon capture and storage to reduce the emissions from ammonia production using the BAT. Additional energy is required to capture, transport and inject the captured CO_2. The International Energy Agency Greenhouse Gas Program undertook technoeconomic analysis of a range of carbon capture and storage approaches for steam methane reforming of hydrogen (International Energy Agency, 2017).

There are three possible points in the steam methane reforming process that CO_2 emissions can be captured for storage, and several different technology options. The economics and overall capture rates vary depending on the technology and point of capture, since it is easier to separate out CO_2 if it is in higher concentrations in the waste stream. The IEA analysis identified the quantum of additional methane input required for capture and compression of the CO_2 and the corresponding reduction in electrical energy available from the modelled plants cogeneration facility for different technology options. Transport and injection of the capture gas was not included in the analysis as this depends strongly on the location of suitable geological storage facilities nearby. Incorporation of carbon capture after the water shift reaction (56% capture case 1A) reduces direct emissions by 0.93kg per kg of ammonia, but requires an additional 0.12kg of methane as fuel and reduces the electrical energy available for the Haber-Bosch process to 0.18 kWh per kg of ammonia. Achieving higher capture rates of 90% is more challenging and requires capturing carbon dioxide from the dilute stream in the flue gases (90% capture Case 3A). This also increases capital and operational costs as the total quantum of methane input increases by 0.36 kg per kg of ammonia and the electrical transfer reduces to only 0.05 kWh/kg. Overall, the IEAGHG study showed that CCS at

56% capture rate increases the cost of hydrogen by 18%, while 90% capture rates increase the cost by 45%.

The decrease in energy transfer to the Haber-Bosch processing resulting from the carbon capture in hydrogen formation is assumed to be replaced by increased methane combustion. Smith et al (2020) analysed current and future Haber-Bosch processes and determined that an all electrical process would require 2.7GJ (0.75kWh) input. Assuming steam turbine efficiencies of 45%, this requires an additional 0.10 and 0.12 kg of methane for the water shift and flue capture options respectively.

3.3. **Ammonia Production from Renewable Electricity**

A third technology option is the production of ammonia from renewable electricity. Electricity derived from renewable sources can replace some, or all, of the energy input for Haber-Bosch ammonia production. The carbon emissions from ammonia production are predominantly embedded in steam methane reforming to produce hydrogen. Electrolysis of hydrogen, via alkaline or polymer electrolyte membrane (PEM) electrolyzers eliminates the bulk of these emissions, with the remainder associated with the sourcing of nitrogen and compression of process gases. Electrolysers currently consume approximately 54 to 58 MWh per tonne of hydrogen (Commonwealth Scientific and Industrial Research Organisation, 2018) equating to 9.5 to 10.2 kWh of electricity input per kg of ammonia.

A major Australian ammonia producer, Yara Pilbara, is developing “renewable ammonia” by providing some of the hydrogen input to the Haber-Bosch plant derived from electrolysis driven by 2.5MW of solar photovoltaic generation plant. Yara claims direct emission reductions of 0.98kg CO_2 per kg of ammonia (Yara, 2020). These reductions appear conservative based on Smith’s determination of 2.7 GJ of electrical energy for the

Haber-Bosch process (Smith, Hill and Torrente-murciano, 2020). Provision of this energy from 42% to 48% efficient steam compressors requires an extra 0.11 to 0.13 kg of methane per kg of ammonia above the electrical input resulting in direct emissions of 0.31 to 0.35 kg of CO_2 per kg of ammonia.

Ammonia with 100% renewable electricity inputs is also possible. Smith, Hill and Torrente-Murciano (2020) assume 38.2 GJ (10.6 MWh) of electrical energy per tonne of ammonia in their analysis of current low emissions ammonia production, with a range of future improvements offering the potential of reductions of more than 2kWh/kg. The major ammonia plant engineering and manufacturing firm, Thyssenkrupp, reports development of a fully electrically driven plant (Thyssenkrupp, 2019) resulting in near zero direct emissions using 9.6MWh per tonne based on 300 tonne per day production for a 120MW input power.

The use of renewable electricity results in no direct emissions from energy use, although there are indirect emissions associated with the construction of renewable energy generators. Solar and wind, which dominate new generation in Australia, are assumed to be the sources of renewable generation. Nugent and Sovacool (2014) analysed 150 life cycle analysis studies, and determined an average construction related emission intensity of 9.0 and 14.4 g/kWh for solar and wind respectively. These would result in emissions of 0.09 to 0.14 kg of CO_2 per kg of ammonia over the life of the renewable generators. Emissions associated with the manufacture of the plants, for example solar module manufacture, are excluded as these do not occur in Australia.

3.4. Emissions from Ammonia Manufacture by Technology

Figure 3 directly compares the energy input and emissions required to produce one kg of ammonia in Australia using different processes.

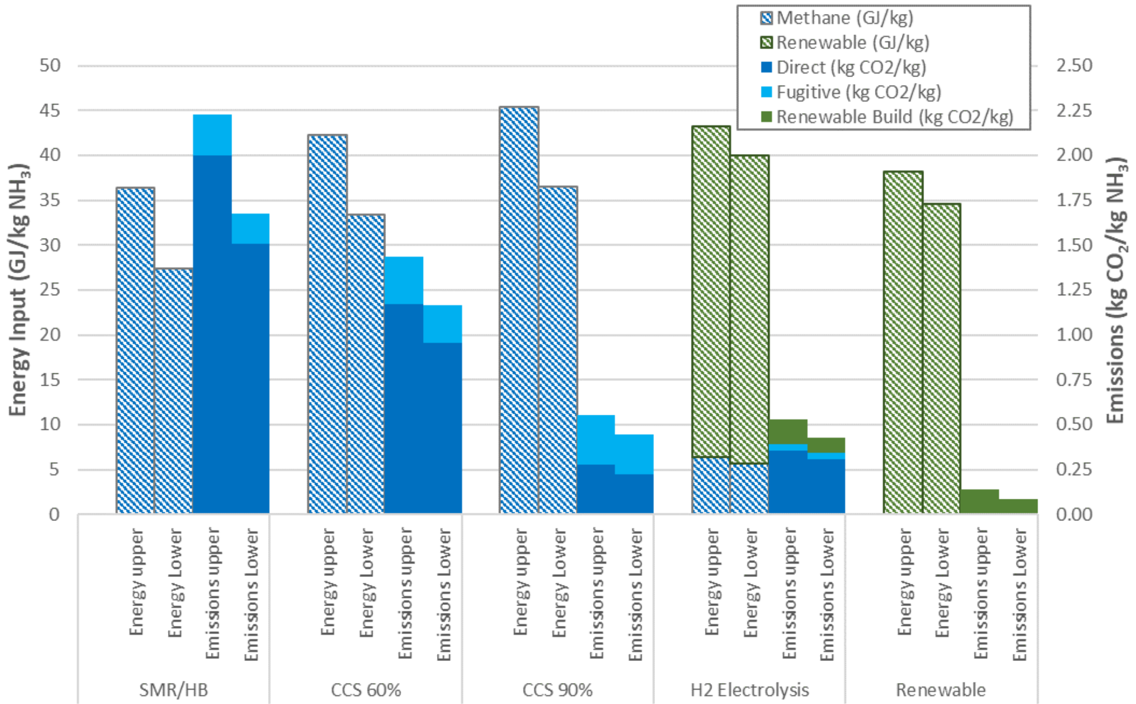

Figure 3. Energy and emissions intensity per kg of ammonia for the production scenarios. Blue represents methane related inputs and green represents renewable electricity. The energy inputs (left axis) are represented by the patterned bars while the carbon emissions are solid. While the energy input across the various manufacturing options are similar, there are large differences in emissions intensity of the five options. Using these calculations, the results show the choice of synthesis method has significant consequences for the emissions associated with ammonia manufacturing.

The standard steam methane reforming and Haber Bosch (SMR/HB) process has the highest direct emissions intensity of 1.5 to 2.0 kg CO_2 per kg of ammonia (dark blue). These direct emissions are significantly reduced with carbon capture and storage. The two capture rates considered represent a moderate rate that has already been achieved in operating, large scale CCS plants (60%), and the upper limit for existing, large scale CCS technology (90%). Both CCS scenarios require additional energy input in the form of natural gas, which reduces the CCS benefit of the direct emissions reductions relative to the base case.

In all processed involving methane as a feedstock or fuel, we include the fugitive emission associated with natural gas production (light blue). It is worth noting explicitly here that CCS only reduces direct process emissions and does not reduce the fugitive emissions. Importantly, the reductions in emissions are not as great as the carbon capture rate due to the increased direct emissions associated with the extra energy consumption required, and the increased methane related fugitive emissions. The use of 60% to 90% CCS in the ammonia synthesis process reduces the emissions associated with production by approximately 35% and 75%, respectively.

The decrease in emissions from hydrogen electrolysis process relative to the baseline process highlights the emissions intensity of the hydrogen supply in the Haber-Bosch process with most of the emissions attributable to the direct and fugitive emissions from the methane consumption for the Haber-Bosch process. The total emissions intensity is similar to that of the highest level (90%) of CCS. The 100% renewable ammonia process has the lowest emissions intensity: up to 96% lower than the current industry standard process. Most importantly, this process also results in significantly lower emissions than both replacing SMR with renewable hydrogen in the Haber Bosch process and employing 90% capture rate CCS to the standard SMR/HB process.

4. Results: Supply Chain Emissions Analysis from Ammonia Coal co-burning

The emissions implications of co-burning ammonia, produced in Australia by a range of technologies, in Japanese coal fired power stations can now be estimated.

Emissions savings are calculated relative to Japan’s projected 2030 fleet, assuming that the changes proposed by ANRE will go ahead, resulting in a reduction of the overall capacity and replacement of older, high emissions plants, with low emissions USC and IGSC technologies. These changes are expected to contribute to 47 MT of emissions savings in 2030.

Displacing 20% of Japan’s projected 2030 coal generation with ammonia in this scenario would require co-combustion of 22.7 MT of ammonia. The avoided coal would result in an additional emissions saving of 40 MT (Figure 4, Black bar) based on the expected emissions intensity of the 2030 Japanese coal fleet. This is a significant contribution towards Japan's 2030 NDC reduction target for the electricity sector of 190MT, and is similar to the reduction associated with the proposed ANRE plan to replace of older technologies in the coal fleet.

Assuming that the displaced coal is from Australia, since it is the major provider of coal to Japan, there is also a 1 MT to 10 MT reduction in fugitive emissions (grey bar), depending on the mining depth of the coal, from coal extraction in Australia (Australian Government, 2019b).

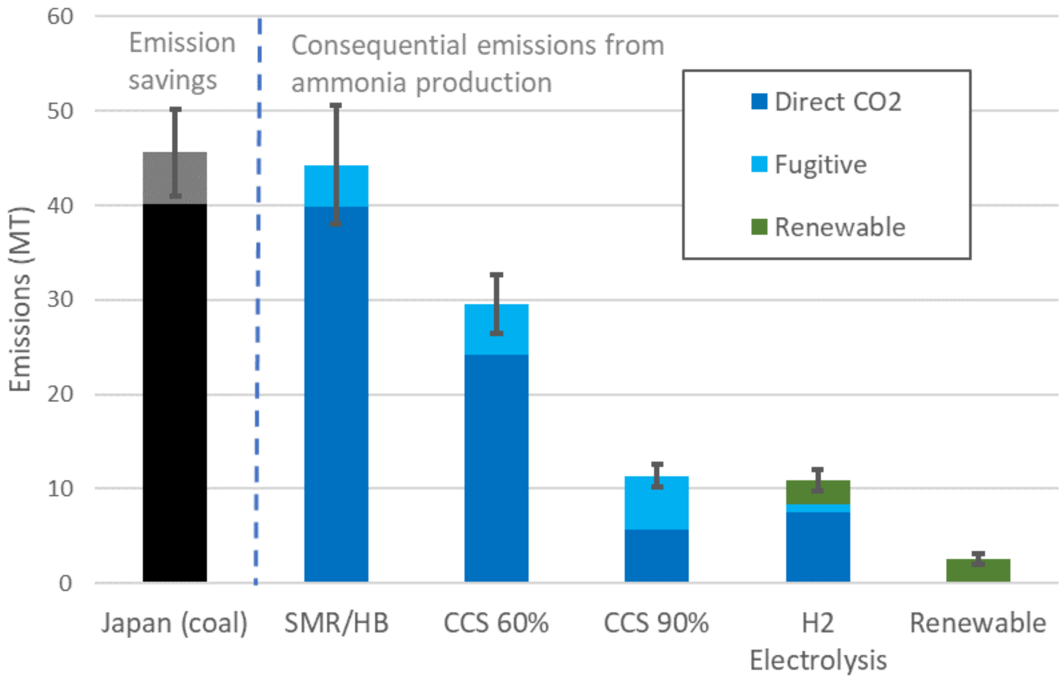

Figure 3. Emissions savings due to 20% ammonia/coal co-burning in Japan's 2030 coal fleet, and consequential emissions from ammonia manufacture. The black bar represents the direct emission savings from coal in Japan while the grey is the coal fugitives with the range of fugitive emissions represented by the error bar. Dark and light blue are direct and indirect emissions associated with methane use while green is the in-direct renewable emissions. The ammonia manufacturing error bars represent the range of high and low emissions in Figure 2.

Despite this reduction due to avoided coal use, ammonia production using different technologies will mostly lead to increased emissions in Australia. The magnitude of the emissions increase varies markedly, however, depending on the production technology used. The direct emissions of the SMR/HB process vary from 34MT for the best available technology, to 45MT for average regional level intensities. Therefore, in this scenario the direct emissions saving in Japan would be balanced by a similar *increase* in emissions in Australia, due to the CO_2 produced during the SMR-HB process. A further 5 to 6 MT of emissions would result from average fugitive emissions from methane production in Australia, while 1 to 10 MT of fugitive emissions from coal would be offset. Taken together, the co-combustion of ammonia from the SMR/HB process does not decrease total GHG emissions, and effectively becomes a transfer of emissions for the energy service from Japan to Australia (see Figure 3).

In contrast, the use of 60% to 90% CCS in the ammonia synthesis process reduces the net increase in emissions in Australia to between 24 +/- 8 MT to 6 +/- 6 MT per annum for the 60% and 90% CCS cases respectively. The net reduction in global emissions from co-burning 20% ammonia from SMR/HB with CCS is then between 16 +/- 8 MT and 34+/- 6 MT per annum.

Renewable electricity use for hydrogen production has a similar total emissions (11 +/- 1 MT) to the SMR/HB process with 90% CCS. Approximately 80% of these emissions are associated with the methane consumed to provide the energy input. Reductions in coal fugitive emissions would result in an emission change in Australia of 6 +/- 6 MT. The net emission change is 35 +/-6 MT compared to burning 100% coal in the projected 2030 coal fleet.

Finally, analysis of the 100% renewable electricity driven process shows it would result in emissions reductions across the total supply chain over the lifetime of the project. Annual lifetime emissions associated with the construction of the renewable energy supply (2 to 3 MT per annum) would likely be offset in Australia by the reductions in emissions from coal extraction, except for the lowest coal fugitive emission sources. Net emissions reductions would be significant at 43 +/-5 MT per annum, 95% lower than burning coal.

This comparative analysis highlights the importance of the choice of ammonia manufacturing technology for reducing global emissions. While the co-burning of ammonia with coal leads to substantial emission reductions in Japan, most of the production options lead to significant increases in emissions in Australia reducing global benefit. Within uncertainties, the BAT technology would result in no net change in total emissions and would result in an effective transfer of emissions from Japan to Australia. The 60% and 90% CCS options would only enable 35% to 75%, respectively, of the global benefit relative to the coal burning savings. The renewable hydrogen option delivers similar benefits (76%) due to the use of methane in the Haber-Bosch process. Only the 100% renewable electric driven Haber-Bosch process would likely result in net emissions reductions in both countries with 95% lower net emissions than burning 100% coal.

5. Conclusion and Policy Implications

Japan is a leader in the development of international trade in ammonia intended for co-burning in thermal coal facilities. The Japanese government led the formation of the Green Ammonia Consortium, which has proposed the development of global supply chains in ammonia, including with Australia, Norway, Qatar, Saudi Arabia South Africa, the United States (Muraki, 2018). Japan estimates that 40 megatons of CO_2 could be saved from co-burning 20 percent ammonia in its existing thermal coal generation fleet, stating this represents approximately 3 per cent of aggregate national emissions, or 7 per cent of emissions associated with the power sector (2013 baseline).

We compared the emissions implications of using different ammonia manufacturing technologies, using the empirical setting of a supply chain incorporating Japan and Australia. Four technology options were considered in the analysis: 1) Haber-Bosch with methane reforming; 2) the inclusion of CCS with 60% and a theoretical 90% capture rate; 3) the use of renewable energy in the Haber Bosch process; 4) renewable energy to produce hydrogen via electrolysis.

In this paper we show that the degree of emissions reduction associated with ammonia coal co-burning is strongly affected by the production method. The findings show that there is little to no gain in emissions reductions on a supply chain basis through the co-combustion of ammonia in Japan's coal fleet, if a standard Haber-Bosch with methane reforming approach is used. Net emissions remain substantial if CCS is applied at already demonstrated capture rates of 60%, with reductions of 16 +/- 8 MT, or 35% less than 'business as usual' coal burning (BAU). A theoretically achievable CCS capture rate of 90% leads to an emissions reduction of 34 +/- 6 MT, or 75% less than BAU, which is equivalent to using hydrogen produced with renewable energy as an input to the Haber Bosch process. Finally, our results show that the use of fully electrified ammonia production technology leads to a substantial reduction in emissions across the supply chain of 43 MT, or 95% less than BAU 45+/- 5 M.

We have not considered the change in emissions associated with transport of coal and ammonia from Australia to Japan. This is because emissions associated with international shipping fall outside both the Japanese and Australian accounting frameworks. However, traditional fuel oil used for shipping is one of the most polluting forms of fossil fuels, and emissions from the maritime sector are significant. In recognition of this, the International

Maritime Organisation is moving to decarbonise the industry by switching to clean fuel, including hydrogen and its derivatives like ammonia (DNV GL, 2018).

The policy implications of our analysis are substantial. If the ammonia used to co-combust in thermal coal generation is both produced and consumed within Japan, then the emissions from different ammonia production methods are internalized within Japan's national commitments under the Paris Agreement.

In contrast, if there is trade in ammonia between Australia and Japan, the emissions implications between the two countries diverge. For Japan there is a benefit from co-burning ammonia equivalent to the avoided CO_2 emissions from thermal coal combustion regardless of production technology. In Australia, on the other hand, ammonia producers have an incentive to utilize the lowest cost production method. Under current technologies, and in the absence of mechanisms to account for the social cost of emissions, manufacturers are more likely to utilize emissions intensive technologies. In this case the Australian government is required to consider the emissions implications of increasing ammonia production within Australia's own national commitments. Further, the challenge inherent in this trade-off becomes more acute as the market for ammonia grows. If countries beyond Japan adopt similar strategies for reducing near-term emissions from the power sector through ammonia co-burning, for example, emissions-intensive ammonia exports will grow as the market share of Australian producer's increases.

How can this problem be managed with policy?

Under an uncoordinated approach, Japan has an incentive to promote the co-combustion of ammonia regardless of source. For Australia, the deployment of an economy-wide carbon price consistent with a zero-carbon target would manage any increase in emissions from an increase in ammonia manufacturing, while ensuring emissions reductions occur at the lowest marginal abatement cost across the economy. In the absence of a carbon price, the Australian government could also tax or regulate more emissions-intensive ammonia manufacturing methods. Australia could also recognize the environmental benefit of low emissions ammonia production methods by valuing the avoided emissions, similarly to the use of Australian Carbon Credit Units.

In this case, a key challenge is that Japan still has an incentive to import from lower costs suppliers, even if Australia implements policy designed to account for the social cost of more emissions intensive ammonia. Beyond national approaches, Article 6.2 of the Paris Agreement allows for the use of Internationally Transferred Mitigation Outcomes (ITMOs). In this case, carbon offsets - as provided for in Japan's current bilateral crediting agreements - could provide an incentive for Japan to facilitate investment in low emissions ammonia, up to the point that the marginal cost of investment exceeds alternative approaches available to reduce emissions within Japan. In this case the environmental value of avoided emissions accrues in Japan, and recognizes the emissions avoided from the non-burning of thermal coal using low-emissions ammonia. Japan currently utilizes a bilateral Joint Crediting Mechanism with a number of developing countries, with credits transferred to Japan.

The use of ITMOs faces challenges. Both Australia and Japan have economy-wide emissions reduction targets. It is nevertheless important to avoid double-counting, whereby Japan would count the direct emissions benefit from the reduction in coal use in the power mix, and the environmental value created by the emissions avoided relative to a baseline of current BAT ammonia production technologies. In addition, it is important to ensure the environmental integrity and to properly account for transfers, especially as ammonia produced for exports represent an increase in aggregate emissions in Australia relative to a baseline in which that activity would not have occurred (Schneider and La Hoz Theuer, 2019).

While this paper has examined the emissions implications of trade in ammonia using different technologies that encompasses an Australia-Japan supply chain, an additional and crucial issue lies in growth in a regional or global market for ammonia with multiple suppliers and consumers, under which there remains an advantage to use higher emitting production technologies at current prices, absent a coordinated policy approach.

Given this, a third approach recognizes the tension between commercial and climate change-related goals by including multiple stakeholders to negotiate appropriate standards for recognizing the environmental value of low—carbon ammonia production. Such an approach must manage the competitive implications of low carbon ammonia across the supply chain by, for example, requiring the use of ammonia production technologies below a certain emissions threshold, thus removing the incentive for utilizing lower cost but higher emissions production methods. In this case, as the findings here show, ensuring the environmental integrity of emissions reductions across the supply chain is paramount.

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