The Outsized Effect of Minute Contaminants on the Physical Properties of H_2 as Shown Through the Example of Industrial Forced Draft Burners

HYDROGEN SAFETY

RESEARCH

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ABSTRACT

As of today, multiple gaseous H_2 quality specifications and a single H_2 quality standard (ISO 14687:2025) exist. These specifications allow a varying amount of contaminant gases, including contaminants which have no heating value, such as CO_2 or N_2. Due to the large difference in the physical properties (e.g. density) between these contaminants and H_2, even minute amount of contaminant can change the properties of the mixed gas significantly. For example, allowing 2% CO_2 in H_2 means that the density increases by approximately 40% and the Wobbe index decreases by almost 20% compared to pure H_2. As pure H_2 fulfils all the specifications and quality grades, changes between high-quality H_2 and H_2 with contaminants might happen in a supply chain hour-by-hour along with the changes in physical properties; this might lead to significant challenges, for example in metering, dimensioning the infrastructure or the like. In this paper an example of forced draft burners is presented, and it is shown that changes in the gas quality can lead to potentially dangerous working points while still fulfilling the requirements of ISO 14687:2025 Grade A, if no mitigating steps are taken. A guideline for adjusting large, forced draft burners to ensure safe working conditions is presented, along with an estimate on lost efficiency if no other action is provided underlining the importance of an oxygen trim system. Showing these effects in a specific example highlights the importance of taking gas quality, and specifically the possibility of minute amounts of heavy contaminants into account, when considering the safety of H_2 containing systems or modeling and simulating the behavior of these.

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INTRODUCTION

In the energy transition hydrogen (H_2) is expected to play a significant role and as a result of this, infrastructure for distribution and transportation as well as for use of H_2 is expected to become more widespread. Today, H_2 is almost only used in the industry as feedstock and for oil refining (IEA, 2024), but eventually other use cases will play a more significant role. This means that in the future other applications will appear, each with their own requirements for H_2 quality (Boufaied *et al*., 2021; Spath and Dayton, 2003). Along with this change, the large scale and relatively long-distance transport of H_2 in pipelines can be envisioned, either as a blend with natural gas (with or without deblending) or by itself as H_2 pipelines (ENTSOG, GIE and Hydrogen Europe, 2021). The quality of H_2 in pipelines in Europe is an ongoing discussion, partially due to the common European Hydrogen Backbone project (Wang *et al*., 2021). At the core of this discussion, one finds a question of technical feasibility (i.e. what quality is technically possible and realistic to maintain in a large-scale pipeline infrastructure with underground storage sites and repurposed pipeline sections) and economic considerations (i.e. how purification costs should be shared between the producers and consumers). Techno-economic analyses of different quality levels based on the purification costs have been conducted for the Dutch case (Polman *et al*., 2023; Van *et al*., 2022), and a similar study is currently being carried out on European level. However, these studies only consider purification costs and do not regard other challenges caused by different H_2 quality levels and potentially allowing significant variations of H_2 quality in the future infrastructure.

Due to the small size and weight of the constituent molecules, H_2 gas has physical properties that significantly differ from other gases, with the exception of helium (He). This leads to rapidly changing properties, when contaminants are introduced to H_2 gas. Together with the variations in gas quality allowed in the different quality specifications, this potentially leads to significant fluctuations in the physical properties of the gas found at different points of the value chain. These changes in physical properties can have an impact on metering, infrastructure capacity (pressure drop), safety (spreading of plumes) and other areas as well. In this paper, the effect of H_2 specifications and minor contaminants on the adjustment of large industrial forced draft burners and the consequence of these are explored and showcased.

RESULTS AND DISCUSSION

In the following sections first (in Section 2.1) the effect of contamination on the physical properties of H_2 will be illustrated by a selection of properties relevant for H_2 as a fuel gas. In Section 2.2 an example is given, where the addition of 2% nitrogen (N_2) into H_2 causes significant changes in the combustion process of a forced draft burner. In Section 2.3 a description is given of how large burners can be adjusted to accommodate the different contaminants allowed in the different standards. Finally in Section 2.4 an estimate is given regarding the loss of efficiency caused by implementing this adjustment protocol if no other mitigating steps are taken.

PHYSICAL PROPERTIES OF H_2 CONTAINING CONTAMINATIONS

Table 1 shows selected physical properties of 100% H_2 gas and gas with the worst-case concentration of allowed contaminants according to selected H_2 quality specifications. It is worth mentioning that pure (100%) H_2 fulfils any of the specifications, as they contain minimum requirements. This means that, for example, ISO 14687 Grade A allows approximately 40% density variation or approximately 16% variation in the speed of sound (at 0°C and 101.3 kPa). In a situation where a distribution pipeline system is available, producents of both green H_2 (from electrolyzers, very high quality) and blue H_2 (steam reforming of methane with carbon capture) are connected, and for example ISO 14687 Grade A is chosen as the quality specification, this effect can lead to significant changes in the quality within minutes or hours, depending on the local conditions.

As mentioned, the significant influence of even minute amounts of contaminants together with the possibility of rapidly changing quality has far-reaching potential consequences. A few areas where the effect of these changes should be investigated and considered are:

Pipeline capacity and economic consequences: Due to the potential significant increase in density, choosing a lower H_2 quality specification leads to the decrease of the maximum pipeline capacity of a given pipe and the pipeline system will have to be designed for the possibility of

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a larger pressure drop in general. This could lead to significant economic consequences due to decreased future cash flows (lower capacity), lower portion of the existing infrastructure being feasible to be converted (lower capacity) or increased compression costs (higher pressure drops).

Metering: Due to significant and potentially rapid changes in physical properties, metering might be challenging. Apart from positive displacement flow meters, other types of meters can be expected to be influenced substantially by the changing physical properties. This means that each metering point has to be equipped with gas quality measurement (e.g. a gas chromatograph) or that another method of rigorous gas quality tracking should be implemented in the system, all adding costs and difficulties.

Safety: The effect of changing quality and physical properties should be investigated further. Intuitively, the significant changes in density and other properties could influence plumes and the spreading of H_2 in case of releases and hence also safety distances. It also seems possible that the ignition energy changes with the presence of contaminants. Thereby, for example safety modeling studies conducted in connection to H_2 filling stations or H_2 powered vehicles, where the H_2 quality is close to pure H_2, might not describe the situation well in case of a large-scale pipeline infrastructure with lower quality H_2. Furthermore, even some (possibly most) of the existing experimental studies conducted in connection to using H_2 for heating, for which ISO 14687:2025 Grade A can be considered as quality specification, were also based on high purity H_2, for example in the safety assessment activities of the Hy4Heat project (Brown, Posta and McLaughlin, 2021).

SPECIFICATION/ STANDARD	MINIMUM H_2 CONCENTRATION (mol%)	WORST CASE CONTAMINANT (mol%)	HIGHEST DENSITY[a] (g/m^3)	LOWER HEATING VALUE[b] (MJ/kg)	SPEED OF SOUND[c] (m/s)	WOBBE INDEX[d] (288.15 K /288.15 K) (MJ/m^3)
Pure H_2	100%	–	89.9	119.9	1260	45.89
ISO 14687:2025 Grade B	99.9%	0.1% CO_2	91.8	117.3	1247	*45.37*
Grade A+ proposal[e]	99.5%	0.5% Ar	98.4	109.5	1205	**43.65**
CEN/TS 17977:2023	98%	0.91% Ar[f]	105.4	101.5	1165	**42.00**
ISO 14687:2025 Grade A	98%	2% CO_2	127.4	83.0	1057	*37.78*

Table 1 An overview of the effect of H_2 quality specifications on selected physical properties of the gas along the worst-case allowed contaminant. Note: pure H_2 fulfills any of the specifications as they are minimum specifications.

[a]: At 273.15 K and 101.3 kPa, calculated according to ISO 6976:2016.

[b]: At 293.15 K, calculated according to ISO 6976:2016.

[c]: At 273.15 K and 101.3 kPa. Value from Aspen HYSYS V14, calculated using the hydrogen fluid package.

[d]: The Wobbe index (WI) shows the interchangeability of fuel gases and is defined as $WI = V_c / \sqrt{G_S}$ where V_c is the higher heating value [MJ/m^3] and G_S is the specific gravity of the gas compared to air. The column contains either a specific limit listed in the given specification (denoted by **bold** numbers) or one calculated from the worst-case contaminant situation (denoted by *italic* the number). Calculations according to ISO 6976:2016.

[e]: Proposed by Kiwa for the Dutch hydrogen backbone (Polman *et al.*, 2023).

[f]: Calculated from the lower Wobbe index limit listed in the specification (42 MJ/m^3 [288.15 K/ 288.15K]).

EFFECT OF MINUTE CONTAMINATIONS ON THE O_2 CONTENT IN THE FLUE GAS OF A FORCED DRAFT BURNER

In order to illustrate the outsized effect of minute contaminants on forced draft burners, a 100 kW industrial burner was tested at 27 kW power in a stainless-steel condensing boiler (Riello TAU 210 N), using both 100% H_2 and a mixture of 98 mol% H_2 and 2 mol% N_2. This mixture has been chosen to replace the role of limit gases defined in EN 437:2021 for testing combustion appliances designed for traditional fuel gases of first, second or third families. This standard does not contain guidance for appliances designed for H_2, thus an extreme case was chosen, which is at the limit of what ISO 14687:2025 Grade A allows. N_2 was chosen as the example contaminant, due to its potential appearance in real life (from purging and flushing gas systems), its availability and affordable price, along with its straightforward handling (posing no additional safety risks concerning fires or explosions).

H_2 was supplied from cylinders containing a minimum of 99.9 mol% H_2, while N_2 was supplied from a cylinder containing 2.6 (99.6 mol% N_2) quality (both supplied by Nippon Gases Danmark A/S). The mixture of H_2 and N_2 was created by a custom-made gas mixing station based on calibrated mass flow meters. During the experiments with the gas mixture, the fuel gas was collected in a sampling bag and analyzed with a Scion Instruments 456 refinery gas analyzer gas chromatograph (GC), equipped with a flame ionization detector (FID) and two thermal conductivity detectors (TCD)—one specialized for the measurement of He and H_2. In case of the measurements presented here, the measured fuel composition of the blend was approximately 98.05 mol% H_2 and approximately 1.95 mol% N_2, being close to the target

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2 mol% N_2 content. The burner was not equipped with an automatic oxygen (O_2) trim system and the O_2 content of the dry, air-free flue gas was continuously monitored using a Servomex 4900 gas analyzer through a chiller to remove the moisture content. Figure 1 shows the measured O_2 concentration in the flue gas, while changing from 100% H_2 as fuel to a mixture of 98% H_2 and 2% N_2 (Figure 1a), and when changing in the opposite direction, from the mixture to 100% H_2 (Figure 1b). At the start of each test, the burner was adjusted to an air excess corresponding to the standard air–to-fuel ratio (λ) value of 1.15, based on the dry air-free O_2 content of the flue gas.

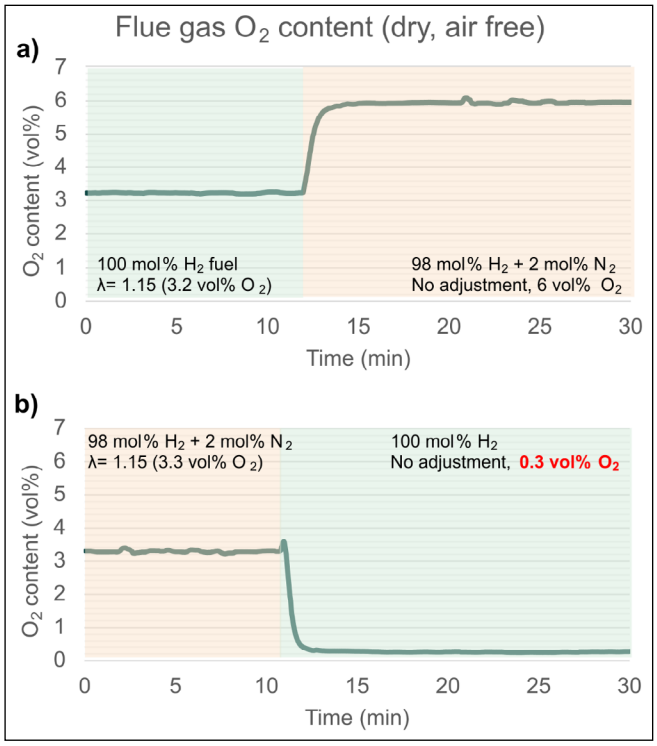


Figure 1 The effect of changing fuel gas quality and minor contaminants on the O_2 content of the flue gas from an industrial forced draft burner installed in a stainless-steel condensing boiler. **a)** Burner adjusted to 3.2 vol% O_2 in the flue gas, while using 100 mol% H_2 as a fuel (λ = 1.15), and the effect of changing to a fuel containing 98 mol% H_2 with 2 mol% N_2. **b)** Burner adjusted to 3.3 vol% O_2 in the flue gas while using 98 mol% H_2 with 2 mol% N_2 as a fuel (λ = 1.15) and the effect of changing to a fuel of 100 mol% H_2.

When starting and operating the burner with 100 mol% H_2, the standard λ value of 1.15 corresponds to a dry, air free flue gas O_2 content of approximately 3.2 vol%. After the burner was adjusted to this value during the measurements, the fuel gas was changed to 98 mol% H_2 containing 2 mol% N_2 and as a result, the O_2 content of the dry, air free flue gas increased from approximately 3.2 vol% to approx. 6 vol%, which is almost a 100% increase. A reverse fuel gas exchange test was conducted going from 98 mol% H_2 with 2 mol% N_2 to 100 mol% H_2 fuel gas, and where the burner was initially again adjusted to a λ value of 1.15 (dry, air free flue gas O_2 content of approximately 3.3 vol%). In this case the O_2 content of the flue gas dropped significantly after changing the fuel gas composition, ending at a value of approximately 0.3 vol% O_2 (dry, air free), corresponding to a λ value of approximately 1.01. A sample taken from the flue gas at this working point contained approximately 0.6 mol% unburned H_2 (as measured by a Scion Instruments 456 gas chromatograph). This shows that slight changes in the fuel quality can move from the intended and safe state to close to a potentially hazardous, stoichiometric combustion with unburned H_2 in the flue gas within seconds or minutes.

The surprisingly large effect of a small amount of inert contaminant can be explained by the unique properties of H_2 mentioned in Section 2.1. The addition of even minor amounts of contaminants having no heating value decreases the Wobbe index (WI) of the gas mixture significantly. In the case shown, the WI decreased from 45.89 MJ/m³ (288.15 K/ 288.15 K) when using 100 mol% H_2 to 40.09 MJ/m³ when 2 mol% N_2 was added. It is worth noting that 2 mol% N_2 in H_2 does not fulfil ISO 14687 Grade A requirements, as the maximum allowed N_2 content is 1.9 mol%. However, 2 mol% carbon dioxide (CO_2) is for example allowed by the standard, which would lead to an even larger drop in the Wobbe-index (Table 1), corresponding to an even more significant change in the combustion parameters.

The scenario presented here could theoretically happen in a gas distribution system, where high purity H_2 is supplied by electrolysis, but when green electricity is not available or expensive, H_2 is then supplied from underground gas storages with a significantly lower quality just

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fulfilling ISO 14687:2025 Grade A or a similar specification. Another possible scenario could be errors in flushing procedures in process equipment, where the N_2 used enters the delivered gas stream. Depending on the conditions and flow speeds, the change in gas quality in such a distribution system can happen within minutes. Burner adjustment has to accommodate this risk, otherwise a fast enough O_2 trim system has to be mandated. In this contribution a method for determining the air excess for burner adjustment—considering among others the possibility of gas quality changes allowed by different gas quality specifications—is shown, along with the consequences for burner efficiency. This highlights the importance of the allowed gas quality variations for the safe and efficient utilization of H_2 in combustion applications.

GUIDELINE FOR ADJUSTING LARGE, FORCED DRAFT BURNERS FOR OPERATION WITH NATURAL GAS AND H_2

When adjusting large natural gas burners, the safety of the operation must be ensured, for which 'safe operation' should be defined. When operating a burner with natural gas and lowering the air excess ratio (λ value), meaning the O_2 content of the air/fuel mixture and thereby the O_2 content of the flue gas, at a certain flue gas O_2 concentration level, carbon monoxide (CO) emission from the burner will start to increase rapidly. The flue gas O_2 concentration corresponding to this 'tipping point' should be known, as it indicates optimal combustion conditions with high efficiency and minimum flue gas losses. Decreasing the air/fuel ratio further, incomplete combustion occurs leading to increasing CO emission (Testo, 2018). This tipping point is different from burner-to-burner and can be measured using flue gas analyzing equipment, even in the field at industrial sites. The aim of adjusting burners is to operate the burner above or as near as possible to this tipping point, avoiding safety risks and CO emissions while maximizing efficiency.

In order to avoid flue gas O_2 concentrations below this tipping point leading to unsafe operations due to CO emissions, the variations of multiple parameters have to be taken into account. These parameters are chimney draft, air pressure (barometer level), combustion air temperature, air humidity, fuel gas temperature, fuel Wobbe index (gas quality), pressure variations of the fuel gas and variations in the mains voltage. Fluctuations in each of these parameters lead to changes in the air excess ratio and thereby the O_2 content of the flue gas. For example, when the barometric pressure decreases, the amount of oxygen in the same volume of combustion air decreases leading to a lower flue gas O_2 concentration. Assuming, that normal distribution describes the variations of the above-mentioned parameters over a given year and based on many years of experience within the Danish gas industry, the values of these parameters are 99% of the time within the limits listed in Table 2 in given year and at sea level. This means that when adjusting a burner, the air excess and with it the flue gas O_2 concentration have to be adjusted high enough above the tipping point to accommodate the possible variations in the different parameters and ensure safe operation. The effect of the variation in each individual parameter on the air excess ratio is shown in Table 2.

PARAMETER		AIR EXCESS RATIO (λ) VARIATION
Chimney draft	$\Delta p_{chimney} = \pm 0.025$ *kPa from mean*	±1%
Air pressure	$p_{air} = 101.3 \pm 2.7$ *kPa*	±1.5%
Air temperature	$\Delta T_{air} = \pm 15$ *K from mean*	±5%
Air humidity	0 – 13 g_{H_2O} / $kg_{dry\ air}$	±0.5%
Fuel gas temperature	$\Delta T_{fuel\ gas} = \pm 5$ *K from mean*	
Wobbe index	$\Delta WI = \pm 6\%$ *from mean*	±6%
Fuel gas pressure variation	$\Delta p_{fuel\ gas} = \pm 2\%$ *from mean*	±1%
Mains voltage	$\Delta U_{mains} = \pm 15$ *V from mean*	±1%

Table 2 Overview of parameters influencing the required air excess when adjusting natural gas burners at sea level. The variations assumed are based on years of statistical experience and data from Denmark and result in the given parameter being within the range shown 99% of the time. Along with the range of the different parameters, their possible individual effect on the air excess ratios is also shown.

To ensure the safe operation of a gas burner under all operational conditions, the additional amount of combustion air required to accommodate the entire possible variation of all the parameters independently leads to a very high air excess and consequently low efficiency.

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Under realistic conditions, however, the different parameters do not reach their extreme values at the same time. For example, the fuel gas temperature and the mains voltage can be assumed to be independent variables. Moreover, measuring some of the listed parameters at the time of adjustment can also help decrease the additional combustion air required for safe operation. Out of the parameters listed, measuring the air pressure and temperature at the time of adjustment can be carried out with relative ease. With the assumptions described in this section and by accepting a statistical maximum of 9 h per year and per installation with CO emission over the 500 ppm limit defined for normal operation, the required additional combustion air—and with it flue gas O_2 content—above the tipping point can be calculated.

This method has been used in Denmark for the adjustment of large natural gas burners for years. An easy-to-use Microsoft Excel spreadsheet was developed to help technicians at the time of adjustment, along with a web application, both which are available upon request. Further details can be found in (Niels Bjarne Rasmussen, 2024).

The same approach can be used for H_2 burners as well, although the definition of the tipping point or the limit for safe operation must be changed. When H_2 is used as fuel gas, lowering the air excess—and with it the amount of O_2 in the flue gas—below a certain level leads to rapidly increasing concentration of unburned H_2 in the flue gas (IGU, 2025). Using this point from which the unburned H_2 concentration starts to increase as the tipping point, the method for adjusting and calculating the required air excess for natural gas burners can be adapted for H_2 burners as well. It is worth mentioning that based on experience, when unburned H_2 appears in the flue gas, some CO can also be detected, thus the similarities are even more obvious. The appearance of CO in the flue gas is due to the reverse water-gas shift reaction, in which the CO_2 content of the atmospheric air reacts with the unburned H_2 in the presence of the heat from the combustion, forming CO and H_2O. When comparing the consequences of the adoption of different H_2 specifications, the allowed Wobbe index variation should be changed compared to Table 2, based on the contaminants permitted by the different specifications.

The process of adjusting burners and the safety risks caused by the changing Wobbe index were made largely non-existent by the introduction and spread of automated O_2 trim systems. However, investigating the effects and risks of implementing different H_2 quality specifications shows that even minor differences in H_2 quality can have outsized effects in areas which are not immediately obvious or considered.

EFFECT OF THE H_2 QUALITY SPECIFICATION ON THE EFFICIENCY OF H_2 FUELED BURNERS

Using the discussed method, the target flue gas O_2 concentration corresponding to the Wobbe index variations allowed by the different H_2 quality specifications can be calculated. Table 3 lists the different specifications from Table 1, the minimum Wobbe indices allowed and the calculated target O_2 concentrations in the flue gas at the time of adjustment, assuming 1 vol% flue gas O_2 concentration at the tipping point, 100 kPa air pressure and 293.15 K air temperature. Pure H_2 fulfills any of the specifications and thus the corresponding Wobbe index gives the upper limit of the allowed Wobbe index range of any of the other specifications.

SPECIFICATION/ STANDARD	MINIMUM H_2 CONCENTRATION (mol%)	LOWEST WOBBE INDEX[a] (288.15 K/ 288.15 K) (MJ/m³)	TARGET O_2 CONCENTRATION IN FLUE GAS AT ADJUSTMENT[b] (vol%)
Pure H_2	100	45.89	3.02
ISO 14687:2025 Grade B	99.9	*45.37*	3.27
Grade A+ proposal[c]	99.5	**43.65**	4.08
CEN/TS 17977:2023	98	**42.00**	4.85
ISO 14687:2025 Grade A	98	*37.78*	6.76

Table 3 An overview of the effect of H_2 quality specifications on the target flue gas O_2 concentration (dry, air free) at the time of adjustment at sea level, assuming 100 kPa air pressure and 293.15 K air temperature.

[a]: Either a specific limit listed in the specification (denoted by bold numbers) or calculated from the worst-case contaminant situation (denoted by italic the number). Calculations according to ISO 6976:2016.

[b]: Unburnt fuel tipping point (O_2 concentration in flue gas below which unburned H_2 concentration increases rapidly in the flue gas) at 1 vol% O_2 in the flue gas, 100 kPa air pressure and 293.15 K air temperature. Value in dry, air free flue gas.

[c]: Proposed by Kiwa for the Dutch hydrogen backbone (Polman *et al.*, 2023).

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It is clear from the table that ISO 14687 Grade A leads to the highest required flue gas O_2 content with 6.76 vol%, while pure H_2 requires less than half of this, specifically 3.02 vol%. It is important to note that none of the discussed consequences are due to the lower quality of the fuel gas, but they are a consequence of the large variations in fuel quality (Wobbe index) allowed by the specifications corresponding to the lower qualities. For example, ISO 14687:2025 Grade A, which was specifically created with combustion processes in mind, is an exception as it has no specific Wobbe index limit or a specific limit for heavy contaminants without heating values defined in the standard. This is in contrast with CEN/TS 17977:2023 specification, which also specifies a minimum H_2 content of 98 mol%, but has a specific lower Wobbe index limit, thereby leading to significantly smaller allowed quality variations and correspondingly a lower required flue gas O_2 concentration at the time of adjustment. The existence of a specific lower Wobbe index limit in CEN/TS 17977:2023 is also the reason why only approximately 0.91 mol% Ar is allowed, even though the specification contains a 98 mol% H_2 limit, thereby theoretically 2 mol% other contaminants. More than approximately 0.01 mol% Ar would lead to a Wobbe index lower than the defined lower limit of 42 MJ/m³ (288.15 K/288.15 K), as shown in Table 1.

In a combustion process an increasing flue gas O_2 concentration leads to increasing flue gas loss. If all other loss mechanisms are assumed to be the same, this directly translates to the decrease of the efficiency of the combustion process. The influence of the H_2 quality specification can, for example, be visualized by calculating and plotting the flue gas losses as a function of flue gas temperature (Figure 2), for both pure H_2 (3.02% O_2 content in dry, air free flue gas) and ISO 14687:2025 Grade A (6.76% O_2 content in the dry, air free flue gas). Flue gas losses were calculated based on data and formulas adapted from (Geerssen, 1988).

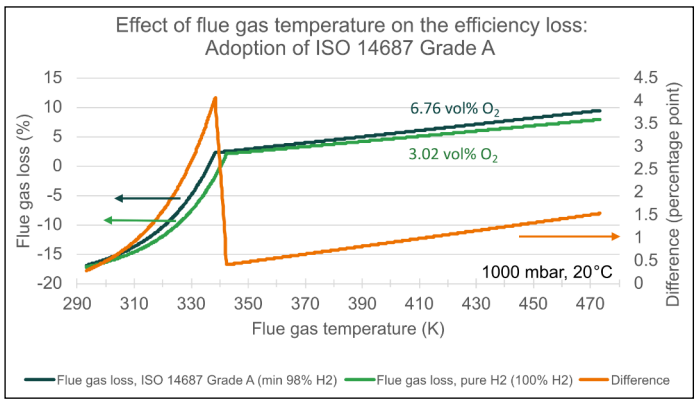


Figure 2 Calculated flue gas losses as a function of flue gas temperature, assuming 100 kPa air pressure and 293.15 K air temperature, for pure H_2 (3.02 vol% O_2 in the dry, air free flue gas) or ISO 14687 Grade A (6.76 vol% O_2 in the dry, air free flue gas) as H_2 quality specification. Along with the actual flue gas losses, the difference of the two curves is also shown for illustration purposes.

The flue gas loss vs flue gas temperature curves corresponding to pure H_2 and ISO 14687 Grade A follow each other closely. Below approximately 340 K (65–70°C) flue gas temperature, the flue gas losses are changing rapidly and calculated to be negative. This is due to the possibility of condensation below the dew point utilized in condensation boilers. Above the dew point (approximately 340 K, 65–70°C) the flue gas losses are increasing linearly with the flue gas temperature. The efficiency difference of the heating process when the burner is for example integrated into a condensing boiler can be approximated by the difference of the two curves, also shown in Figure 2. The importance of the dew point is also visible on this efficiency difference curve. Below the dew point, the difference in efficiency is rapidly increasing with the flue gas temperature, reaching a sharp maximum at approximately 338 K and 4.1 percentage points, below which it rapidly decreases. Above the dew point, the difference drops sharply and then starts increasing slowly again. In case of a condensing boiler, the flue gas temperature is strongly correlated to the return water temperature in the system. The temperature where the efficiency loss is the greatest at just below 338 K coincides with the flue gas temperatures expected in private household boilers, meaning that using H_2 as a fuel gas in private homes would coincide with the region where the highest efficiency differences can be expected.

The impact of this efficiency difference on the total projected European H_2 consumption for heating can also be estimated. An earlier study, connected to the European Hydrogen Backbone project, estimated the 2050 H_2 demand for low temperature heating applications to be 150–160 TWh/y (Wang et al., 2021). In the calculations presented below, the average of these numbers (155 TWh/y) was used. Assuming 333 K flue gas (corresponding to gas

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boilers for heating) and 293.15 K air temperature, 100 kPa air pressure and a λ value of 1.15, estimates can be given for the expected fuel gas consumptions depending on which H_2 quality specification is implemented. Based on these parameters, the flue gas losses corresponding to the O_2 content in the flue gas required for safe operation (Table 3) to each quality specification can be calculated. Assuming that all other loss mechanisms are the same—regardless of the fuel gas used—and negligible, a projected fuel gas consumption can be calculated, using the following formula and the lower heating values from Table 1:

$$Q = \left(E_{demand}^{2050} \times 3600\right) / \left(H_L \times \left(1 - I_{flue}\right)\right), \quad (1)$$

where Q : fuel gas flow, kt/y; E_{demand}^{2050}: energy demand, TWh/y; H_L: lower heating value, MJ/kg; I_{flue}: flue gas loss, -.

Neglecting other loss mechanisms means that the actual fuel gas consumption will be higher, however the relative differences between the different H_2 quality specifications will not change. The calculated annual European fuel gas flows to cover the expected low temperature heat demand of 155 TWh/y—with the assumptions and simplifications described—are shown on a mass flow basis in Figure 3a and on a volumetric flow basis in Figure 3b, based on the lower heating values corresponding to the worst-case contaminations listed in Table 1 of the different H_2 quality specifications.

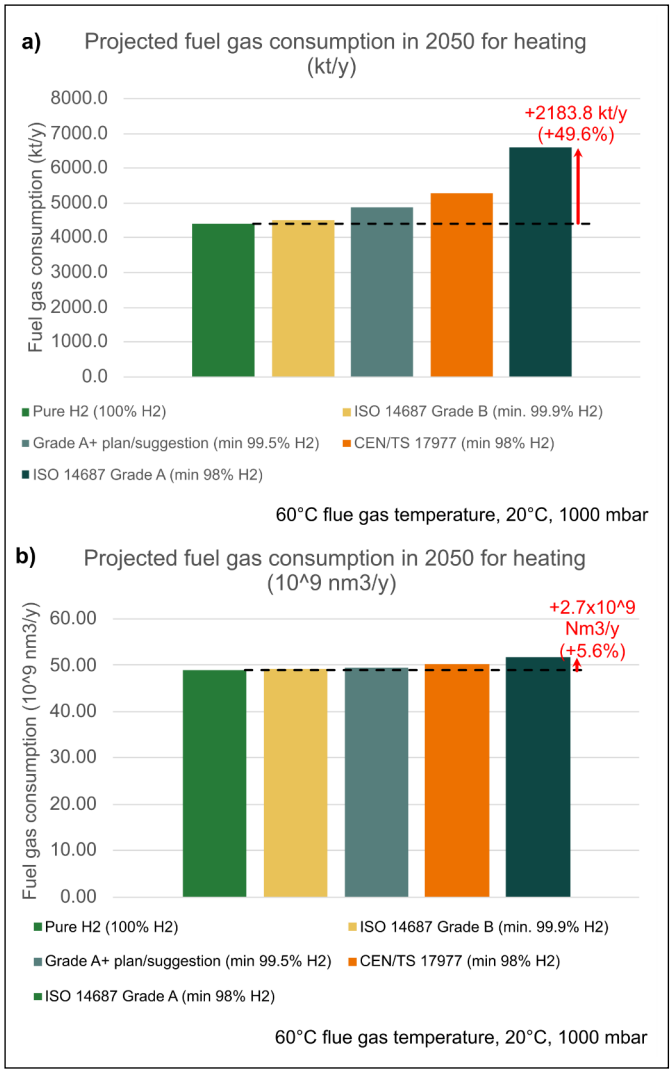


Figure 3 Calculated fuel gas consumption in 2050 for low temperature heating purposes on a mass flow **(a)** and on a volumetric flow basis **(b)**, as a function of H_2 quality specification and assuming the contaminants listed in Table 1.

Compared to 100% H_2, the calculated additional fuel gas consumptions stem both from a decreased efficiency (higher air excess ratio required for safe operation) and from a lower fuel gas heating value and higher density. In the worst-case scenario of ISO 14687:2025 Grade A, an approximate 2200 kt/y higher fuel gas consumption (+49.6%) can be expected on a mass flow basis on a European level, compared to a pure H_2 scenario. However, this only corresponds to an approximate 5.6% additional fuel consumption on a volumetric basis,

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indicating the significant effect of even minor contaminants on the density of H_2. Of the 49.6% additional fuel consumption (mass flow basis) in the ISO 14687:2025 Grade A specification scenario, approximately five percentage points are due to the lower efficiency and approx. 44.5 percentage points are due to the higher density. Examining some of the other specification scenarios, it is visible that although the additional fuel consumption is less pronounced, significant increases can still be expected in mass flows, even assuming the Grade A+ (+10.5%) or CEN/TS 17977:2023 (+20%) specification scenarios. Further details and data can be found in (Sebok, 2024).

Even though the loss of efficiency due to the variations in the fuel gas quality can be avoided using an automatic O_2 trim system, this does not alleviate the potential challenges—such as higher pressure drops in the distribution system—with increased fuel gas density and mass flow supplied to consumers.

CONCLUSIONS

This paper illustrates the surprising effect of even minor amounts of contamination on the physical properties of H_2 gas, through the example of the adjustment of H_2 fired burners. Today, there are multiple H_2 quality specifications and standardized grades published. For example, ISO 14687:2025 Grade A is created as a H_2 quality specification for combustion applications. It specifies a minimum H_2 content of 98 mol%, while allowing 2 mol% other contaminants, for example CO_2. Having 2 mol% CO_2 in H_2 leads to an increase of gas density of approximately 42%, a significant decrease in speed of sound, heating value and Wobbe index. As the ISO 14687:2025 Grade A standard specifies minimum requirements, it allows significant variations in the gas quality, for example 100% H_2 also fulfils the requirements. This means that in a hypothetical situation, a H_2 distribution system following ISO 14687:2025 Grade A can have gas with significantly changing properties in a relatively short amount of time, which might lead to—among other things—unsafe conditions in the case of H_2 burner operation, as illustrated in this study. In order to mitigate these risks, burners should be adjusted to a higher air excess ratio (higher λ values), to accommodate the potential changes in the fuel gas quality. Using higher air excess ratios, in turn, lowers the efficiency of the combustion process, highlighting the cascade effect where allowing more variations in the gas quality, which requires higher air excess to keep the process safe, leads to additional fuel gas consumption. Comparing the loss of efficiency for 100% H_2 (best case) to the variations allowed in ISO 14687:2025 Grade A (worst case) based on the additional combustion air required for safe operations, up to four percentage points of efficiency loss can be expected, leading to an additional fuel gas consumption of up to approximately 2200 kt/y on a European level. Implementing more restrictive quality specifications and thereby allowing smaller variations in the physical properties of the fuel gas, would lead to less additional combustion air required to ensure safe operation, resulting in a smaller loss of efficiency and lower fuel gas consumption. It is important to emphasize that the effect described here is not due to lower quality fuel gas, but specifically due to the larger variations allowed in the physical properties by the quality specifications containing lower H_2 content.

The effects of the allowed change in physical properties shown in this contribution are illustrated with the worst-case scenario, meaning the theoretical adoption of the ISO 14687:2025 Grade A specification and assuming 2 mol% CO_2 as a contaminant. In practice, the probability of 2 mol% CO_2 contamination in H_2 is not particularly high and the implementation of an O_2-trim system would both keep the combustion safe and help with optimizing the efficiency of the process. Apart from relying on the probabilities of different contaminations and an O_2-trim system, choosing a stricter quality specification than ISO 14687:2025 Grade A or implementing a Wobbe index limit in the Grade A specification would also help solving the challenges associated with the changing gas quality. Nevertheless, the effects of gas quality variations shown in this study highlight the outsized influence of minor contaminants on the properties of H_2 gas. Consequently, the results also show that when considering the H_2 quality specification of the future H_2 infrastructure, not only the purification costs should be considered but also the costs associated with the difficulties due to variation of the physical properties (metering, pressure drop etc.). Apart from the challenges the changing gas quality might pose to the day-to-day operation of the infrastructure, the significantly different physical properties might also lead to safety risks, as the resulting gas might behave substantially differently than expected from pure H_2.

Another conclusion is that when discussing H_2 in the context of value chains not related to fuel cell road vehicles, meaning that a higher concentration of contaminants can be allowed, the simulation of gas behavior cannot be based on the properties of 100% H_2. For example, in such cases, it seems plausible that the behavior of releases and spreading of H_2 in a release event is different compared to pure H_2, and that the risk profiles could be different as well, due to changes in the ignition energies. These consequences should be investigated further, especially if a 98% H_2 quality level is considered for widespread use in the coming European H_2 infrastructure, either based on ISO 14687:2025 Grade A or CEN/TS 17977:2023.

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

B.S.—Laboratory measurements with the industrial burner, paper concept and writing of the manuscript.

A.K.—Contribution to and critical review of H_2 safety aspects, refinement of the paper concept and review of the manuscript.

N.B.R.—Interpretation of data and input to the flue gas O_2 content in case of burners, calculation of the target O_2 content of the flue gas under different conditions, reviewing of the manuscript.

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