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Published in:
Energies

DOI:
10.3390/en15217990

Published: 27/10/2022

energies

Article

Impact of Hydrogen on Natural Gas Compositions to Meet Engine Gas Quality Requirements

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Abstract: To meet the target of reducing greenhouse gas emissions, hydrogen as a carbon-free fuel is expected to play a major role in future energy supplies. A challenge with hydrogen is its low density and volumetric energy value, meaning that large tanks are needed to store and transport it. By injecting hydrogen into the natural gas network, the transportation issue could be solved if the hydrogen–natural gas mixture satisfies the grid gas quality requirements set by legislation and standards. The end consumers usually have stricter limitations on the gas quality than the grid, where Euromot, the European association of internal combustion engine manufacturers, has specific requirements on the parameters: the methane number and Wobbe index. This paper analyses how much hydrogen can be added into the natural gas grid to fulfil Euromot's requirements. An average gas composition was calculated based on the most common ones in Europe in 2021, and the results show that 13.4% hydrogen can be mixed with a gas consisting of 95.1% methane, 3.2% ethane, 0.7% propane, 0.3% butane, 0.3% carbon dioxide, and 0.5% nitrogen. The suggested gas composition indicates for engine manufacturers how much hydrogen can be added into the gas to be suitable for their engines.

Keywords: hydrogen; natural gas; methane number; Wobbe index; gas composition; hydrogen blend

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Citation: Ingo, C.; Tuuf, J.; Björklund-Sänkiaho, M. Impact of Hydrogen on Natural Gas Compositions to Meet Engine Gas Quality Requirements. *Energies* **2022**, *15*, 7990. https://doi.org/10.3390/en15217990

Academic Editor: Andrzej Teodorczyk

Received: 29 September 2022
Accepted: 23 October 2022
Published: 27 October 2022

1. Introduction

Hydrogen, as a zero-emission fuel, has gained an important position in recent years to reduce greenhouse gas emissions. Although it is a carbon-free fuel, the manufacturing of hydrogen from fossil fuels such as natural gas, petroleum, and coal releases much carbon dioxide [1]. A more environmentally friendly method, where no carbon dioxide is formed, is by electrolysis of water using wind or solar energy as a power source [2]. This technique is quite expensive compared to the traditional steam methane reforming of natural gas, but it will become cheaper since both the efficiency of the electrolysers is improving, and the cost of renewable sources is decreasing [3]. Hydrogen is an energy carrier, and it is used in the industry, transport, power, and building sectors [4]. The storage and transportation of hydrogen are difficult because of its low density and volumetric energy value, meaning that large tanks are needed [5]. One way to solve this issue is by injecting hydrogen into the existing natural gas network, where it can be transported to its consumers [4]. However, the amount of injected hydrogen must be checked so that the hydrogen–natural gas mixture satisfies the gas quality requirements of the pipeline set by legislations and standards [6].

Several studies, e.g., [7–12], have been made to find the maximum level of injected hydrogen into the natural gas network by investigating how the thermodynamic properties of the mixture, piping material, and end consumers are affected. For example, the technical conditions for a natural gas transmission system can be significantly impacted by the injection of hydrogen [7]. An advantage when injecting hydrogen is a lower pressure drop in the gas network, meaning that the hydrogen–natural gas admixture can be transmitted long distances without additional gas compression stations [8]. However, the volumetric flow is decreased due to the low density of hydrogen, which will increase the pipeline diameter to match the same flow as pure natural gas [9]. Another challenge is the reduced energy output at the offtakes when hydrogen is added to the grid [10]. Even in this case, bigger pipes are needed to obtain the same energy as natural gas. In a simulation made by Quintino et al. [9], 20 vol-% hydrogen was injected into the natural gas network without changing the pipeline diameter. The results showed that a pressure drop of 11% occurred if the energy demand was maintained. In a study by Shouthen et al. [11], it was noticed that injection of 10 mol-% hydrogen required a 9% higher flow rate to transport the same amount of energy.

The injection of hydrogen into the natural gas network can also have an impact on piping material, especially steels and alloys since they are prone to hydrogen embrittlement and can, in the worst case, lead to pipe cracking [12,13]. There is no issue to add up to 10 vol-% hydrogen for steel pipelines at a pressure above 16 bar, and the amount can be increased to 25 vol-% if the pressure decreases below 16 bar [14]. Gas turbines are more sensitive to hydrogen, where concentrations ranging from 1 to 5% are advised by the manufacturer without any technical adjustments to the turbines [15]. Compressors and dryers can tolerate 5 vol-% hydrogen, while gas chromatographs are typically only designed for less than 0.2 vol-% [14]. The accuracy of existing gas meters is also influenced by hydrogen mixtures, and depending on the meter design, it can be enough with recalibration if only a small amount of hydrogen is added to the grid [16].

The thermodynamic properties of a gas, such as density, calorific value, and compressibility factor, can directly be affected by hydrogen injection, where the gas mixture's properties in turn can impact the end users [8]. In an investigation [17] where 25 mol-% hydrogen was injected into the natural gas grid, it was noted that the relative density, heat capacity, and higher heating value of the mixture changed significantly by the presence of hydrogen. The sound speed and compressibility factor were also explored, where the sound speed was considerably impacted by small levels of hydrogen, while the compressibility factor was more influenced by hydrogen content at high metering pressures compared to low pressures.

Most of the previous studies have investigated the effect of hydrogen injection into the natural gas networks by using pure methane as the gas composition. However, the compounds in natural gas can vary depending on their origin [18]. For example, if the natural gas contains higher hydrocarbons, there is a risk of condensation at the injection points since the addition of 25 vol-% hydrogen can drop the temperature by several degrees [11]. Various natural gas compositions from Iranian gas fields were analysed by Deymi-Dashtebayaz et al. [19] to examine the gas properties by mixing up to 10 vol-% hydrogen. The results showed that the relative density, lower and higher heating values, and the Wobbe index were reduced with increased amounts of hydrogen. In contrast, the higher hydrogen content raised the lower and upper flammability limits of the mixture.

In Europe, the gas quality requirements of the transported gas in the natural gas network must comply with the recommendation of the European standard EN 16726:2015+A1:2018 [20] as well as the consumer gas installations that are part of the network [21]. A major part of Europe's natural gas in 2020 was used for energy generation, households, and the industry sector [22]. In these sectors, end users, such as boilers, burners, and gas engines, have their own specifications on gas quality parameters, e.g., calorific value, Wobbe index, specific gravity, and methane number (MN), to achieve their maximum performance [12]. The Wobbe index is the interchangeability between gaseous fuels, where gases with the same Wobbe index, but different compositions, can be replaced with each other as they release the same amount of energy [19]. The methane number is used by engine manufacturers to describe the quality of the gas and is a definition of the knock resistance of a gaseous fuel [23]. A higher methane number means a better quality, where a composition consisting of 100% methane has a MN of 100. By adding higher hydrocarbons, such as ethane, propane, butane, and pentane, as well as hydrogen, the MN decreases, and the engine becomes more sensitive to knock [24]. When carbon dioxide is mixed with pure methane, the methane number can rise above 100 [23], while the addition of nitrogen does not have a big impact on the MN for a certain natural gas composition [24].

A minimum energy level of the distributed gas is also required by the end consumers, meaning that the energy output must be controlled if injecting hydrogen into the natural gas grid [11,13]. Euromot, which is the European association of internal combustion engine manufacturers, has some technical specifications of natural gas quality at exit points in the European gas distribution system to guarantee that the engines produced by Euromot reach their performance [25]. These limitations are a Wobbe index of 49.0–52.7 MJ/m^3 and a methane number of 70.0 or higher. The position also states that most gas engines can operate on a mixture consisting of up to 20 vol-% hydrogen if the final blend at the exiting point complies with all other gas quality requirements.

This study aims to determine the hydrogen amount which can be injected into the European natural gas network and still attain a mixture within the limits set by Euromot. Since the composition of natural gas determines the maximum level of injected hydrogen [26], the most common natural gas and liquefied natural gas (LNG) compositions in Europe in 2021 have been analysed to find how much hydrocarbons and inert gases the gas can contain. Parameters such as the Wobbe index and methane number have been calculated to see their influence on an increased amount of hydrogen. The presented gas composition will indicate for the engine manufacturers how much hydrogen can be added into the gas to be suitable for their engines.

2. Gas Compositions

Europe is the biggest importer of natural gas in the world, where 68% of the imported gas comes via pipeline and 32% is transported as LNG by ship from around the world [27]. The quality of the gas varies depending on where it is extracted from, how it is processed, and if it is mixed with other natural gases in the gas infrastructure [28]. LNG has a higher gas quality compared to natural gas since an extra purification step is done, where higher hydrocarbons, carbon dioxide, hydrogen sulphide, and other impurities are removed before liquefying the gas into liquid [29]. When LNG is sent to the natural gas network, it is re-gasified back to gas mode before entering the pipe.

In Figure 1, the major trade movements of pipeline gas and LNG are shown for the whole world. The statistics are from 2021, before the Ukraine war, which has changed the market since then. According to this figure, Russia, Norway, Algeria, and Azerbaijan supplied most of the natural gas to Europe, while LNG came mainly from the USA, Qatar, Russia, Algeria, and Nigeria.

In this study, the most common natural gas and LNG compositions imported to Europe, as well as from Norway have been studied, as presented in Table 1. These compositions are approximate since they can change day by day depending on the export source. The content of higher hydrocarbons, such as pentane, hexane, and heptane, are usually small and they have been added to the pentane content as an approximation. In the same table, it also mentions what percent the specified gas constitutes of the total amount of natural gas and LNG trade movements to Europe in 2021.

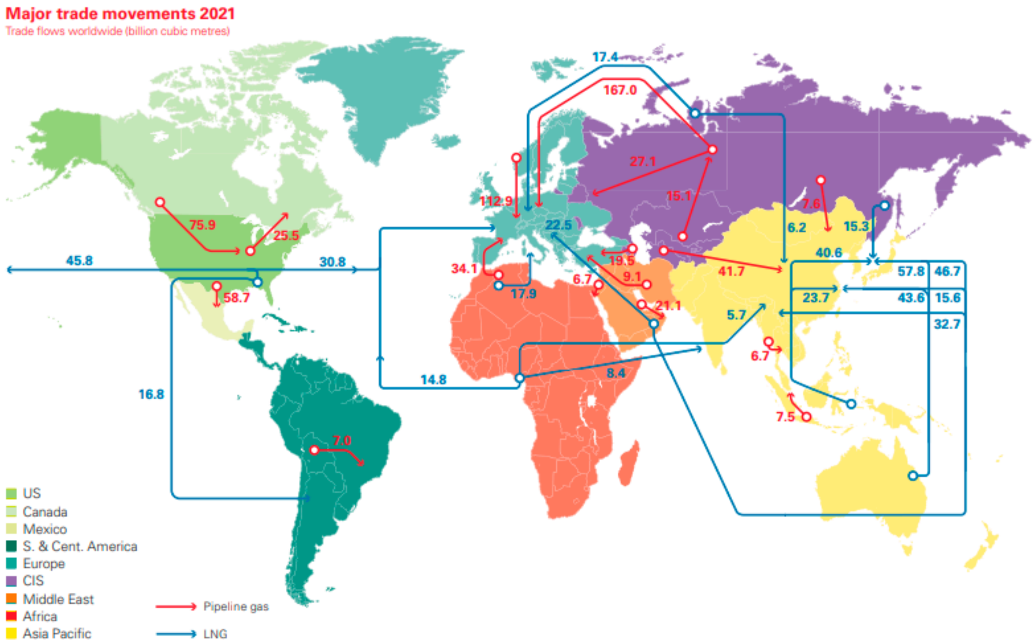

Figure 1. Major trade movements of pipeline gas and LNG in the world in 2021 [27].

Table 1. The most common natural gas [30,31] and LNG compositions [32] in Europe and their proportional amount of the total trade movements to Europe in 2021, as shown in Figure 1 [27].

Origin	Methane [mol-%]	Ethane [mol-%]	Propane [mol-%]	Butane [1] [mol-%]	Higher Hydrocarbons [mol-%]	Carbon Dioxide [mol-%]	Nitrogen [mol-%]	Hydrogen Sulphide [mol-%]	Trade Movement [%]
Russia [2]	98.79	0.44	0.10	0.04	0.03	0.05	0.55	0.00013	35.0
Norway [2]	92.64	5.08	0.89	0.21	0.06	0.61	0.52	0.00012	23.7
Algeria [2]	91.10	7.48	0.82	0.10	0.00	0.00	0.51	0.00013	7.1
Azerbaijan [2]	92.85	3.24	1.67	0.79	0.24	1.07	0.14	0.00	4.1
Algeria–Skikda [3]	91.40	7.35	0.57	0.05	0.00	0.00	0.63	0.00	1.1
Algeria–Bethioua [3]	89.55	8.20	1.30	0.31	0.00	0.00	0.64	0.00	1.1
Algeria–Arzew [3]	88.93	8.42	1.59	0.37	0.00	0.00	0.71	0.00	1.1
Egypt–Idku [3]	95.31	3.58	0.74	0.34	0.00	0.00	0.02	0.00	0.3
Egypt–Damietta [3]	97.25	2.49	0.12	0.12	0.00	0.00	0.02	0.00	0.3
Nigeria [3]	91.70	5.52	2.17	0.58	0.00	0.00	0.03	0.00	2.7
Norway [3]	92.03	5.75	1.31	0.45	0.00	0.00	0.46	0.00	0.1
Peru [3]	89.07	10.26	0.10	0.01	0.00	0.00	0.57	0.00	0.3
Qatar [3]	90.91	6.43	1.66	0.74	0.00	0.00	0.27	0.00	4.7
Russia–Sakhalin [3]	92.53	4.47	1.97	0.95	0.00	0.00	0.07	0.00	3.6
Trinidad [3]	96.78	2.78	0.37	0.06	0.00	0.00	0.01	0.00	0.5
USA–Alaska [3]	99.71	0.09	0.03	0.01	0.00	0.00	0.17	0.00	6.5

[1] Butane has been taken as a mixture of 50% n-butane and 50% i-butane.[2] Natural gas composition. [3] LNG composition.

3. Materials and Methods

This section describes how to calculate the thermodynamic properties of hydrogen-natural gas mixtures with various compositions, as well as the methane number and the average gas composition. The requirement for the Wobbe index set by Euromot [25,33] has been specified at reference conditions of 15 °C and an absolute pressure of 101.325 kPa, which also have been used in this work. Tables 2 and 3 show the input data required for the calculations, and the used Equations (1)–(6) are according to ISO 6796:2016 [34].

Table 2. Input data for calculating thermodynamic properties of gas mixtures.

Name	Value	Unit
Pressure at metering reference conditions, p_2	101.325	kPa
Absolute pressure, p_0	101.325	kPa
Temperature at metering reference conditions, T_2	288.15	K
Molar gas constant, R [1]	8.3144621	J/(mol·K)
Molar mass of dry air of reference composition, M_{air} [1]	28.96546	g/mol
Compression factor of dry air at metering reference composition, $Z_{air,2}$ [1]	0.999595	-

[1] Data is taken from [34].

Table 3. Input data, taken from [34], for the components in the gas mixtures.

Component	Molar Mass, M_i [g/mol]	Summation Factor at 15 °C, s_i	Ideal Gross Molar-Basis Calorific Value at 15 °C, $[(Hc)_G^o]_i$ [kJ/mol]
Methane	16.04246	0.04452	891.51
Ethane	30.06904	0.0919	1562.14
Propane	44.09562	0.1344	2221.1
n-butane	58.12220	0.184	2879.76
i-butane	58.12220	0.1722	2870.58
n-pentane	72.14878	0.2361	3538.6
i-pentane	72.14878	0.2251	3531.68
Carbon dioxide	44.0095	0.0752	0
Hydrogen sulphide	34.08088	0.0923	562.38
Hydrogen	2.01588	−0.01	286.15
Nitrogen	28.0134	0.017	0

3.1. Calculation of Thermodynamic Properties

The compression factor of a mixture at metering reference conditions is calculated according to Equation (1).

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

where:

Z_2 Compression factor at metering reference conditions;
p_2 Pressure at metering reference conditions, kPa;
p_0 Absolute pressure, kPa;
x_i Mole fraction of component *i*;
s_i Summation factor at metering reference conditions.

The summation factor for each gas component, s_i, at 15 °C can be found in Table 3 and have been taken from ISO 6976:2016 [34].

The gross calorific value, or higher heating value, is the amount of heat that is released during the complete combustion of a specified amount of gas, where the products of combustion are returned to the original pre-combustion temperature and all products are in a gaseous state except for water which is condensed to a liquid state [24,34]. The value on a molar basis at the combustion reference temperature for a gas mixture of known composition is calculated according to Equation (2).

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

where:

$(Hc)_G$ Real gas gross molar-basis calorific value of the gas mixture, kJ/mol;
$(Hc)_G^o$ 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*, kJ/mol.

Numerical values of $\left[(Hc)^o_G\right]_i$ at 15 °C are given in Table 3.

The gross calorific value on a real gas volume basis at a combustion temperature of 15 °C for a gas mixture of known composition measured under metering reference conditions is calculated using Equation (3).

$$(Hv)_G = \frac{(Hc)^o_G}{V} \quad (3)$$

where:

$(Hv)_G$ Real gas gross volume-basis calorific value of the gas mixture, MJ/m^3;

V Real gas molar volume of the gas mixture at metering reference conditions, which is calculated from Equation (4), m^3/kmol.

$$V = Z_2 \cdot R \cdot \frac{T_2}{p_2} \quad (4)$$

where:

R Molar gas constant, J/(mol·K);

T_2 Temperature at metering reference conditions, K.

The Wobbe index can be calculated by dividing the gross calorific value with the square root of the relative density at the same specified metering reference conditions, Equation (5).

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

where:

I_w Wobbe index, MJ/m^3;

G Relative density of a real gas at the metering reference condition.

The definition of relative density is the ratio of the density of a gas mixture to the density of dry air of the reference composition at the same specified conditions of pressure and temperature [17]. For a real gas mixture, it can be calculated according to Equation (6) [34].

$$G = \frac{\sum_{i=1}^{n} x_i \cdot M_i}{M_{air}} \cdot \frac{Z_{air,2}}{Z_2} \quad (6)$$

where:

M_i Molar mass of component i, g/mol;

M_{air} Molar mass of dry air of reference composition, g/mol;

$Z_{air,2}$ Compression factor of dry air at metering reference composition.

The values for the molar mass of each component, M_i, are given in Table 3.

3.2. Calculation of the Methane Number

There is no standard method to calculate the methane number based on gas composition, and many engine manufacturers are using their own calculation tools to achieve the best engine performance [35]. In this work, the methane number has been calculated according to EN 16725:2015 [20], which is also used by Euromot to achieve the gas quality requirements set by them.

3.3. Calculation of the Average Gas Composition

The average gas composition of the ones presented in Table 1 was calculated for each component as the sum of all countries' mole fractions of component i times its trade movement value. Since only the major trade movements in Europe are considered, the sum has been divided by the sum of trade movements given in Table 1; refer to Equation (7).

$$n_{i,avg.} = \frac{\sum_{y=country} x_{i,y} \cdot T_y}{\sum_{y=country} T_y} \cdot 100\% \quad (7)$$

where;

$n_{i,avg.}$ Average mole percent of component i, %;
$x_{i,y}$ Mole fraction of component i from country y;
T_y Trade movement of country y, %.

4. Results and Discussion

The most common natural gas compositions in Europe have been investigated to see whether the addition of hydrogen affects the Wobbe index and the methane number. Table 4 presents the calculated methane number and Wobbe index for the original gas compositions, given in Table 1, before any hydrogen has been added. The methane number is highest for the gases from Russia and the USA, which both have a high content of methane and smaller amounts of ethane, propane, and butane. The gases with the lowest methane number, from Algeria–Arzew, Nigeria, and Qatar, have in contrast the highest Wobbe index, and they consist of a lower level of methane and higher amounts of ethane, propane, and butane.

Table 4. Calculated methane number and Wobbe index for the original gas compositions.

Origin	Methane Number	Wobbe Index [MJ/m^3]
Russia	95.9	50.4
Norway	80.4	51.0
Algeria	77.5	51.9
Azerbaijan	76.9	51.2
Algeria–Skikda	78.8	51.7
Algeria–Bethioua	74.7	52.1
Algeria–Arzew	73.4	52.3
Egypt–Idku	83.6	51.7
Egypt–Damietta	89.8	51.2
Nigeria	74.9	52.5
Norway	77.3	51.9
Peru	76.5	52.0
Qatar	74.3	52.4
Russia–Sakhalin	75.1	52.4
Trinidad	88.3	51.3
USA–Alaska	97.3	50.6

The injection of up to 20 mol-% hydrogen has been analysed since most engines produced by Euromot member companies can accept such a level if the final blend at exit points complies with the technical gas quality requirements [25]. The mole fractions of other components have been reduced proportionally based on the hydrogen blending level. Figure 2 presents the methane number as a function of the hydrogen level in mol-%, where the vertical red line shows the allowable limit according to Euromot's requirement, which is a methane number higher than 70. A hydrogen content of up to 9% can be mixed with all analysed gases, where the restricted gas from Algeria–Arzew contains a lower level of methane, high amounts of ethane, and some parts of propane and butane. Four natural gases, from Russia, Egypt–Damietta, Trinidad, and the USA, can be blended with 20% hydrogen and still have a MN above 70. Common for these gases is a high content of methane and lower levels of ethane, propane, butane, and higher hydrocarbons. Another observation is that the methane number increases for most of the gases when 1% hydrogen has been added and thereafter starts to decrease again. Since the mole fractions of gas components are reduced proportionally when hydrogen is added, 1% of hydrogen has a more positive effect on the MN compared to the original gas which consists of higher amounts of ethane, propane, butane, and higher hydrocarbons which decreases the methane number [24]. However, this does not apply for the gases with the highest MN, probably because the amount of ethane, propane, butane, and higher hydrocarbons is so small that the addition of hydrogen has only a negative influence on the methane number.

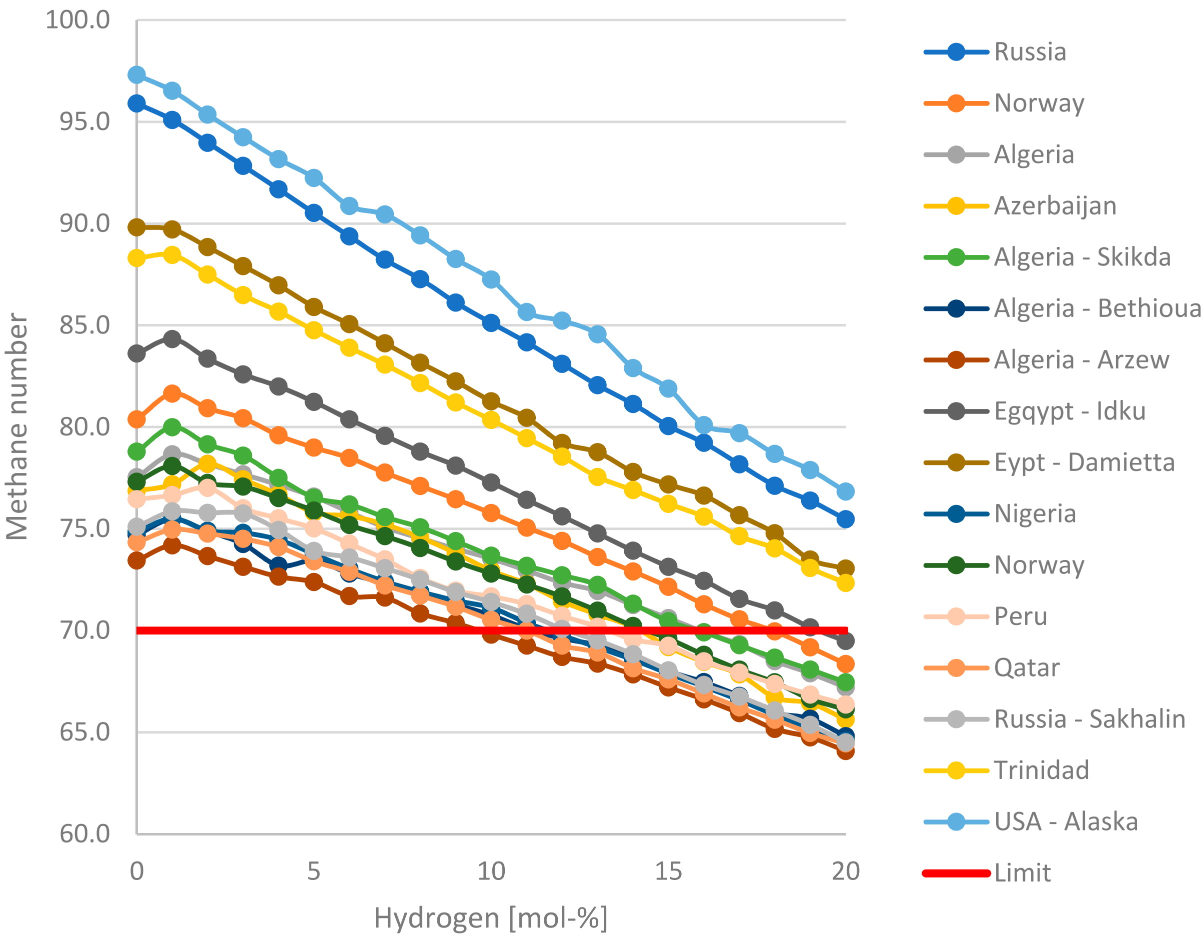

Figure 2. Calculated methane number as a function of hydrogen level in the natural gas blend.

The Wobbe index as a function of hydrogen level is presented in Figure 3, where the acceptable values according to Euromot must be between 49.0–52.7 MJ/m^3. With a hydrogen injection of up to 20 mol-%, the Wobbe index decreases where a content of 12% and 13% is the maximum for the gases from Russia and the USA, respectively. These gases have a high content of methane and lower levels of ethane, propane, and butane. The same applies to the gases from Egypt–Damietta and Trinidad, which can be mixed with up to 17% and 18% hydrogen. The Norwegian and Azerbaijani gases consist of a lower level of methane, some amounts of ethane, propane, butane, and higher hydrocarbons, as well as carbon dioxide and nitrogen. Nitrogen, as an inert gas, has a negative impact on the calorific value which means a lower Wobbe index [36], and the same applies to carbon dioxide. This is the reason why only 16% hydrogen can be added to the gases from Norway and Azerbaijan, since they consist of the highest amount of carbon dioxide among all the analysed gases. The rest of the gases can be mixed with up to 20 mol-% hydrogen and still attain a Wobbe index of 49.0 MJ/m^3.

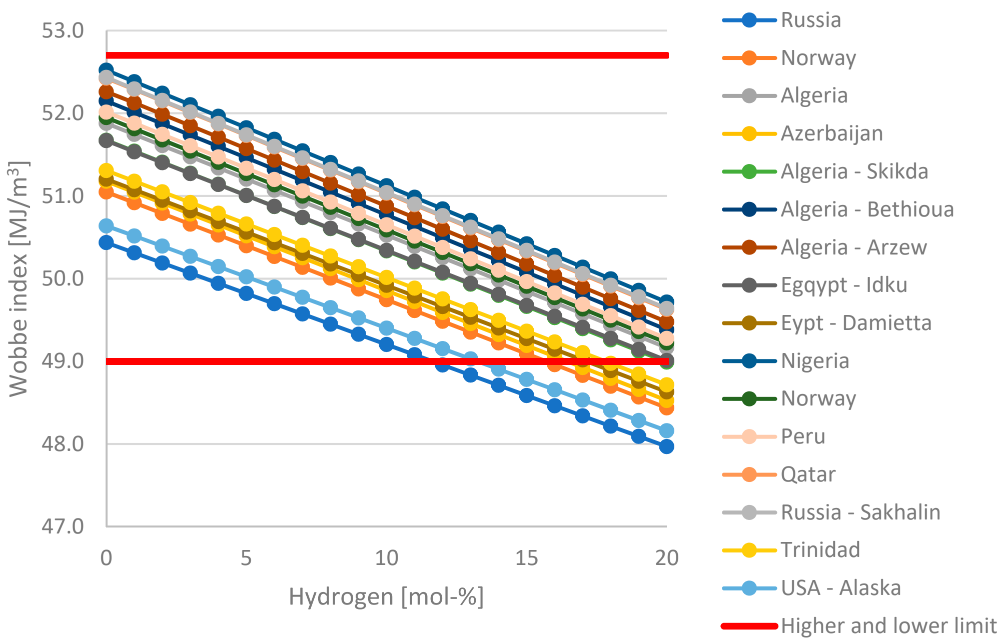

Figure 3. Calculated Wobbe index as a function of hydrogen level in the natural gas blend.

Table 5 shows how much hydrogen can be added to the examined gases to reach a methane number higher than 70.0 and a Wobbe index between 49.0–52.7 MJ/m^3. The methane number and Wobbe index of the hydrogen blend are also presented.

Table 5. The calculated maximum amount of added hydrogen for gases to meet the required methane number and Wobbe index set by Euromot, as well as the methane number and Wobbe index of the hydrogen blend.

Origin	Max H_2 Level [mol-%]	Methane Number at Max H_2 Level	Wobbe Index at Max H_2 Level [MJ/m^3]
Russia	12.0	83.1	49.0
Norway	16.0	71.3	49.0
Algeria	15.0	70.6	49.8
Azerbaijan	14.0	70.2	49.3
Algeria–Skikda	15.0	70.5	49.7
Algeria–Bethioua	11.0	70.1	50.6
Algeria–Arzew	9.0	70.4	51.0
Egypt–Idku	19.0	70.2	49.1
Egypt–Damietta	17.0	75.7	49.0
Nigeria	11.0	70.4	51.0
Norway	14.0	70.2	50.0
Peru	13.0	70.2	50.2
Qatar	11.0	70.0	50.9
Russia–Sakhalin	12.0	70.1	50.8
Trinidad	18.0	74.0	49.0
USA–Alaska	13.0	84.6	49.0

The highest level of hydrogen can be injected into gases from Egypt and Trinidad which contain a high amount of methane and some percent of ethane, while for example, the USA gas, consisting of 99.7% methane can only be mixed with 13% hydrogen, whereafter the Wobbe index becomes too low. This is due to the ideal gross calorific value being much lower for hydrogen compared to methane, ethane, propane, butane, and higher hydrocarbons; refer to Table 3. Although the gas mixture accomplishes the requirements set by Euromot, it must be noticed that hydrogen will also have an impact on combustion aspects, such as adiabatic combustion temperatures and laminar combustion velocities [28], which are important parameters for an engine to achieve good performance.

Table 6 presents the calculated average gas composition of the ones given in Table 1, as well as the limit content of each component when the maximum amount of hydrogen has been added. This composition is taken as an average of the gas compositions with the maximum hydrogen level, Table 5, to fulfil Euromot's technical gas quality requirements.

Table 6. Calculated average gas composition and suggested limit content of natural gas components with the maximum amount of added hydrogen.

Component	Average Gas Composition [mol-%]	Limits with Added Hydrogen [mol-%]
Methane	95.1	>82.4
Ethane	3.2	<2.8
Propane	0.7	<0.6
Butane	0.3	<0.2
Higher hydrocarbons	0.04	<0.03
Carbon dioxide	0.3	<0.2
Nitrogen	0.5	<0.4
Hydrogen sulphide	0.00009	<0.00008
Hydrogen	0.0	<13.4

The results in Table 6 show that up to 13.4 mol-% hydrogen can be injected into the natural gas grid if the original gas consists of 95.1% methane, 3.2% ethane, 0.7% propane, 0.3% butane, and 0.04% higher hydrocarbons. The levels of the inert gases, carbon dioxide and nitrogen, are 0.3% and 0.5%, respectively. The methane number decreases from 83.9 to 75.0 and the Wobbe index from 51.0 to 49.3 MJ/m^3 when 13.4% hydrogen is added to the above-mentioned gas composition. This means that there is still a small margin before Euromot's lowest gas quality requirements are achieved.

To be noted is that the specified gas composition in Table 6 is an average of the most common ones in Europe in 2021 and gives an indication that the overall gas quality was good that year. However, the gas situation in Europe is not the same today, and the amount of injected hydrogen is dependent on which components the gas constitutes and what their levels are [26]. Nitrogen and carbon dioxide have a negative impact on the Wobbe index since their ideal gross calorific value is zero, as shown in Table 3. The opposite is valid for hydrocarbons, where their calorific values increase with raised amounts of carbon, meaning that the Wobbe index becomes higher for gases with high levels of ethane, propane, butane, and pentane. These gases give a low methane number compared to a gas consisting of only methane, which has a MN of 100 [24]. Carbon dioxide increases the methane number [23], while nitrogen does not affect the MN so much [24]. If the natural gas consists of only methane, the Wobbe index quickly becomes too low when higher amounts of hydrogen are added, which was noticed for the gases from Russia and the USA in Figure 3. Based on the results in Table 5 and the above analysis, the maximum level of hydrogen can be added to a gas consisting of high amounts of methane and some percent of ethane to fulfil Euromot's requirement. The suggested average gas composition in Table 6 agrees quite well with this one.

Most engines produced by Euromot member companies can accept up to 20% hydrogen in the gas if the final blend at the exit points complies with the technical gas quality requirements [25]. In this study, it was stated that 13.4% hydrogen can be added to the gas grid in Europe based on the most common natural gas compositions in 2021 to satisfy the requirements set by Euromot. However, there are limitations in the natural gas network which must be observed. For example, the low energy density of hydrogen will increase the volumetric flow, meaning that bigger pipelines are required. Alternatively, a higher operating pressure is required [12]. The piping material, compressor stations, and measuring instruments must also be controlled to ensure that they can withstand the hydrogen level. In addition, safety issues increase with a raised amount of hydrogen, which leads to a higher risk of overpressure, explosions, and leakage [12]. A technical feasibility study for the whole system must therefore be carried out to find out what the most critical components or parameters are. End users other than engines must also be considered since, depending on the application, the change in fuel composition can be very different for various processes [28]. In addition, the regulations of the European natural gas network have a maximum permissible hydrogen content which is between 0.1–12 vol-% depending on the country, meaning that the injection of 13 mol-% is not allowed today [7]. However, the target is to increase the limit content of the grid [13], and there are many projects ongoing in Europe where hydrogen levels between 2–100 vol-% are being studied [12].

Another challenge with the addition of hydrogen is its impact on the combustion process, resulting in a high adiabatic flame temperature which triggers the formation of nitrogen oxides [37]. In several studies of boilers [37–39], it was observed that the use of excess air in the combustion process could limit the temperature peaks, which led to fewer formed nitrogen oxides as well as a lower level of carbon emissions. Parameters such as combustion temperature and flame speed are therefore important to follow when adding hydrogen to ensure complete combustion and reduced emissions [12]. Further research in these areas is necessary for engine manufacturers to conduct.

5. Conclusions

Many countries are investigating the possibility of injecting hydrogen into the existing natural gas network to solve the challenge of hydrogen transportation since huge tanks are required for this. The addition of hydrogen decreases the relative density, heating values, and Wobbe index, while the volumetric flow increases if the energy output at the exit points is kept at the same level as pure natural gas [9,19]. Therefore, the gas quality of the hydrogen–natural gas mixture must be controlled so that it is within the limits set by regulations and standards. The end consumers of the gas grid usually have other requirements than the grid, where most of the internal combustion engines are following Euromot's limitations, which are a methane number higher than 70 and a Wobbe index between 49.0–52.7 MJ/m^3 for the supplied gas.

In this paper, the limit content of natural gas components with the maximum amount of injected hydrogen into the natural gas grid was determined to meet the requirements set by Euromot. An average gas composition of the most common natural gases in Europe in 2021 was calculated, where the results show that 13.4% hydrogen can be injected into the network if the original natural gas consists of 95.1% methane, 3.2% ethane, 0.7% propane, 0.3% butane, 0.3% carbon dioxide, and 0.5% nitrogen. When hydrogen is mixed with this gas composition, the methane number becomes 75 and the Wobbe index 49.3 MJ/m^3. The above-mentioned gas composition agrees quite well with the one that can accept the highest amount of added hydrogen. This gas consists of high content of methane and some percent of ethane, where the methane level ensures a high methane number, and the ethane raises the Wobbe index. The suggested gas composition indicates for engine manufacturers how much hydrogen may be added into the gas to be suitable for their engines.

Although the gas composition is appropriate for the engines and fulfils Euromot's requirements, the limitations in the natural gas grid when hydrogen is injected should also be checked. These are, for example, to control if the piping material, compressor stations, and measuring instruments can withstand a certain amount of hydrogen, if the operating pressure must be increased, or if the raised volumetric flow is acceptable. A further investigation of these areas could be conducted for the European natural gas network.

Author Contributions: Conceptualization, C.I.; methodology, C.I.; validation, C.I.; formal analysis, C.I.; investigation, C.I.; writing—original draft preparation, C.I.; writing—review and editing, C.I., J.T. and M.B.-S.; visualization, C.I.; supervision, J.T. and M.B.-S.; funding acquisition, J.T. and M.B.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Abo Akademi University (ABO) for open access (APC-pool) and Högskolestiftelsen i Österbotten.

Data Availability Statement: Not applicable.

Acknowledgments: Thanks to Kaj Portin and the colleagues at Wärtsilä for their support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hermesmann, M.; Muller, T.E. Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. *Prog. Energy Combust. Sci.* **2022**, *90*, 100996. [CrossRef]
2. Gahleitner, G. Hydrogen from renewable electricity: An international review of power-to gas pilot plants for stationary applications. *Int. J. Hydrogen Energy* **2013**, *38*, 2039–2061. [CrossRef]
3. Howarth, R.W.; Jacobson, M.Z. How green is blue hydrogen? *Energy Sci. Eng.* **2021**, *9*, 1676–1687. [CrossRef]
4. Wang, A.; Jens, J.; Mavins, D.; Moultak, M.; Schimmel, M.; van der Leun, K.; Peters, D.; Buseman, M. Analysing Future Demand, Supply, and Transport of Hydrogen. European Hydrogen Backbone in Cooperation with Gas for Climate. 2021. Available online: https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021_v3.pdf (accessed on 17 August 2022).
5. Aziz, M.; Wijayanta, A.T.; Nandiyanto, A.B. Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. *Energies* **2020**, *13*, 3062. [CrossRef]
6. Pellegrini, M.; Guzzini, A.; Saccani, C. A Preliminary Assessment of the Potential of Low Percentage Green Hydrogen Blending in the Italian Natural Gas Network. *Energies* **2020**, *13*, 5570. [CrossRef]
7. Ogden, J.; Myers Jaffe, A.; Scheitrum, D.; McDonald, Z.; Miller, M. Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature. *Energy Policy* **2018**, *115*, 317–329. [CrossRef]
8. Kuczy'nski, S.; Łaciak, M.; Olijnyk, A.; Szurlej, A.; Włodek, T. Thermodynamic and Technical Issues of Hydrogen and Methane-Hydrogen Mixtures Pipeline Transmission. *Energies* **2019**, *12*, 569. [CrossRef]
9. Quintino, F.M.; Nascimento, N.; Fernandes, E.C. Aspects of Hydrogen and Biomethane Introduction in Natural Gas Infrastructure and Equipment. *Hydrogen* **2021**, *2*, 301–318. [CrossRef]
10. Guandalini, G.; Colbertaldo, P.; Campanari, S. Dynamic modeling of natural gas quality within transport pipelines in presence of hydrogen injections. *Appl. Energy* **2017**, *185*, 1712–1723. [CrossRef]
11. Schouten, J.A.; Michels, J.P.J.; Janssen-van Rosmalen, R. Effect of H2-injection on the thermodynamic and transportation properties of natural gas. *Int. J. Hydrogen Energy* **2004**, *29*, 1173–1180. [CrossRef]
12. Mahajan, D.; Tan, K.; Venkatesh, T.; Kileti, P.; Clayton, C.R. Hydrogen Blending in Gas Pipeline Networks—A Review. *Energies* **2022**, *15*, 3582. [CrossRef]
13. Mayrhofer, M.; Koller, M.; Seemann, P.; Prieler, R.; Hochenauer, C. Assessment of natural gas/hydrogen blends as an alternative fuel for industrial heat treatment furnaces. *Int. J. Hydrogen Energy* **2021**, *46*, 21672–21686. [CrossRef]
14. Bard, J.; Gerhardt, N.; Selzam, P.; Beil, M.; Wiemer, M.; Buddensiek, M. The Limitations of Hydrogen Blending in the European Gas Grid. Available online: https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FINAL_FraunhoferIEE_ShortStudy_H2_Blending_EU_ECF_Jan22.pdf (accessed on 20 August 2022).
15. Gondal, I.A. Hydrogen integration in power-to-gas networks. *Int. J. Hydrogen Energy* **2019**, *44*, 1803–1815. [CrossRef]
16. Melaina, M.W.; Antonia, O.; Penev, M. *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*; National Renewable Energy Laboratory: Golden, CO, USA, 2013. [CrossRef]
17. Dell'Isola, M.; Ficco, G.; Moretti, L.; Perna, A.; Candelaresi, D.; Spazzafumo, G. Impact of hydrogen injection on thermophysical properties and measurement reliability in natural gas networks. *E3S Web Conf.* **2021**, *312*, 1004. [CrossRef]
18. Abeysekera, M.; Wu, J.; Jenkins, N.; Rees, M. Steady state analysis of gas networks with distributed injection of alternative gas. *Appl. Energy* **2016**, *164*, 991–1002. [CrossRef]
19. Deymi-Dashtebayaz, M.; Ebrahimi-Moghadam, A.; Pishbin, S.I.; Pourramezan, M. Investigating the effect of hydrogen injection on natural gas thermo-physical properties with various compositions. *Energy* **2019**, *167*, 235–245. [CrossRef]
20. *DS/EN 16726:2015+A1:2018*; Gas Infrastructure—Quality of Gas—Group H. Dansk Standard: Nordhavn, Denmark, 2018.
21. Latõšov, E.; Pakere, I.; Murauskaite, L.; Volkova, A. Impact of Grid Gas Requirements on Hydrogen Blending Levels. *Environ. Clim. Technol.* **2021**, *25*, 688–689. [CrossRef]
22. Di Bella, G.; Flanagan, M.; Foda, K.; Maslova, S.; Pienkowski, A.; Stuermer, M.; Toscani, F. Natural Gas in Europe: The Potential Impact of Disruptions to Supply. International Monetary Fund 2022. Available online: https://www.imf.org/en/Publications/WP/Issues/2022/07/18/Natural-Gas-in-Europe-The-Potential-Impact-of-Disruptions-to-Supply-520934#:~:text=Our%20findings%20suggest%20that%20in,by%20up%20to%206%20percent (accessed on 22 August 2022).
23. Zivkovic, M.; Ivic, M.; Ivezic, D.; Madzarevic, A. Effect of natural gas composition on methane number: A case of gas reservoirs in Serbia. *Energy Sources Part A Recovery Util. Environ. Eff.* **2017**, *39*, 2157–2165. [CrossRef]
24. Kuczy'nski, S.; Łaciak, M.; Szurlej, A.; Włodek, T. Impact of Liquefied Natural Gas Composition Changes on Methane Number as a Fuel Quality Requirement. *Energies* **2020**, *13*, 5060. [CrossRef]

25. Euromot, Position Paper: Revision of EU Rules on Gas Market Access—Euromot Position on Gas Quality Requirements. 2021. Available online: https://www.euromot.eu/wp-content/uploads/2021/06/EU-gas-legislation-revision_EUROMOT-position-on-gas-quality-requirements_FINAL_16-June-2021.pdf (accessed on 18 June 2022).
26. De Vries, H.; Mokhov, A.V.; Levinsky, H.B. The impact of natural gas/hydrogen mixtures on the performance of end-use equipment: Interchangeability analysis for domestic appliances. *Appl. Energy* **2017**, *208*, 1007–1019. [CrossRef]
27. *BP, Statistical Review of World Energy 2022*, 71st ed. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf (accessed on 22 August 2022).
28. Leicher, J.; Schaffert, J.; Cigarida, H.; Tali, E.; Burmeister, F.; Giese, A.; Albu, R.; Görner, K.; Carpentier, S.; Milin, P.; et al. The Impact of Hydrogen Admixture into Natural Gas on Residential and Commercial Gas Appliances. *Energies* **2022**, *15*, 777. [CrossRef]
29. Baccanelli, M.; Langé, S.; Roccob, M.V.; Pellegrini, L.A.; Colombo, E. Low Temperature Techniques for Natural Gas Purification and LNG Production: An Energy and Exergy Analysis. *Appl. Energy* **2016**, *180*, 546–559. [CrossRef]
30. Papadopoulo, M.; Kaddouh, S.; Pacitto, P.; Prieur Vernat, A. Life Cycle Assessment of the European Natural Gas Chain Focused on Three Environmental Impact Indicators. Marcogaz. 2011. Available online: https://www.cgoa.cz/informacezezahranici/pdfdoc/marcogazudrzitelnost/2011/WG-LCA-12-01_D023_WG_LCA_Final_Report_Life_Cycle_Assessment.pdf (accessed on 26 June 2022).
31. GGTC—Natural Gas Composition. Available online: https://e-platform.ggtc.ge/gasanalisisen.aspx (accessed on 23 August 2022).
32. International Group of LNG Exporters (GIIGNL), Annual Report 2018, International Group of LNG Exporters. 2018. Available online: https://giignl.org/wp-content/uploads/2021/08/rapportannuel-2018pdf.pdf (accessed on 25 June 2022).
33. Euromot, Position Paper: Requirements on the Quality of Natural Gas. 2017. Available online: https://www.euromot.eu/wp-content/uploads/2018/02/EUROMOT-Position-Gas-Quality-2017-11-09-.pdf (accessed on 28 June 2022).
34. *DS/EN ISO 6976:2016*; Natural Gas—Calculation of Calorific Values, Density, Relative Density and Wobbe Indices from Composition. Dansk Standard: Nordhavn, Denmark, 2016.
35. Palmer, G. Methane Number. *J. Nat. Gas Eng.* **2017**, *2*, 134–142. [CrossRef]
36. Zachariah-Wolff, J.L.; Egyedi, T.M.; Hemmes, K. From natural gas to hydrogen via the Wobbe index: The role of standardized gateways in sustainable infrastructure transitions. *Int. J. Hydrogen Energy* **2007**, *32*, 1235–1245. [CrossRef]
37. Lamioni, R.; Bronzoni, C.; Folli, M.; Tognotti, L.; Galetti, C. Feeding H2-admixtures to domestic ceondensing boilers: Numerical simulations of combustion and pollutant formation in multi-hole burners. *Appl. Energy* **2022**, *309*, 118379. [CrossRef]
38. Balanescu, D.T.; Homutescu, V.M. Effects of hydrogen-enriched methane combustion on latent heat recovery potential and environmental impact of condensing boilers. *Appl. Therm. Eng.* **2021**, *197*, 117477. [CrossRef]
39. Roslyakov, P.V.; Rybakov, B.A.; Savitenko, M.A.; Ionkin, I.L.; Luning, B. Assessment of the Potential for Decreasing Greenhouse Gas Emissions in Burning Fuels in Boilers at Thermal-Power Plants (TPP) and Boiler House. *Therm. Eng.* **2022**, *69*, 718–726. [CrossRef]