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ORIGINAL ARTICLE

The role of ammonia as an alternative fuel by mixing it into natural gas and satisfying the gas quality requirements

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Abstract

Ammonia as a carbon-free e-fuel has a good potential as a future energy vector to contribute to reducing greenhouse gas emissions. By mixing it into natural gas (NG), the carbon dioxide emissions are decreased when the mixture is burnt. To study the change in the gas properties of different NG compositions with and without added hydrogen, 0–20 mol% ammonia was mixed and various parameters were calculated. The results show that a higher content of ammonia decreases the compression factor, lower heating value, and Wobbe index (WI). Depending on the gas composition the relative density is either increasing, for NGs containing a high level of methane and/or hydrogen, or decreasing, for gases with larger quantities of higher hydrocarbons and/or inert gases. NGs with added hydrogen are more impacted by addition of ammonia, where the relative density can be improved by mixing the gas with ammonia to satisfy the gas quality requirements. However, taking the WI limits into account, more ammonia can be added into a NG without any hydrogen compared to one with hydrogen. The addition of ammonia into NG is possible considering the gas quality parameters, even in the case when the gas contains some hydrogen.

KEYWORDS

ammonia, ammonia blend, gas compositions, gas quality, natural gas

1 | INTRODUCTION

The European Commission has a key target to cut greenhouse gas emissions by at least 40% in 2030 compared to the level in the 1990s, which is stated in the 2030 climate and energy framework.[1] In September 2020, the level was increased to 55% to make it feasible for the EU to be climate-neutral by 2050, meaning an economy with net-zero greenhouse gas emissions.[1] One way of reaching this goal is to enhance the utilization of carbon-free fuels such as hydrogen (H_2) and ammonia (NH_3), which do not release any carbon dioxide when they are burnt. A lot of research is ongoing regarding hydrogen, mainly how to produce it in a green way but also its usage as fuel in combustion processes.[2–5] As an energy carrier, hydrogen has a high energy content per kilogram but a low density and volumetric energy value, meaning that large tanks and/or high pressures are required to store and transport it which makes it not economically affordable.[6] One option could be to mix it into the natural gas (NG) grid and transport it along the pipelines.[7] Another alternative is to utilize ammonia as a hydrogen storage since ammonia has a high volumetric hydrogen density and low storage pressure.[8,9] Ammonia has been used for over a century and its manufacturing, storage, and transportation are well-known.[10] The most common way to produce ammonia (gray ammonia) is from fossil fuel using the Haber–Bosch process, but this method is set to be replaced in 2025 by blue ammonia which also uses fossil fuel but with carbon dioxide capture and storage.[11] In 2030, the target is to replace blue ammonia with green ammonia, which is derived from renewable sources such as hydrogen, manufactured from electrolysis of water, and nitrogen taken from the air.[10,12]

At ambient conditions, ammonia is a colorless gas with a strong irritating.[13] It is a toxic chemical and already low concentrations of ammonia can be dangerous for the human, meaning that it requires additional safety measures compared to other fuels, such as hydrogen and liquified natural gas (LNG).[14] Ammonia is corrosive, especially in the presence of moisture, to copper, zinc, brass, and tin, and therefore it is crucial to use the correct material for piping and gaskets to prevent leakage.[13,15]

Ammonia is mostly used as a raw material for agricultural fertiliser, refrigerant gas and in the manufacture of plastics, explosives, and other chemicals.[8] It can also be utilised as a fuel for combustion in engines, boilers, and gas turbines.[15] However, ammonia requires a high energy to ignite and has a lower burning velocity compared to conventional hydrocarbons.[16] Its heating value is low and during its combustion high fuel nitrogen oxides (NO_x) emissions are formed.[11] Nitrogen oxides are though, not the final product of ammonia combustion since the overall reaction of ammonia is $4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$ when considering the Gibbs free energy of the combustion products.[10] By mixing ammonia with methane the burning velocity can be increased and the blend is easier to ignite compared to pure ammonia.[11,16] Even carbon dioxide emissions are reduced when ammonia and methane are blended.[11]

Several studies[16–24] have been carried out to understand the ammonia combustion behavior and the focus has been to examine the combustion and emission characteristics of blends with ammonia and NG/methane. Ishaq and Dincer[19] investigated the combustion performance of an ammonia–NG blend in terms of energy and exergy efficiencies, as well as carbon dioxide emissions. The results showed that the addition of ammonia (0–20 mol%) into NG decreased the oxygen flow rate as the combustion reaction proceeded, while the nitrogen flow increased because ammonia combustion evolves nitrogen. With a raised amount of ammonia in the mixture, the combustion process heat rate reduced, which also was the case for the carbon dioxide emissions. Both the energy and exergy efficiency were increased when ammonia was added.

In a study by Oh et al.,[20] an experimental investigation with a NG–ammonia spark-ignited engine was performed to check its feasibility for marine engine operation. The results indicated that carbon dioxide emissions were reduced up to 28% when about 50 vol% of ammonia had been mixed with NG. It was also observed that with an increased amount of ammonia, the NO_x emissions increased.[21] The same phenomenon was discovered by Bonasio and Ravelli,[6] which examined the direct combustion of an ammonia–NG blend in a micro gas turbine. By feeding more ammonia into the turbine, the carbon dioxide emission was continuously decreased while the NO_x was increased. To solve this problem, the authors suggested installing a selective catalytic reduction system in the stack to reduce NO_x concentration in the exhaust gas. Looking at ammonia's impact on carbon monoxide emission, it was negligible according to Henshaw et al.,[22] who were investigating a premixed ammonia–methane–air combustion in an adiabatic flat flame burner.

A main challenge with ammonia is its slow chemical reaction rate, leading to a lower laminar burning velocity.[23] This is the explanation why the overall burning velocity is decreased in the combustion of ammonia and NG, which has been detected in both experimental and simulated results.[20,22] Research has also proved that the addition of ammonia prefers a lower air–fuel ratio to get the lowest possible emissions, where Oh et al.[20] discovered that more gaseous discharges were formed with a higher lambda, and the same was noted by Selfarski et al.[24] who investigated nitrogen oxide.

Liquified ammonia has a low volumetric energy density, which is about half of LNG and a third of conventional oil fuels, meaning that a larger amount of ammonia is required to get out the same energy.[13] Looking at its calorific value on a mass basis, it is about two and a half times less than NG, half of gasoline, and more than six times smaller than that of hydrogen.[11,25] By adding ammonia into NG, the total fuel flow must increase to compensate for its lower heating value (LHV) and to keep a constant energy level of the flow.[6,21] This is important to consider since a larger flow can create vibrations in the pipe if it is only designed for a certain amount of NG without any margin.[26] However, mixing ammonia into NG does not happen directly into the NG grid which can be the case for hydrogen.[7] Pieces of research, for example, Ogden and colleagues,[27–32] have been made to find out the maximum allowed level of injected hydrogen into the NG grid by examining how the gas properties of the mixture, piping material, and end consumers are influenced. This is due to the challenges with the transportation and storage of hydrogen and a cheaper way is to add a small amount of it directly into the existing NG grid.[6] The case is different when ammonia is planned to be blended with NG. Ammonia can be stored and transported in liquid mode at 8 bar and at room temperature, and its cost per volume of stored energy is three times less expensive than that of hydrogen.[25] Therefore, there is no problem to transport ammonia and its mixing with NG occurs by first heating-up the ammonia liquid to gas which is supplied in a separate pipeline to a mixing unit, where the mixing takes place, whereafter the ammonia–NG blend is fed into the combustion system according to Figure 1. In this figure, the addition of hydrogen into the NG grid is also shown since this will be a possible scenario in the near future.[7] Depending on the operating pressure used in the process, it is important to have a high enough temperature of the mixture to ensure that no ammonia droplets are formed.

Previous studies of ammonia–NG mixtures have been focusing on combustion properties and released emissions.[18–24,33] The gas quality of the fuel is important to be aware of to achieve the highest performance of end applications, such as boilers, burners, and gas engines since they have their own gas specifications.[34,35] These specifications are, among others, how much impurities the gas can contain (eg. hydrogen sulphide, total sulphur, oxygen, and carbon dioxide), and within which range the relative density and Wobbe index (WI) can be.[36] The WI indicates the interchangeability between gaseous fuels, where gases with the same WI, but different compositions, can be replaced with each other as they release the same amount of energy.[37] Since the gas quality specifications are different across the European Uion,[38] the EASEE-gas (European Association for the Streamlining of Energy Exchange-gas) has established and promoted standard NG quality specification at cross-border points in Europe and made a recommendation of gas quality parameters which is stated in Common Business Practice (CBP) 2005-001/02 "Harmonisation of Natural Gas Qualities."[39] In this document, a WI between 46.4 and 54.0 MJ/m^3 and a relative density from 0.554 to 0.699 are proposed at the reference conditions 15°C and 101.325 kPa.

There are no comparable investigations to our knowledge of the impact of ammonia on the main characteristics of different NG compositions. The present work is concentrating on how the addition of ammonia gas into NG with and without added hydrogen affects the gas quality parameters, for example, relative density, WI, and compressibility factor. A comparison to the recommended specifications in the EASEE-gas CBP is also done to see how much ammonia can be added to fulfill the limits set by EASEE-gas. The purpose of this study is to show that an ammonia–NG mixture can accomplish the gas quality requirements of the end consumers and be used as a fuel in combustion systems (combustion engines, gas turbines, furnaces), which in turn lead to lower carbon dioxide emissions of the application.

2 | MATERIALS AND METHODS

2.1 | Gas compositions

NG consists mainly of methane, but it can also contain small amounts of higher hydrocarbons (e.g., ethane, propane, and butane) and inert gases such as carbon dioxide and nitrogen.[40] The gas composition varies depending on its origin, how it is treated, and if it is blended with other NGs in the gas infrastructure.[35,41] In Europe, most NG is transported by pipeline but it can also be shipped in liquified mode as LNG.[42] The LNG can be sent to the NG network, but it must first be re-gasified back to gas mode before entering the pipe. In this paper, the most common NG and LNG compositions, constituting about 74% of the total imports to Europe in 2021 have

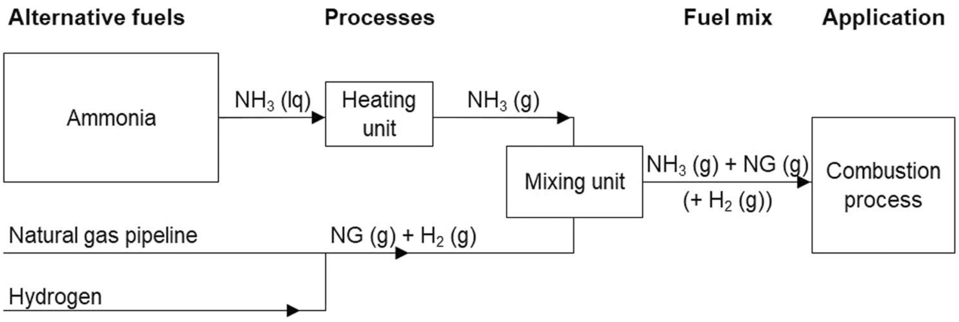

FIGURE 1 Suggested procedure of mixing ammonia and natural gas with each other, with a possibility to inject hydrogen into the natural gas grid (lq = liquid, g = gas).

been analyzed.[42–44] In addition, an average gas composition, which was calculated by Ingo et al.[7] based on the most common NG and LNG compositions that were imported to Europe in 2021, was examined. Ingo et al.[7] made a study on how much hydrogen can be added into the NG grid to fulfill Euromot's requirements, the European association of internal combustion engine manufacturers, and got a result of 13 mol% added hydrogen. In this study, the same average gas composition without and with 7 mol%, respective 13 mol% added hydrogen are used to see how ammonia affects a NG with added hydrogen and what the maximum level of ammonia is to accomplish with the WI range of 49.0–52.7 MJ/m^3 set by Euromot.[45] The gas compositions are shown in Table 1 and the unit is in molar percentage.

2.2 | Calculation of gas properties

This section describes how the gas properties of ammonia–NG mixtures with various compositions were calculated. Since the standard reference conditions for NG are at a temperature of 15°C and an absolute pressure of 101.325 kPa, the same conditions have been used in this work.[46] Table 2 shows the needed input data for each component to be able to calculate the gas properties according to Equations (1)–(8), which can be found in ISO 6796:2016.[47]

Equation (1) shows how to calculate the compression factor, or compressibility factor of a mixture at metering reference conditions.

$$Z_2 = 1 - \left(\frac{p_2}{p_0}\right) \times \left[\sum_{i=1}^{n} x_i \times s_i\right]^2, \tag{1}$$

where Z_2 is compression factor at metering reference conditions, p_2 is pressure at metering reference

TABLE 2 Summation factor, ideal gross molar-basis calorific value, and molar mass for each component presented in in the gas mixtures.[47]

Component	Summation Factor at 15°C, s_i	Ideal gross molar basis calorific values at 15°C, $\left[(Hc)_G^o\right]_i$ (kJ/mol)	Molar mass, M_i (g/mol)
Methane	0.04452	891.51	16.04246
Ethane	0.09190	1562.14	30.06904
Propane	0.13440	2221.10	44.09562
n-Butane	0.18400	2879.76	58.12220
iso-Butane	0.17220	2870.58	58.12220
n-Pentane	0.23610	3538.60	72.14878
iso-Pentane	0.22510	3531.68	72.14878
Nitrogen	0.01700	0.00	28.01340
Carbon dioxide	0.07520	0.00	44.00950
Hydrogen	−0.01000	286.15	2.01588
Ammonia	0.11000	383.51	17.03052

TABLE 1 Investigated natural gas[43] and LNG[44] compositions given in mol%, as well as the average gas composition without and with added hydrogen.[7]

Component	Russia[a]	Norway[a]	Algeria[a]	Qatar[b]	Russia—Sakhalin[b]	Average gas comp. with 0% H_2	Average gas comp. with 7% H_2	Average gas comp. with 13% H_2
Methane	98.79	92.63	91.10	90.91	92.53	95.10	88.58	82.40
Ethane	0.44	5.08	7.48	6.43	4.47	3.20	2.98	2.80
Propane	0.10	0.89	0.81	1.66	1.97	0.70	0.65	0.60
n-Butane	0.02	0.11	0.05	0.37	0.48	0.15	0.14	0.10
iso-Butane	0.02	0.11	0.05	0.37	0.48	0.15	0.14	0.10
n-Pentane	0.02	0.03	0.00	0.00	0.00	0.02	0.02	0.15
iso-Pentane	0.01	0.03	0.00	0.00	0.00	0.02	0.02	0.15
Nitrogen	0.55	0.51	0.51	0.27	0.07	0.50	0.47	0.40
Carbon dioxide	0.05	0.61	0.00	0.00	0.00	0.30	0.28	0.20
Hydrogen	0.00	0.00	0.00	0.00	0.00	0.00	7.00	13.40

[a] Natural gas composition.

[b] LNG composition.

conditions; 101.325 kPa, p_0 is absolute pressure; 101.325 kPa, p_0 is mole fraction of component i, s_i is summation factor at metering reference conditions, which can be found in Table 2.

The amount of heat which is released during complete combustion of a specified quantity of gas is defined as the gross calorific value, where the combustion products are returned to the same precombustion temperature and all products are in a gaseous mode except for water which is in liquid mode.[47] Equation (2) can be used to calculate the value on a molar basis at the combustion reference temperature, which is 15°C in this study.

$$(Hc)_G = (Hc)_G^o = \sum_{i=1}^{n} x_i \times \left[(Hc)_G^o\right]_i, \tag{2}$$

where $(Hc)Go$ is real gas gross molar-basis calorific value of the gas mixture (kJ/mol), $(Hc)_G^o$ is ideal gas gross molar-basis calorific value of the gas mixture (kJ/mol), $\left[(Hc)_G^o\right]_i$ ideal gross molar-basis calorific value of component i, which can be found in Table 2 (kJ/mol).

The real gas gross volume-basis calorific value, or higher heating value on volume basis, can be determined according to Equation (3).

$$(Hv)_G = \frac{(Hc)_G^o}{V}, \tag{3}$$

where $(Hv)_G$ is real gas gross volume-basis calorific value of the gas mixture (MJ/m^3), V is real gas molar volume of the gas mixture at metering reference conditions, which is calculated according to Equation (4) (m^3/kmol).

$$V = Z_2 \times R \times \frac{T_2}{p_2}, \tag{4}$$

where R is molar gas constant; 8.3144621 J/mol K[47] and T_2 is temperature at metering reference conditions; 288.15 K.

When the gross calorific value is divided by the square root of the relative density at the same metering reference conditions, the quotient is the WI according to Equation (5).

$$I_w = \frac{(Hv)_G}{\sqrt{G}}, \tag{5}$$

where I_w is WI (MJ/m^3) and G is relative density of a real gas at the metering reference conditions.

The relative density can be defined as the ratio of the density of a gas mixture to the density of dry air at the same specified conditions of pressure and temperature.[37,47] Equation (6) shows how to calculate the relative density for a real gas mixture.

$$G = \frac{\sum_{i=1}^{n} x_i \times M_i}{M_{\mathrm{air}}} \times \frac{Z_{\mathrm{air},2}}{Z_2}, \tag{6}$$

where M_i is molar mass of component i, which can be found in Table 2 (g/mol), Z_{air} is molar mass of dry air; 28.96546 g/mol,[47] and $Z_{\mathrm{air},2}$ is compression factor of dry air at metering reference conditions; 0.999595.[47]

The net calorific value or LHV, is the amount of heat which is released by complete combustion with oxygen of a specified gas quantity, where the combustion products are returned to the same precombustion temperature as that of the reactants and all products are in gaseous state.[47] The value on a molar basis at the combustion reference temperature of 15°C can be calculated by using Equation (7).

$$(Hc)_N = (Hc)_N^o = (Hc)_G^o - \sum_{i=1}^{n} x_i \times \frac{b_i}{2} \times L^O, \tag{7}$$

where:

$(Hc)_N$ is real gas net molar-basis calorific value of the gas mixture (kJ/mol), $(Hc)_N^o$ is ideal gas net molar-basis calorific value of the gas mixture (kJ/mol), b_i is the number of hydrogen atoms present in each molecule of component i, L^O, is standard enthalpy of vaporization of water at metering reference conditions; 44.431 kJ/mol.[47]

A common unit for the LHV is MJ/kg, which can be calculated by dividing the ideal gas net molar-basis calorific value with the molar mass of the gas mixture according to Equation (8).

$$(Hm)_N = (Hm)_N^o = \frac{(Hc)_N^o}{\sum_{i=1}^{n} x_i \times M_i}, \tag{8}$$

where $(Hm)_N$ is real gas net mass-basis calorific value of the gas mixture (MJ/kg) and $(Hm)_N^o$ is ideal gas net mass-basis calorific value of the gas mixture (MJ/kg).

3 | RESULTS AND DISCUSSION

Different NG and LNG compositions have been examined to see whether ammonia addition affects the gas quality properties of the blend. Table 3 presents the relative density, WI, compression factor, and LHV of the analyzed gases when no ammonia has been added. All gases, except the Average gas composition with 7% and 13% hydrogen, fulfill the recommended values of the relative density and WI set by EASEE-gas, which is

TABLE 3 Calculated relative density, Wobbe index, compression factor, and lower heating value for the studied gas compositions when no ammonia has been added.

	Relative density	Wobbe index (MJ/m^3)	Compression factor	LHV (MJ/kg)
Russia	0.562	50.4	0.9980	49.4
Norway	0.600	51.0	0.9977	48.5
Algeria	0.603	51.9	0.9976	49.2
Qatar	0.614	52.4	0.9975	49.3
Russia—Sakhalin	0.610	52.4	0.9975	49.5
Average gas comp. with 0% H_2	0.588	51.0	0.9978	49.0
Average gas comp. with 7% H_2	0.552	50.2	0.9981	49.6
Average gas comp. with 13% H_2	0.516	49.3	0.9985	50.4

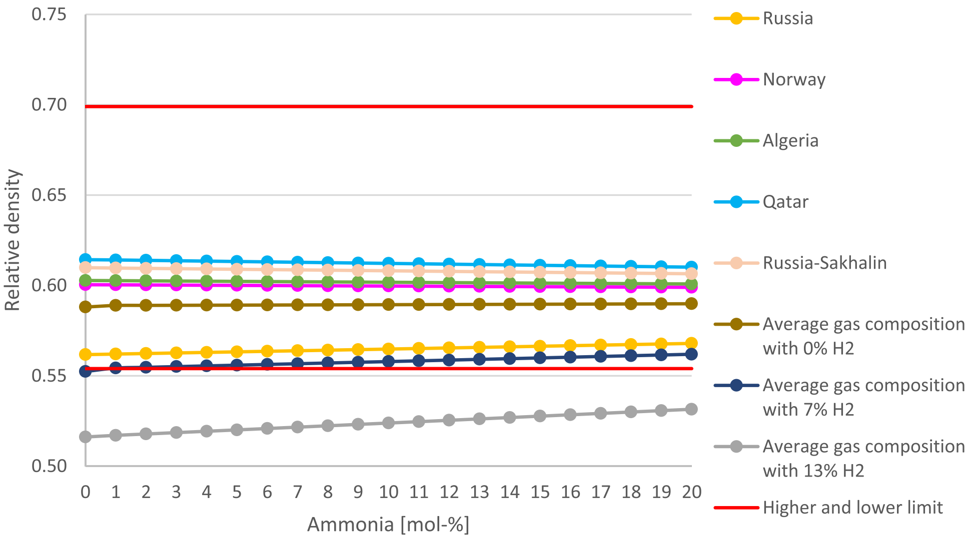

FIGURE 2 Calculated relative density as a function of ammonia percent in the natural gas mixture.

0.554–0.699 and 46.4–54.0 MJ/m^3.[39] The relative density is highest for the gas from Qatar, consisting of a low content of methane and nitrogen, and higher amounts of higher hydrocarbons, while it is lowest for the Average gas composition with 13% hydrogen. The WI is the highest for the gases from Qatar and Russia—Sakhalin, which contain a high level of higher hydrocarbons and a low level of methane. Even in this case the Average gas composition with 13%, respective 7% hydrogen have the lowest values due to their high content of hydrogen and small content of methane, but also the gas from Russia with a high amount of methane has a low WI. The compression factor is approximately in the same range for all examined gas compositions and the LHV is smallest for the Norwegian gas, which has the highest content of inert gases among the analyzed gases, and it is highest for the Average gas composition with 13% hydrogen.

In Europe, the NG quality specification does not mention if there is a maximum allowed ammonia content,[48] and an addition of up to 20 mol% ammonia into NG was used in this study. The mole fractions of other components have been reduced proportionally based on the ammonia mixture level. The relative density as a function of the mixture's ammonia mol% is shown in Figure 2, where the higher (0.699) and lower (0.554) limits stated in the EASEE-gas CBP are shown as well.[39] By adding at least 1 mol% ammonia, all gases, except the Average gas composition with 13% hydrogen, achieve this requirement. The relative density can either increase or decrease when ammonia is added, where the gases consisting of hydrogen have the biggest change with an increasing relative density due to the light molecular mass of hydrogen compared to ammonia.[47] The gas from Russia and the average gas composition with 0% hydrogen have also a raised relative density, which can be explained by the fact that they consist mainly of methane which has a lower molar mass than ammonia. The rest of the cases contain less methane and higher hydrocarbons, and the relative density is decreasing for these cases.

Figure 3 shows the WI as a function of the mixture's ammonia mol% and for all cases it decreases as the ammonia content increases. In this figure, the higher and lower limits for both EASEE-gas CBP (46.4–54.0 MJ/m^3)[39] and Euromot (49.0–52.7 MJ/m^3)[45] are visible, and most ammonia with a value of 19 mol% can be added to the Qatar and Russia—Sakhalin gases to fulfill the limit of 46.4 MJ/m^3 set by EASEE-gas. The requirements set by Euromot are stricter, and an ammonia level of 11 mol% can be mixed with the same gases and still be within the limits. These gases have a high content of higher hydrocarbons and less methane. The composition is similar for the gas from Algeria into which 9 mol% ammonia can be added. Looking at the Average gas composition with 0% hydrogen calculated by Ingo et al.,[7] the maximum amount of added ammonia is 7 mol% which can be compared to hydrogen where a level of 13 mol% was acceptable according to Ingo et al.[7] to meet Euromot's boundaries. When ammonia was added into this composition (average gas composition with 13% hydrogen), only 1 mol% was acceptable, while 4 mol% ammonia can be added to the composition consisting of 7% hydrogen. The impact of ammonia on the WI is thereby bigger compared to hydrogen. The WI for the gas from Norway was approximately the same as the average gas composition with 0% hydrogen, refer to Figure 3.

In Table 4, the relative density, WI, compression factor, and LHV of the analyzed gases are shown when 20 mol% ammonia has been added. The biggest change in the relative density was noticed for the Average gas composition with 13% and 7% hydrogen, followed by the gas from Russia, which has a high content of methane. The change in the WI was approximately on the same scale for all analyzed gases; a reduction of ~12%. For the compression factor, the decrease was small and can therefore be neglected, while the LHV was most affected by addition of ammonia for the Average gas composition with 13% and 7% hydrogen, as well as for the Russian gas.

By mixing ammonia into NG, the compression factor, LHV, and WI are reduced. The compression factor is an important parameter in the flow of gases through pipes, where a too big variation in the compressibility factor can be a challenge for the media flowing in the pipeline.[49] When ammonia was added into the different NG compositions, the change in compression factor was minor and it is not a concern for the investigated cases. Instead, the decrease in the LHV with addition of ammonia can be a concern, since a bigger volume flow is needed to keep the same energy content as the original gas.[25] This is something to reflect if an ammonia–NG blend is transported in a pipeline before a combustion process or if it is used as a fuel for a process with limited volume space.

A lower WI can result in the mixture being out of range for a certain end user application, depending on what the gas quality specifications are set to.[35] However, the WI can also be too high for a gas,[50] which means that the addition of ammonia can be a way to fulfill the gas quality requirements. Another parameter that must be considered, looking at the gas quality, is the relative density. When ammonia was mixed with NG, the relative density was either increased or decreased depending on the gas composition. It was shown that gases consisting

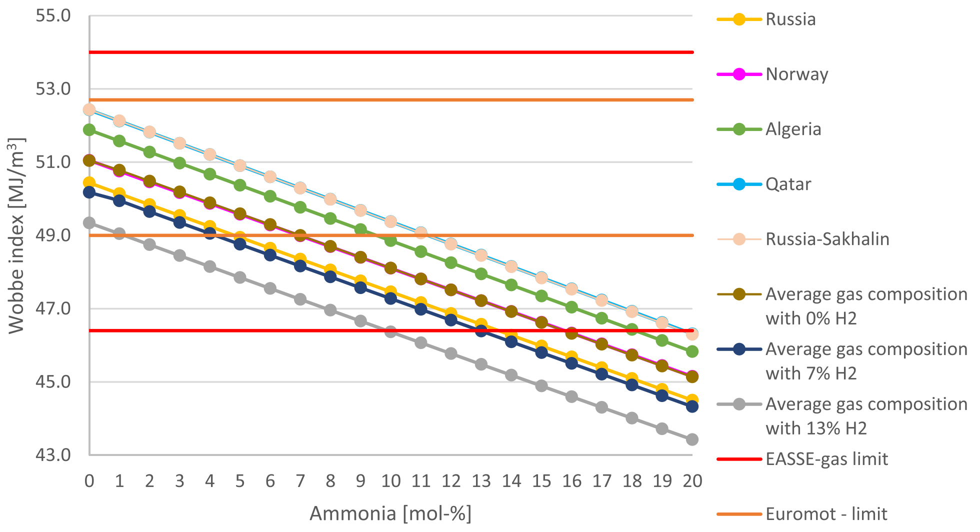

FIGURE 3 Calculated Wobbe index as a function of ammonia percent in the natural gas mixture.

TABLE 4 Calculated relative density, Wobbe index, compression factor, and lower heating value for the studied gas compositions when 20 mol% ammonia has been added.

	Relative density	Wobbe index (MJ/m^3)	Compression factor	LHV (MJ/kg)
Russia	0.568	44.5	0.9967	43.0
Norway	0.599	45.1	0.9963	42.6
Algeria	0.601	45.8	0.9963	43.2
Qatar	0.610	46.3	0.9962	43.4
Russia - Sakhalin	0.606	46.3	0.9962	43.5
Average gas comp. with 0% H_2	0.590	45.1	0.9964	42.9
Average gas comp. with 7% H_2	0.562	44.3	0.9968	43.1
Average gas comp. with 13% H_2	0.532	43.4	0.9971	43.3

of hydrogen and/or a high level of methane got a raised relative density with the addition of ammonia, while it became lower for gases which contained high amounts of inert gases and/or higher hydrocarbons such as ethane, propane, butane, and pentane. By adding at least 1 mol% of ammonia into the average gas composition with 7% hydrogen, the lower limit of the relative density set by EASEE-gas CBP could be satisfied, meaning that ammonia can be a way to improve the gas quality especially if the gas contains much hydrogen. The maximum amount of added ammonia was 13 mol% in this case, otherwise the lower WI limit of 46.4 MJ/m^3 was passed according to EASEE-gas CBP.[39]

Among the investigated gas compositions, the gas that was least affected by addition of ammonia was the one from Norway, which has a low content of methane and higher levels of higher hydrocarbons, as well as some number of inert gases. It was observed that 15 mol% ammonia can be added into this gas to fulfill the relative density and WI requirements of EASEE-gas CBP.[39] To accomplish the WI-limit set by Euromot,[45] 7 mol% was acceptable which is the same amount as the average gas composition with 0% hydrogen can handle. The largest amount of ammonia, with a value of 11 mol%, can be mixed into the gases from Qatar and Russia—Sakhalin, which both consist of a low level of methane and higher levels of higher hydrocarbons, to fulfill Euromot's WI requirement. Euromot has also other parameters which must be achieved before a gas mixture is approved by them, such as the methane number (MN).[45] The MN is a way to describe the gas quality by engine manufacturers and it is a definition of the knock resistance of a gaseous fuel.[51] There is no standard method to calculate the MN and many engine manufacturers are using their own calculation tools to achieve the maximum engine performance.[52] Among the available calculation tools online,[53–55] ammonia gas is not included in these, meaning that engine manufacturers have not yet approved ammonia as a component in the NG mixture.

The gas that was most impacted by ammonia was the average gas composition with 13% hydrogen. This gas did not accomplish the relative density requirements of EASEE-gas CBP and only 1 mol% ammonia could be added to fulfil Euromot's WI limits. If hydrogen will be injected into the NG grid in the future, it is important to check how much hydrogen the gas contains to be sure that all requirements are satisfied. However, the addition of ammonia into the average gas composition with 7% hydrogen could help to meet the relative density boundaries of EASEE-gas CBP, meaning that ammonia can be useful in this way. Today, there is no existing regulation on the use of ammonia as an energy carrier, but the awareness of its potential as a substitute of NG makes it possible to create regulations that enable lower carbon dioxide emission through the ammonia economy.[15,56]

4 | CONCLUSION

The achievement to reduce greenhouse gas emissions requires that carbon-free fuels such as hydrogen and ammonia are used on a wider scale and for more applications. Both fuels can be produced in a green way and no carbon dioxide is released when they are burnt. However, gaseous hydrogen has a low density meaning that large tanks and/or high pressures are needed to transport it, which becomes expensive. Ammonia, on the other hand, is a well-known chemical and it is easy to store and transport. The drawback with ammonia as a fuel is its narrow flammability range and that NO_x are formed during its combustion. By mixing it with NG the combustion properties are improved, and the emissions of carbon dioxide and nitrogen oxides are reduced compared to the combustion of the fuels separately. The gas quality of the mixture also plays a role, where the end users have their own requirements on the fuel characteristics which must be fulfilled before it can be used.

In this paper, the change in gas properties was investigated by adding up to 20 mol% ammonia gas into different NG compositions. Eight case compositions were examined, where two of them consisted of a high content of hydrogen; 7 and 13 mol%, to see the impact of ammonia on NG with added hydrogen. The results show that the addition of ammonia into NG significantly affects the WI and LHV, whereas the relative density is slightly influenced. In particular, the WI and LHV decrease as ammonia content increases and gases which contain higher amounts of hydrogen and/or methane are most affected. Similarly, the compression factor is reduced with a raised ammonia level, but its change is almost negligible. The relative density either increases or decreases depending on the NG composition, where a high content of hydrogen and/or methane leads to an increment with more ammonia content and the relative density is reduced for gases consisting of more inert gases and higher hydrocarbons. The reason for the raised relative density can be explained by the molar mass of ammonia being higher compared to hydrogen and methane.

The gases with added hydrogen were most impacted by ammonia and by mixing 1 mol% ammonia into the NG with 7% hydrogen, the relative density range of 0.554–0.699, set by EASEE-gas CBP, is achieved. Another gas quality requirement of EASEE-gas CBP is that the WI must be between 46.4 and 54.0 MJ/m^3 and therefore only up to 13 mol% ammonia is allowed to mix into the same gas. If a gas consists of too much hydrogen, the relative density limits cannot be attained although 20 mol% ammonia is added, which was the case for the NG with 13% hydrogen. There were two NGs where an amount of 19 mol% ammonia can be mixed into and still be within the limits according to EASEE-gas CBP. These gases have a high content of higher hydrocarbons and less methane. Considering the WI limit (49.0–52.7 MJ/m^3) set by Euromot, it was observed that 11 mol% ammonia can be blended with the same gases. The corresponding value for the gas with 7% hydrogen was 4 mol% added ammonia to satisfy Euromot's boundaries. Ammonia has thereby a bigger impact on NG with added hydrogen and a smaller amount can be mixed with these gases.

There is still no regulation on the use of ammonia as an energy carrier and more effort is needed to examine the change in fuel properties by mixing ammonia with NG. This is something which must be considered when assessing how residential and commercial gas appliances may respond to higher levels of ammonia in NG. Further study is suggested regarding ammonia gas blends to identify critical parameters for various combustion technologies (engines, gas turbines, furnaces) by changing the amount of added ammonia.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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