Testing **Hy**drogen admixture for **G**as **A**pplications

WP5 – Recommendation for mitigation procedures

Review on other projects related to mitigation and identification of usable sensors in existing appliances

Deliverable: D5.1

Status: Final 28/04/2022

Dissemination level: PU = Public

The THyGA project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No. 874983. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Document classification

Title	Review on other projects related to mitigation and identification of usable sensors in existing appliances
Deliverable	D5.1
Reporting Period	M1-M24
Date of Delivery foreseen	M24
Draft delivery date	M26
Validation date	M28

Authors	Stéphane Carpentier[1]
Affiliation	[1] ENGIE, CRIGEN Lab, 4 Rue Joséphine Baker, 93240 Stains, France
Corresponding authors	Stéphane Carpentier, stephane.carpentier@engie.com
Work package	WP 5
Dissemination	PU = Public
Nature	Report
Version	Final
Doc ID Code	THY_WP5_0007_D5.1 Review on other projects related to mitigation and identification of usable sensors in existing appliances
Keywords	Mitigation, sensor, ionization, adjustment, combustion, gas quality

Document History

Partner	Remark	Version	Date
ENGIE	Draft version	1	24/02/2022
GWI, BDR Thermea	Updated version, partner feedback	2	13/04/2022
GWI, ENGIE	Updated version	3	25/04/2022
ENGIE	Finalisation	Final	27/04/2022

Document review

Partner	Approval
GWI	Jörg Leicher (leicher@gwi-essen.de)
BDR Thermea	Sebastiano Temperato (sebastiano.temperato@baxi.it)
ENGIE	Stéphane Carpentier (stephane.carpentier@engie.com), Patrick Milin (patrick.milin@engie.com)

Acknowledgements

The authors would like to express their thanks to the advisory panel group members who helped the project by providing feedback on mitigation and especially their views on the relevance of identified safety aspects to focus on, or technologies which could bring added value to the deliverable.

Executive summary

Adding hydrogen into the gas grid will have a beneficial effect on CO_2 emissions and will contribute to reduce our dependency on fossil fuels. However, due to physico-chemical properties different from those of natural gas, hydrogen, even mixed at low proportion to natural gas, may disrupt the proper functioning of some gas appliances. This was previously discussed in THyGA's report D2.2 [1].

Thanks to an extensive testing programme, Work Package (WP) 3 of the THyGA project will provide information on the extend of perturbations that hydrogen could cause to gas appliances [2].

How can we prevent them?

The main goal of THyGA's WP5 is to investigate ways to adapt residential or commercial appliances that have safety or performance issues, to different levels of H_2 concentrations in natural gas.

This document presents some possible mitigation measures based on a literature study and some calculations.

- Acting on gas quality, to avoid that hydrogen addition enhance current gas properties variations, was explored several times in the past.
- Designing new boilers that could operate with variable gas composition, including hydrogen.
- Dealing with existing appliances in order to guaranty safety for users and appliances.

Gas quality

In future years, the increase in LNG imports, biomethane injection and hydrogen addition to the distributed natural gas will lead to an increase of the effective Wobbe Index (WI) bandwidth of gases at entry points. On the other side, at exit points, manufacturers require narrow WI bandwidth in order to optimize the performances of their appliances. therefore, a first mitigation measure could be to use means of reducing the WI bandwidth of gases at entry points.

In the past, mixing stations have been used to handle this problem by mixing different qualities of gases or by introducing inert gases or high WI gases. However, although adding new gases can improve gas properties on one point, it could also degrade them on others.

Calculations can discriminate impacts, but only tests could quantify them and validate the approach.

New appliances

The study of sensors is a good way to start.

Two groups of sensors can be used depending on loop control:

- With feedforward loop control, the behaviour of appliances is adjusted according to gas quality.
- With feedback loop control, flue gases are analysed and then, the behaviour of the appliance is adapted accordingly.

There are already correlation-based gas sensors available in the industrial gas applications. Technically, they have the potential to be adapted for domestic use. However, they are still very expensive (about one to several thousand euros). Currently, it is not possible to use them in each appliance. However, it could be an interesting perspective for the future.

For the moment, a few sensors exist in domestic appliances.

- Ionization probes are the most widespread. They operate properly as a safety sensor with H_2NG gases up to 60% (according to THyGA tests) and maybe above, but they do not work well for combustion control purpose.
- In the past, Vaillant has manufactured an adaptative combustion controlled function (ACCF) for domestic boiler based on a CO sensor. This could be a mitigation solution to explore in WP5 in order to optimize combustion.

Concerning safety sensors: if one wants to build an appliance that could operate with natural gas or pure hydrogen, there could be a renewed interest for thermocouple as a flame detector. However, the response time of this sensor is slow and may not match current safety requirements, especially for the more powerful appliances. Otherwise, ultraviolet sensors like those used in the industry for flame detection could be an alternative, however costly, solution.

Some patents have also been published concerning the mitigation of the flashback problem. What they suggest is to increase the air/fuel ratio when operating conditions could generate flashback (ignition). One patent describes a method to detect flashback using different kind of sensors on the injector (temperature sensor for example). However, it should be noted that increasing air/fuel ratio to avoid flashback could also bring other problems (blow off, no or delayed ignition) if the air/fuel ratio goes outside the recommended range.

Existing appliances

What to do with existing appliances in order to check that they are suitable for operating with H_2NG mixtures?

This point was investigated in the past during conversion projects:

- From town gas to natural gas
- From pipe gas to LNG
- From L gas to H gas

It is also interesting to cross this information with demonstration projects on H_2NG to see how they have guaranteed safety for users as well as a safe operation of appliances.

When town gas was replaced by natural gas in the 60's, distribution pressure was raised by about 10 mbar and the design of injector/burner holes were adapted.

- However, re-designing a burner can be a complex work as improvements in some areas can lead to drawback in others (ex: improving flashback behaviour is usually compensated by worse blow off behaviour).
- Increasing distribution pressure for H_2NG could be a way to mitigate the loss of heating power for high proportion of H_2. However, this solution would not work for appliances with a pressure regulator. This solution could be tested in WP5, if necessary.

Recent conversion projects from L gas to H gas gave a better view on how a modern conversion is performed. It involves creating an inventory of appliances in each home and the classification in several segments where appliances could operate with both gases without changes or must be changed or require some conversion work. In France, an exhaustive appliance database was built with help of manufacturers in order to classify all encountered appliances in different segments. A similar database could be built for H_2NG with the help of manufacturers: suitable for H_2NG, not suitable, and in-between.

Experimental / demonstration projects on H_2NG are another source of information on how to mitigate the impact of H_2NG on gas appliances. Recently, the HyDeploy project has initiated a safety check work on gas appliances and installations before starting the injection of 20% H_2 in the gas grid. Based on this work, a method of safety check of gas appliances could be initiated and tested in WP5 in order to discriminate used appliances unable to operate with H_2NG from the others.

Grey areas

Some grey areas might require some more investigations in order clear some unknown issues.

- **On site adjustment** will be a major problem if, in the future, the proportion of hydrogen varies on a wide range. In the labs of THyGA partners, adjustment tests are carried out with lab CO_2 analysers (with a CO_2 sensor). However, field adjustment is performed with combustion analysers equipped with O_2 sensors. The analysers convert O_2 data into CO_2 data using a predefined natural gas composition. The impact of this was not measured in THyGA's WP3. Preliminary calculations show that the use of field analysers could be beneficial regarding H_2, but it has also some drawbacks. More interesting, an adjustment based on O_2 levels in flue gases could reveal more adequate for H_2NG mixtures. Detailed tests/analysis of this situation should be performed, with gas analysers and with a specific O_2 range calculated from CO_2 range given in instruction manuals. This could eventually mitigate adjustment problems.
- **Natural draught** should not be an issue on most appliances. Preliminary calculations show that increasing the proportion of H_2 decreases the volume of flue gases and its density (at constant temperature). However, increasing the proportion of hydrogen also increases the air excess, and thus, can also decrease flue gases temperature. As lower flue gases temperature means less natural draught, this point has to be investigated, mainly in extreme conditions, when a boiler is at the limit of a malfunction (partially blocked flue stack to generate pressure loss, for example).

The identified issues will be used as a basis to define the workplan of WP5 to close knowledge gaps (interest of CO sensors, impact of H_2NG blends on exhaust fumes sizing…) and identify methodologies to prepare injection of hydrogen on the field (on-site testing, adjustment requirements). The work is deeply correlated with WP4 (standardization) activities.

List of abbreviations

ACCF	Adaptative Combustion Control Functions
AP	Advisory Panel Group
CH_4	Methane
C_3H_8	Propane
CHP	Combined Heat and Power
CO	Carbon monoxide
EU	European Union
GA	Grant Agreement
GAD	Gas Appliances Directive
GAR	Gas Appliances Regulation
H_2	Hydrogen
H_2NG	Hydrogen / Natural Gas blend
HE	Hydrogen Embrittlement
KER	Key Exploitable Results
HCV	Higher Calorific Value
Lambda	Air excess
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
N_2	Nitrogen
NG	Natural gas
S_L	laminar flame velocity
Tad	Adiabatic Temperature of combustion
TC	CEN/CENELEC Technical Committee
Ws	(Superior) Wobbe Index

Table of contents

Introduction

Adding hydrogen into the gas grid will have a beneficial effect on CO_2 emissions and will contribute to reduce our dependency on fossil fuels. However, due to physico-chemical properties different from those of natural gas, hydrogen, even mixed at low proportion to natural gas, may disrupt the proper functioning of some gas appliances. This was previously discussed in THyGA's report D2.2 [1].

Thanks to an extensive testing programme, Work Package 3 of the THyGA project will provide information on the extend of perturbations that hydrogen could cause to gas appliances [2].

How can we prevent them?

The main goal of THyGA's WP5 is to investigate ways to adapt residential or commercial appliances that have safety or performance issues, to different levels of H_2 concentrations in natural gas.

A first list of solutions that could be used to mitigate problems caused by the presence of hydrogen could be found in the past history of gas use.

- The replacement of town gas by natural gas has initiated the first mitigation solutions for gas conversion and was the beginning of all the work on gas interchangeability.
- Later, the introduction of liquified natural gas (LNG) in Europe has induced new challenges to be solved by gas companies.
- Nowadays, with the depletion of L gas in some parts of Europe, conversion of large areas from L gas to H gas has generated new approaches to gas conversion.

More recently, some demonstration projects have focused their attention on the introduction of H_2NG mixture or on the use of pure hydrogen in gas networks. The solutions they used to guarantee the safe operation of gas appliances and the safety of users is a new source of mitigation solutions.

Technology can also bring solution to gas quality problems.

This report includes the main findings of the projects to prepare a program of tests directly related to mitigation with THyGA WP5's activities, based on

- A review of existing solutions used in the industry and in the residential sector was carried out.
- An analysis of recent patents on hydrogen admixture use in residential and commercial gas appliances was also carried out.
- a survey sent to manufacturer to help prioritizing on the mitigation solutions most relevant for stakeholders.

1. Advisory Panel group's priorities

The THyGA project designed a survey sent to the advisory panel group in August 2021 (M21) in order to get the manufacturer or expert's sensibilities on the topic of mitigation (knowledge, feelings about needed investigation, proposal of test prioritization).

The objective was to get a first evaluation of the identified mitigation issues and technological answers proposed in this deliverable, as well as stakeholders' thoughts about test priorities.

The survey has been constructed on the identified points of attention or problems from THyGA's first works ([1][3][4]) and WP5's first technologies identification from this report. The results have been gathered and main take-over are summarized in this chapter 1, on the basis of the 15 feedbacks gathered (mainly from manufacturers, which were the primary target of the survey), more details being disclosed in Appendix 1. **The results are to be used as guidelines, rather than actual generalized opinions since for some types of technologies, too few answers were gathered for statistical evidence**.

Fuel cells were out of the scope of the survey due to its many specificities, a specific meeting will be scheduled with association CogenEurope and manufacturers.

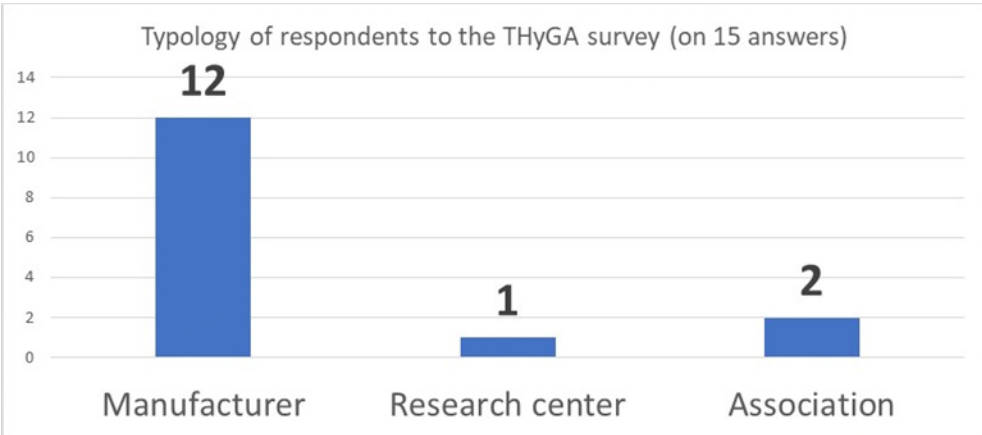


Figure 1: Respondent to the THyGA survey (November 2021)

<u>Expected impact of H_2NG blend that we should focus on primarily</u>

Mitigation can cover different meanings according to the priorities behind: for example, it possible to classify at the same level of priorities safety and comfort risks (we try to solve both problems at the same time), or emphasis could be put on aspects that could block commercialization or deployment, in our case safety.

Table 1 summarizes the main issues with H_2NG blends that should be the subject of thoughts about mitigation from the stakeholders' point of view, the proposals were mainly identified through CEN TC58 risk analysis[1]. Globally, the proposals of prioritization of issues with H_2NG blends match the conclusions from previous THyGA analysis (D2.5 and D3.6),

[1] For the time being, the document has no number. It is referenced prTR XXXX in the WG5 of TC58.

- **Adjustment** is listed as the priority for most premix-based types of technologies, it is directly linked to the incorrect determination of excess air during burning phase. CO formation for fully premix burner is in consequence related to the field adjustment from a situation with hydrogen and an operation without hydrogen (adjustment G, in THyGA WP3 protocol [2]). For partially premix appliances, “field adjustment” generally refers to a pressure inlet value to be adjusted and generate no further risk due to leaner conditions and a smaller thermal load (for cooking appliances), for appliances which do not use a gas pressure regulator.
- **Lightback** is also identified as the major impact that should be looked into, for all technologies/
- **Overheating of components** is seen as problematic, especially for boilers/water heaters and infrared or air heaters. The phenomena could be especially seen at minimal load for partially premix appliances.
- **Delayed ignition** is seen as a risk mainly for boilers and water heaters
- **Performances of the appliances** is one of the most feared factors for all appliances except for premix and partially premix boilers and water heaters, since most test showed that the load would decrease by close to 5% which is deemed acceptable for these types of appliances.

Table 1: Expected issues with H_2NG blends, that should be worked on primarily (THyGA survey, November 2021)

	Boiler / water heaters (premix)	Boiler / water heaters (partially premix)	Engine CHP & GHP	Ad- and Absorption Heat Pumps	Cooking & catering	Space heaters	Infrared radiant and air heaters
Light back detection	👎						
Light back to the injector	👎👎						
Incorrect determination of excess air during burning phase							
Overheating of the components							
CO formation due to incomplete combustion							
Delayed ignition with noise generation or non-volatile lock-out							
Delayed ignition with pulsation							
Flame flashback into the gas supply line							
Gas line leakage							
Higher NOx emissions							
Field adjustment with fluctuating H_2 content (overload due to reduction of H_2 content etc.)							
Appliance behaviour at maximum power							
Appliance behaviour at minimum power							
Appliance performance							

Legend: Main issues **from 0 to 20%H_2 (no icon)**, from **20 to 40%H_2 (👎)**, **from 40 to 60%H_2 (👎👎)**

The survey highlights some specific differences for engines (Gas Heat Pumps and Internal Combustion Engines), notably on emission (CO and NOx) but also the air/excess determination, it needs to be pondered by the low number of answers on the topic (3) and also some statements about CHP not facing issues below 20%H_2.

Above 20%H_2, the most vulnerable operating conditions might be the unsteady processes like ignition or turn-off, which could necessitate significant changes to the combustion system. Cooking appliances manufacturers expect many problems above 30%H_2, going higher would be only realistic through total conversion or modification of appliances.

Some other elements specific to cooking appliances:

- Gas blend density impacting solenoid modulating valves. Dedicated setting probably needed.
- Some feedbacks highlight the risk of the burner coming noisier (higher flame velocity with hydrogen injection), which would result in new injector (profiles) design.

Identification of relevant mitigation strategies

Stakeholders prioritized several mitigation strategies proposed by WP5 according to the different types of appliances, as highlighted in Table 2 (details of the answers are available in Appendix 1). The comments highlight that mitigation measures will probably not be needed below 20%H_2, sensors like measurement of the H_2 content or specifically designed injectors would be an added value, allowing to compensate boiler load deviation, for example but they are not compulsory at this stage.

Table 2: identification of relevant H2NG blends mitigation strategies (THyGA survey, November 2021)

	Boiler / water heaters (premix)	Boiler / water heaters (partially premix)	Engine CHP & GHP	Ad- and Absorption Heat Pumps	Cooking & catering	Space heaters	Infrared radiant and air heaters
Mechanical: Action on grid pressure							
Mechanical: Conversion kit (injectors, diaphragms....)		👎				👎	👎
Software: Dynamic adjustment of the gas quality							
Software update (increase of minimum heating power,)							
Combustion control technology							
Sensor on pre-combustion: Gas quality			👎				
Sensor on pre-combustion: H_2		👎				👎	
Sensor on combustion: ionization probe							
Sensor on combustion: O_2 probe							
Sensor on combustion: UV sensor							
Other type of sensor: Vibration							
Other type of sensor: Burner T°C							
Burner design: smaller/deeper ports	👎	👎		👎👎	👎		👎
Burner design: new materials (higher temperature tolerance)					👎		

Feedback - Burner design: other technology (porous....)							
Primary/secondary air distribution change					👎		
Flame type change (switch from partially to fully premixed)							
Flue gas recirculation							

Legend: Main issues **from 0 to 20%H_2**, from **20 to 40%H_2 (👎)**, **from 40 to 60%H_2 (👎👎)**

For condensing appliances, the water condensing rate from the exhaust will be higher with H_2 percentages rising, which could involve small changes in the design of the heat exchanger.

For CHP and GHP, the Table 2 does not exactly reflect that several answers deemed equally several approached based on pre-combustion measurements (gas quality, H_2 sensor) were as relevant solutions as combustion control approaches based on ionization probe or O_2 sensor.

For cooking and catering appliances, as expected the technological possibilities are limited and mitigation strategies are mainly based on conversion kit (change of injectors etc.) or work on the design of the gas line (Primary/secondary air distribution, materials or conception of the injectors/burners). An interesting comment on smaller flame ports being an adopted option in burner design states that it could also result in more pressure losses. Therefore, some partially premixed combustion systems might turn into powered premix devices (and combustion could be a new generated issue).

<u>**Perspectives for testing**</u>

Most respondents declared that the mitigation work should focus on the 0-20%H_2 range, since it is deemed unlikely that injection rate would go higher on the field. Also, regarding existing appliances, focus should be put on less than 10-year-old installed systems.

- The most feasible actions involve the adjustment of the gas flow in the valve or the increase of the minimal load of appliances, other actions (like new sensors, combustion control introduction or new burner) would lead to a focused development on an old product, difficult to manage.
- Generally, combustion control is seen as a key element to properly work with H_2NG blend, technologies are usually based on feedbacks from an ionization probe, which could prove problematic at higher H_2% content as highlighted in D2.5 [2]. The ionization behaviour with H_2 could be investigated to understand when other sensors have to be introduced (example: O_2 sensor), while a pre-combustion analysis (H_2 sensor) could provide additional info to better perform.
- Burner design/optimization would be good start for high hydrogen burner design. Quenching distance for fuel/air mixtures should be considered.
- A proposal is to work on diaphragms or electronic settings or additional safety interlocks to prevent wrong adjustment on the field, add sensors (i.e.: UV sensor) for proper flame detection.

Note: a respondent reported that some studies indicated that hydrogen embrittlement / decarburization could affect materials at high temperature.

Regarding the parameters better suited to evaluate or compare impacts of mitigation strategies, respondents highlighted the importance of the percentage of hydrogen itself, since it will be very likely to vary during time, it is therefore important to understand the answer of mitigation strategies to fix or dynamic percentages of hydrogen. Compatibility of the approaches with emission regulation is also important since it can involve O_2, CO_2 corrections while impacting heat production and efficiency.

Focus on adjustment

As seen in previous THyGA documents, on field adjustment is critical, especially because the gas quality or the H_2 content in the natural gas is not known. Several options are proposed by stakeholders:

- A radical option is to forbid on-field adjustment and keep the appliance set as the manufacturer decide to do. A default gas quality could be decided, such as G20 for H gas if design lambda has been set using NG plus H_2.
- Some manufacturers think that, since, currently, the %H_2 is not known and could vary in time, the best is to avoid having to correct the combustion parameters and combustion controls is one of the best technology available.
- A complexity can arise from the differences in control from gas appliances, some are using constant heating load control, some are Wobbe Index dependent, some are using constant volume flowrate control. Pre-combustion sensors, especially H_2 sensor, should also be adopted to double check on the hydrogen percentage.
- Regarding the installer, some proposals were issued to help him with in-field actions.
    - Since O_2% is a key parameter, it is important that the flue gas analysers are able to provide this measurement, instead of the CO_2%. The majority of the current gas analysers in the market already have this possibility. However, they may need to evolve since the increase of water content in the flue gases could impact the measurement.
    - Some respondents highlight that a more radical change is needed and that the relevant indicator for adjustment is rather the gas quality, especially H_2 content, sensing on site (e.g., with mobile gas quality sensing equipment) or retrievability of gas quality information at upstream gas network points through public portal, for example. If the installer knows the Wobbe index range, he could be able to choose an intermediate setting thus to allow a proper operation. However, the drawback is that the % of H_2 would probably not be fixed but variable.

Engine CHP can be adjusted correctly by adopting the RPM, up to 20%H_2.

For cooking appliances with surface burners, the adjustment can be made visually while paying attention to the flame, but it does not cover the change of gas composition in time

2. Projects related to gas change and mitigation measures

2.1 First gas conversion: from town gas to natural gas

Before natural gas was discovered, the distributed gas was a syngas produced from incomplete combustion of coal: the town gas. It was mainly composed of methane, hydrogen, and carbon monoxide.

In the mid-20th century, the discovery of the cleaner and cheaper natural gas in the underground of France and in Algeria has initiated the switch from town gas to natural gas. In France for example, this conversion has started in 1961 and ended in 1978 (17 years).

As town gas and natural gas have very different combustion characteristics, it was necessary to adapt gas infrastructures and appliances in order to "convert" them.

The main challenges gas companies were facing were:

1. A higher heating value for the gas. Thus, solutions were required to prevent burners from overheating.
2. A higher stoichiometric air requirement. Thus, solutions were also required to avoid incomplete combustion, and in particular, the production of CO and soot.

For the first problem, the most straightforward solutions were:

1. The reforming of the natural gas in order to produce a syngas whose characteristics were close to those of town gas [5].
2. To convert town gas appliances to natural gas through modifications of injector diameter and burner port size.

To complement the second approach, it was decided to *increase the gas delivery pressure up to 20 mbar and to reduce the injector diameters in order to have more primary air dragged by the gas* (in combination with an increase of the port holes of burners) and to increase the size of the flame ports by 55% for the Lacq gas and 100% for the Groningen gas [6].

For compatible appliances, a simple adjustment/conversion was operated during the period when town gas was switched to natural gas. For other appliances, in order to reduce costs, a conversion to "bi-gas" appliances was favoured (in France, the conversion process was spread over 17 years).

For appliances not designed to be compatible with conversion, the work was carried out in two steps [5]:

- Pre-conversion (preliminary work to make the device suitable for all gases). The device was collected at the user's home (a replacement device was temporarily provided), labelled and then brought to a pre-conversion workshop where the necessary operations were carried out: cleaning, re-drilling of the flame orifice sections, installation of an air adjustment screw, fitting an injector holder that can receive either the town gas or richer natural gas injector, checking the 'rich gas' operation, replacing the town gas injectors and adjusting the gas city. The "rich gas" injectors were stored in bags by the workshop and classified until natural gas was injected in the grid. The device was then returned to the customer.
- The conversion: installation of the injectors for natural gas kept by the workshop during the gas filling of the zone using. The conversion was done at home. The operation within one area was to last no more than three days.

Later, **LNG imported from Algeria arrived in Europe**. During the transportation process, a change occurred to natural gas: there was a preferential evaporation of nitrogen. Thus, when this gas arrived in France, it caused uncomplete combustion problems on some appliances.

Several solutions were explored:

- (1) A specific conversion of appliances to this gas (costly)
- A standard conversion of these appliances to natural gas but:
  - (2) With a pressure decrease from 20 mbar to 18 mbar in the distribution network.
  - (3) Addition of 4% of air to the gas to decrease its heating power

The latter solution (to adjust gas composition) was chosen.

This leads to a new question:

- *Is it possible to adjust gas composition of H_2NG mixtures in order to reduce its impact on appliances?*
- *Does an increase of gas pressure could compensate for H_2 impact?*

2.1.1 Addition of other gases to H_2NG mixtures

In the past, when new gases were introduced in Europe, some gas companies had chosen to adjust the gases compositions to reduce their impact on appliances.

It was the case, for example [7]:

- When LNG gas from Algeria was first imported in France. 4% of air was added in order to prevent uncomplete combustion problems.
- In 1968, at the opening of the LNG terminal of Fos sur Mer, in France. Several solutions were explored to reduce the heating value of the gas: removal of heavy hydrocarbons such as propane and butane, addition of air, mixing gas with CO/H_2 gas or mixing gas with N_2. The last option was used.
- In 1967, in the north of France, the option of removing N_2 from the Groningen gas in order to transform it into H gas was also used to feed the Paris zone.
- Nowadays, a L+ gas is distributed in the North of France. It is a mixture of L gas coming from Groningen and H gas.

This "gas transformation" approach leads to the question: would it be possible to mitigate effects of hydrogen addition by mixing H_2NG to some inert or fuel gases?

The impact of adding 10% of a fuel or an inert gas to hydrogen/methane mixture is presented Table 3. Gases considered here are gases already used previously by gas companies, or at least, projects considered (butane, propane, air, nitrogen), but also gases that might be available on a hydrogen production site, such as O_2 or CO_2. According to this table,

- it is possible to compensate the increase of the laminar flame velocity (S_L) induced by hydrogen[2] with the addition of an inert gas (CO_2, N_2). However, adding inert gases decrease the Wobbe index (Ws).
- Adding higher hydrocarbon fuel gases, such as propane or butane could compensate for the decrease of heating power of hydrogen. However, these gases tend to increase the laminar

[2] See ThyGA report D2.2 "Impact of hydrogen admixture on combustion processes – Part I: Theory"

flame velocity. Moreover, there is a second inconvenient to adding butane or propane: unless bio-propane or bio-butane (produced from vegetal oil and industrial waste) are used, adding these gases to H_2NG will increase CO_2 emissions.

- Adding air or oxygen do not have any positive impact on flame velocity or Wobbe Index.

From Table 3 data, it can be said that it is not possible to compensate for hydrogen impact with another gas because they only have a positive impact on ONE parameter between the Wobbe Index (Ws) and the laminar flame velocity (S_L) but negative impacts on other parameters. Fuel gases compensate on the Wobbe Index, while inert gases compensate on the flame speed.

Table 3 : impact of adding 10% of a fuel/inert component to methane (green=compensate hydrogen, orange=same effect as hydrogen).

Gas/Impact		Ws	HHV	Lambda	S_L (Lambda=1)	Tad
CH_4+10%	H_2	-2,4%	-6,8%	3,3%	6,5%	0,2%
CH_4+10%	C_2H_6	3,2%	7,6%	-2,9%	1,5%	0,3%
CH_4+10%	C_3H_8	6,2%	15,2%	-5,8%	7,4%	0,4%
CH_4+10%	Air	-13,4%	-10,0%	22,3%	0,0%	0,0%
CH_4+10%	N_2	-13,2%	-10,0%	11,7%	-3,1%	-0,6%
CH_4+10%	CO_2	-17,0%	-10,0%	20,6%	-7,7%	-1,1%
CH_4+10%	O_2	-14,2%	-10,0%	23,3%	12,4%	2,2%

One could argue that the change of gas composition can also induce a shift in the air/fuel ratio that could help mitigate hydrogen impact. Figure 2 shows how flame velocity is increased by adding hydrogen and hydrogen/propane mixture to methane, at a constant air excess. In that case, adding heavier fuel gas increases flame velocity.

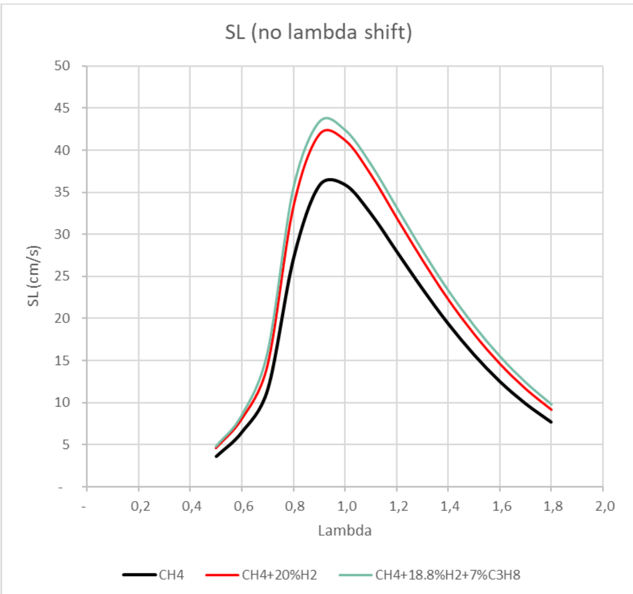


Figure 2: laminar velocity of methane, methane+20%H_2 and (methane+20%H_2) +7% propane.

However, in gas appliances without combustion control, this change is coupled to a **modification of air excess** (increase for H_2, decrease for C_3H_8). This change is taken into account in Figure 3. On this figure, the initial lambda for CH_4 is represented in abscissa. The flame speed corresponding to other gases is, then, read by following the constant lambda line. For example, if Lambda=1.2 for CH_4, using CH_4+20%H_2 mixture does not change the effective flame velocity but using $CH_4+H_2+C_3H_8$ mixture increases flame velocity from 27 cm/s to 33 cm/s.

What Figure 3 shows is:

- Changing methane to CH_4+20%H_2 mixture does not significantly change flame speed for fully premixed appliances without combustion control (Lambda>1.2) but has a strong impact for partially premixed appliances.
- Adding C_3H_8 to the methane/hydrogen can mitigate the impact of H_2 on partially premixed appliances thanks to the shift of air/fuel ratio in the opposite direction of the one generated by H_2 addition.
- On the other side, adding C_3H_8 to the methane/hydrogen mixture increases flame speed for fully premixed appliances.

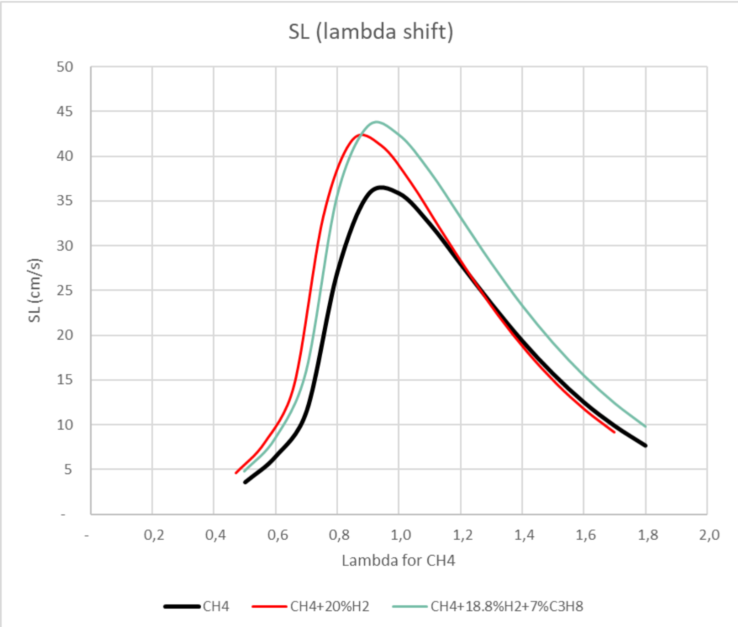


Figure 3: laminar velocity of methane, methane+20%H_2 and (methane+20%H_2) +7% propane, taking into account lambda evolution (initial=methane/air flame).

<u>*Conclusions:*</u> *Once again, positive effects of gas addition are compensated by negative effects, depending on which side of stoichiometry the flame is. Thus, addition of a "compensating" gas to H_2NG could not be a universal solution to mitigate the impact of H_2 to natural gas.*

2.1.2 Pressure increase

In the past, the delivery pressure of gases was changed to accommodate for new gases.

- When town gas was replaced by natural gas, gas pressure was raised from 8 to 20 mbar.
- When LNG gas was introduced, it was considered to reduce gas pressure from 20 to 18 mbar.
- In some European countries, H gas and L gas are delivered (respectively) at 20 mbar and 25 mbar.

The change of pressure can compensate for the decrease of the Wobbe Index, because gas flowrate is proportional to the square root of the relative pressure.

$$Q_{gas} = \mathrm{a}\sqrt{\frac{\mathbf{2}\,\boldsymbol{\Delta P}}{\boldsymbol{\rho_{air}}}}.\frac{\mathbf{1}}{\sqrt{\boldsymbol{d}}}$$

Where:

- ΔP is the relative pressure of the gas
- Q_{gas} is the volumetric gas flowrate
- a is the area of the injector
- ρ_{air} is the mass density of air
- d is the relative density of the gas

Supposing the %H_2 in gas is constant, the pressure increase required for several hydrogen concentration is given in Table 4.

Table 4: Pressure compensation required for the decrease of the Wobbe Index for H_2NG admixtures.

%H2 in G20	Ws kWh/m3	Pressure delivery to compensate for heating power decrease detaP (mbar)
0%	14,09	20
2%	14,02	20
6%	13,88	21
10%	13,75	21
20%	13,40	22
40%	12,73	25
60%	12,11	27
80%	11,76	29
100%	12,70	25

During the previous gas adaptation projects mentioned above, the size of the injector was also usually adapted to the new gas. By applying gas momentum conservation to the exit of an injector, it can be demonstrated that the air/gas ratio after a gas injector is proportional to the ratio of air/gas sections A/a.

$$r = \frac{Q_{air}}{Q_{gas}} = \sqrt{\frac{\boldsymbol{\rho_{gas}}}{\boldsymbol{\rho_{air}}}}.\frac{\boldsymbol{A}}{\boldsymbol{a}}$$

Where:

- Q_{air} is the air flowrate
- Q_{gas} is the gas flowrate
- A is the area of air pipe
- a is the area of the gas injector

<u>Conclusions</u>: changing gas pressure can compensate for the decrease of the Wobbe Index, but the diameter of the gas injector has also to be changed in order to adapt both gas flowrate and air/fuel ratio.

This is what is done on some appliances when, for example, gas family or category is changed. It was also the first conversion operation performed when natural gas replaced town gas.

2.2 Tulipe project – L to H gas conversion of the north of France

Natural gases consumed in France are imported from various producing countries such as Russia, Norway, Algeria, Egypt… Most of them are H gas but historically, the north of France is still supplied with L gas coming from the Netherland: the "Groningen gas". However, as the production from this source reaches its end, gas operators are currently converting this remaining L gas network to H gas.

The Tulipe project, conversion from L to H gas, started in 2014, a few years before the beginning the first tests of network conversion in late 2017. The end of this project is planned for 2029 (12 years long).

The first task of the project was to define a safe and reliable conversion procedure from L (25 mbar) gas to H (20 mbar) gas. The main problem to be solved is the intermediate phase between the change of the pressure regulator (25 → 20 mbar) and the moment the gas is switched from L to H in the network.

1. The first option, which consists in **injecting H gas first** and then **replace pressure regulators afterwards** was quickly rejected due to the risks of overheating of appliances as well as a high risk of CO emissions.
2. The second option, which consists in **changing pressure regulators**, **switch off appliances**, **switch gas from L to H** and then **switch on appliances** again after converting them in the safer approach, but has to be avoided as much as possible to avoid leaving users without heating or cooking appliance.
3. The third option, which consists in a **change of pressure regulator, while still in L gas, without switching off appliances, if possible,** was chosen. This approach can work on certain appliances, not on others. As a consequence, several meetings with manufacturers and some lab tests were performed to classify appliances by segments.

The conversion procedure was lab-tested on a panel of selected and representative appliances used in France:

- Atmospheric burner
- First generation of condensing boiler
- Modern premixed condensing boiler
- Water heater
- Some catering equipment

Extra pressure tests were also performed at 17mbar (L gas) and 14 mbar (H gas).

These tests confirmed that **no universal conversion procedure could be used, that the market needed to be segmented,** and conversion procedure has to be adapted to each segment:

- **Segment 1:** no adjustment necessary on the device, the change of pressure regulator at the installation inlet is sufficient.

- **Segment 2:** an adjustment (with or without changing parts) is necessary and it is carried out upstream of the arrival of the H gas, without requiring any new intervention once the H gases are present.
    - Segment 2a: an adjustment is necessary (with or without changing parts), but it requires 2 operations, one before changing the gas, and a second one to refine the adjustment once the H gas is present.
- **Segment 3:** the device cannot be adjusted before the arrival of the H gas, and it must be switched off before the arrival of the H gas. When H gas is injected into gas network, the appliance is put back into service and adjusted.
- **Segment 4:** the device cannot operate with H gas, and it must be replaced before changing the gas.
- **Segment 5:** B_{11} devices, but non-BS (no safety system to prevent burnt gases from flowing back into the room).

Based on their knowledge of their products, manufacturers were able to classify all of their appliances in one of the previously defined segments, to write the conversion procedure and identify parts required to do it if necessary. For orphan appliances (where the manufacturer no longer exists), the category of appliance, according to EN gas standards, the publication of the Gas Appliance Directive, as well as the manufacture year, helped choosing the adapted segment.

On the field, the conversion required several visits per customer:

1. all gas appliances needed to be identified (kind of appliance, manufacturer, model, gas category, serial number),
2. if necessary, appliances were converted or stopped between pressure regulator change and H gas injection.
3. Some appliances were checked or put back in operation after H gas injection in the network.

Note: nowadays, gas customers can also perform the inventory of their gas appliances by themselves [8]. This helps to reduce the number of visits.

For non-compatible appliances, the mitigation measure was to replace them. For appliances that could cause safety issues, such as non-BS B_{11} boilers, CO detectors were installed in order to prevent CO intoxications.

Although the described procedure is quite interesting and could prefigure some kind of NG to H_2NG conversion, the situation of L to H conversion is quite different from the injection of H_2 into gas networks since gas appliances are certified for L and H groups.

Although hydrogen admixtures could be in the defined Ws range of H gas, they have characteristics that are different from natural gases. EN standards have to be adapted to this new gas mixture[3]. For current appliances, a decision has to be taken on their treatment regarding H_2NG.

<u>Conclusions</u>: the methodology used for L to H conversion cannot be fully used as it is, it requires to be updated with points specific to H_2NG admixtures.

[3] See ThyGA report D4.1 "Overview of current standardization and certification framework"

2.3 US experience

Although, strictly speaking, it is not a conversion project, California Energy Commissions has missioned the Gas Technology Institute and the Lawrence Berkeley National Laboratory to check the impact of introducing Liquefied Natural Gas (LNG) in California [9].

The goal of their study was to measure the effect of gas quality variability on pollutant emissions:

- From new and used common appliances.
- In lab conditions, but also in homes.
- During steady state operations.
- During operating cycles that start with ignition and include transient periods when the burner is not fully warmed.

They have tested 13 cooktop burners, 12 oven bottom burners, 5 broilers, 5 storage water heaters, 6 tankless water heaters, 4 central forced air furnaces, one wall furnace. New appliances were bought from the market while used appliances were bought through a second-hand sale website (craiglist.org).

Residential experiments were conducted on home appliances as they were installed in user's home. Home appliances tested were:

- boilers,
- storage water heaters,
- tankless water heaters,
- one cooktop

For field-testing, the installation was modified temporarily to allow connection of test gas bottles and a gas meter between the local shut-off valve and the appliance. When possible, a pressure sensor was connected to the burner side of the pressure regulator of the appliance (this was only possible for water heaters and furnaces, but not for cooking appliances). For cooking appliances, a careful cleaning was operated in order to avoid dirt from perturbating measurements. This was especially important due to the measurement of pollutants sensible to dirt (ultrafine particles). The document [9] details the cleaning procedure.

For most appliances tested in situ, installation/removal of equipment and tests were performed within a day. Specific burner operating cycles were developed with the objective of capturing key features of realistic use patterns with a total cycle time that would allow completion of three to four experiments—with setup and calibration—in a single day. During day-long experiments, it took about 1.5 to 2 hours to perform tests and 1 to 1.5 hour to remove the experimental appliances.

Data collected from these experiments included:

- Fuel composition obtained by analysis of collected fuel sample(s).
- Fuel supply parameters (pressure, pressure at appliance inlet and volumetric fuel flowrates).
- Ambient and combustion air temperature (T) and relative humidity (RH).
- Sampling system conditions, including exhaust air temperature at the point of pollutant sampling.
- Time-resolved concentrations of exhaust constituents (O_2, CO_2, CO, NO, NO_X, NO_2, and particle numbers) measured during periods of burner operation and background periods.
- Performance for cooking appliances.

<u>Conclusions:</u> This study shows that testing appliances on site could be a way to check safety of operation for high amounts of H_2 in natural gas/hydrogen admixtures. However, the experiments performed by

the GTI/LBNL shows that it is time consuming: about a day per appliance. With this method, on site testing of appliances may only be possible for a selection of appliances carefully chosen: the most sold, the one where problems could be expected…

2.4 Interchangeability method

At first, interchangeability methods were based on numerous indices such a Wobbe Index, Combustion potential, yellow flame tip index, sooting number… Nowadays, only Wobbe index is used. However, hydrogen addition to natural gas may require introducing a second dimension to interchangeability numbers in order to prepare for H_2NG. As the main characteristic of hydrogen is a higher laminar flame velocity, this new index could be flame velocity, %H_2 or combustion potential, for example.

This chapter gives an overview of interchangeability indices and how they were used in the past to adapt to the introduction of new gases.

2.4.1 Interchangeability indices

The switch from town gas to natural gas in the 60's initiated a new area of research for gas companies: interchangeability. A set of new indices was established to compare the impact of fuel gases on the behaviour of gas appliances.

In France, the Delbourg interchangeability method was mainly based on two indices:

- The well-known **Wobbe index** which was linked to the heating power of the appliance. However, instead of using the standard superior Wobbe index (Ws), a "refined" calculation method was used: the Wobbe index was corrected by experimental correlations.
- The **combustion potential** (C) which was closely related to maximum flame velocity:

$$C = \frac{H2 + 0.3\,CH4 + 0.6\,CO + 0.3\,C_nH_m}{\sqrt{d}}$$

Two empirical secondary indices were also introduced, the yellow tip index and the sooting index. These indices were mainly designed to characterize an incomplete combustion.

It is interesting to notice that Delbourg interchangeability method was established when gas was changed from a hydrogen-rich gas and methane rich gas. Not only the heating value of these two gases is quite different but also flame velocity. This is the reason why two indices were required, representing two uncorrelated properties of fuel gases. These indices were used to build stability diagrams in order to define a safe zone of operation around the reference gas (Figure 4). Nowadays, as natural gases and LPG are dominating the gas market, the second index, combustion potential, is no longer used.

<u>Conclusions</u>: Some standardization groups, such as CEN TC238 and CEN TC109 are considering the re-introduction of a second index to classify methane/hydrogen mixtures. For the moment, the %H_2 seems to be the index of choice. However, the question of the second index should be still open: %H_2, maximum laminar velocity, combustion potential? Is it possible to use them to establish new interchangeability limits or delivery gas specifications?

2.4.2 Interchangeability limits

When the Lacq gas was introduced in France, it was necessary to create interchangeability indices, limits and test gases. So, the next step after having chosen interchangeability indices was to set up interchangeability limits.

First of all, a sampling of appliances was established, i.e., appliances chosen among the most representative ones. This operation was delicate because the sample had to represent both old appliances still in service on the gas distribution networks and modern ones.

Selected appliances were collected in a laboratory and set to operate with a reference gas and, afterwards, supplied with gases of varying chemical compositions. After repeating the operation with a sufficient number of gases, all points were reported on a (Ws, C) diagram in order to delimit the area in which the operation of all the selected devices remains satisfactory (Figure 4).

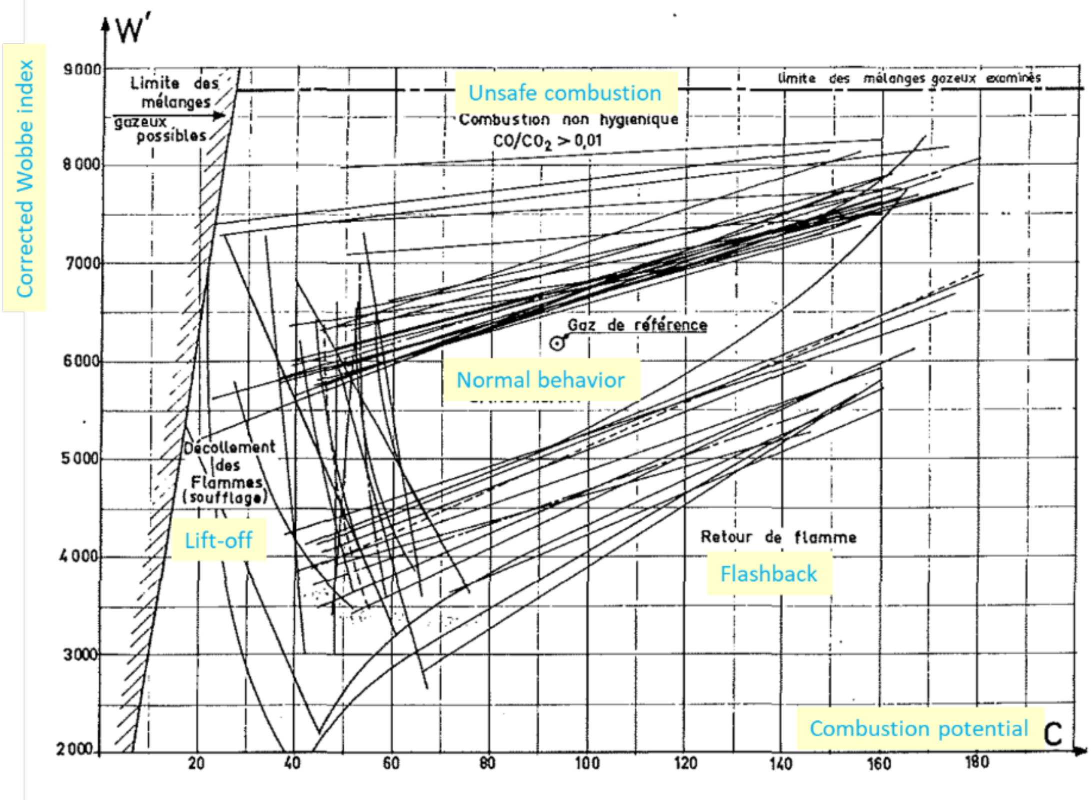


Figure 4: Interchangeability limits for several gas appliances adjusted for 1st family gases (source: [6])

In the case of the Lacq gas, a set of 24 appliances was tested [7]:

- 8 cooking appliances
- 8 water heaters
- 8 heating appliances

After stability limits were established, they were corrected to take into account several return of information from the field [7].

- The first point is in relation to user comfort. It was considered that when a gas changes from Gas 1 to Gas 2, the **decrease of the heating power should not be more than 5%** in general (0.95xWs of the reference Lacq gas), and **10% maximum** (0.9xWs of Lacq gas) **for a few days during the peak of the heating season**. These limits were added on the stability diagram.

- Another limit was added later because, **when delivery pressure was over 20 mbar**, some hot water generators were emitting dangerous levels of CO. At that time (1963), **it was considered that delivery pressure could vary by ±10% at the delivery point**. This limitation was taken into account in the stability diagram and **test pressure raised to 22 mbar**.
- A third correction of the diagram was performed after an air/propane mixture was introduced in the gas network in replacement of the Lacq gas causing either the **appearance of yellow tip flames** (uncomplete combustion) or **flashback** when the burner was adjusted to avoid yellow tip flames.

<u>Conclusion</u>: Although it requires lots of lab testing, this method could be of interest to establish the limits for the proportion of hydrogen that appliances are able to tolerate, but also to establish mixing rules for H_2NG that could satisfy both gas producers and appliance manufacturers.

2.5 Gas quality recommendations / ranges

In Europe, most, if not all, transport gas grids of neighbour countries are inter-connected at their frontiers. Thus, good practices for gas transport have been agreed at European levels (EASEE-gas, ENTSOG). CEN has published a reference standard for gas quality (EN 16726 [10]) but without specifying any Wobbe Index range or including hydrogen-natural gas mixtures.

As a complement, each European country has declared to the European Union, the Wobbe Index range of natural gases used in its networks [11]. This declared range is often quite large and sometimes has values outside the H gas category defined in standard EN 437 [12] for tests gases/pressures (Figure 5).

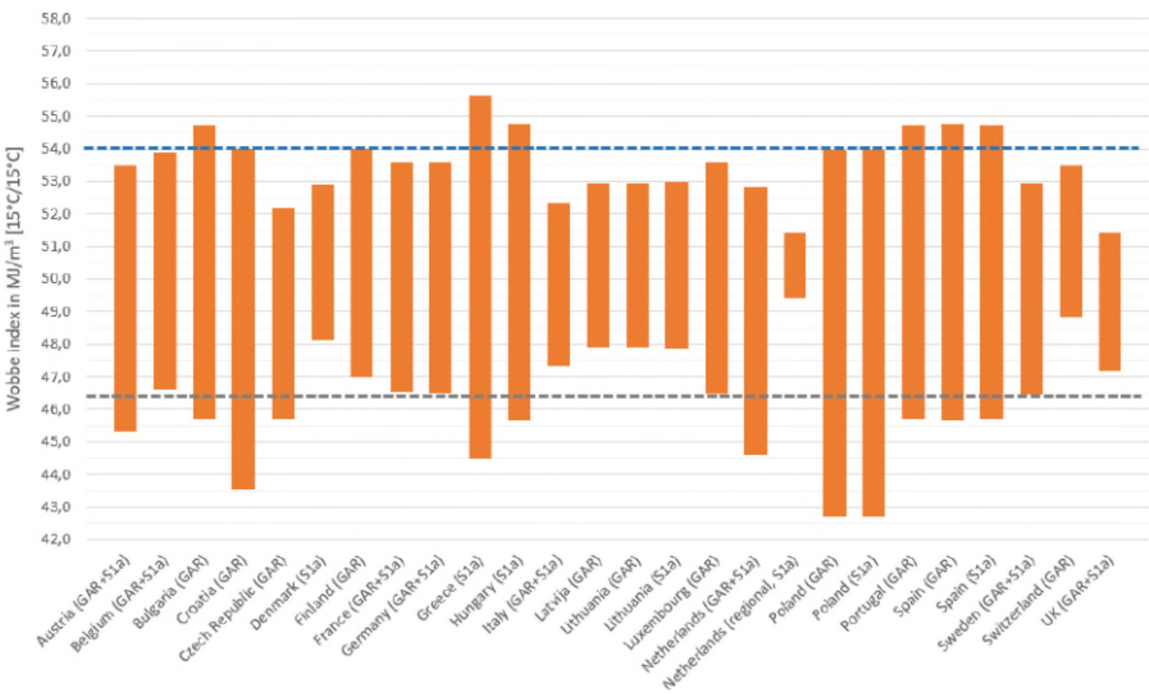


Figure 5: Wobbe Index range declared by European Countries (source:[11]).

Recently, CEN Sector Forum Gas has underlined the tendency of gas operator to increase the Wobbe Index range used in their networks due to LNG importations and biomethane production [11]. They have also underlined the requirement of industrial gas users and gas appliance manufacturer to keep the Wobbe Index range in a narrow band in order to optimize the performance of their appliances/process.

Based on statistical studies on gas quality in Europe, CEN Sector Forum Gas has very recently (2021) published a recommendation concerning gas quality:

- To limit **WI range at entry points** between 46.44 MJ/m3 and 54 MJ/m3 (15°C/15°C) (WI range of 7,6 MJ/m3).
- To define a **WI range at exit points**:
  - Specified class with a WI range of 3.7 MJ/m3
  - Extended class for other situations
- The maximum allowable hydrogen concentration is defined by the lower WI limit of the class assigned to the impacted exit point

Note: EN 437 category of gas H has a WI range of 9.0.

If the WI range at entry points is higher than the WI range at exit points, mitigation measures to reduce WI range have to be taken, such as gas stripping or gas blending, as it was done in the past.

It could be of interest to study how these mitigation measures impact the behaviour of gas appliances for blending with nitrogen, air, ethane or propane. These gases can bring back WI range within requirements but have impacts on other parameters such as laminar flame velocity, CARI (combustion air ratio index)… and could have some negative impact on gas appliances that should be anticipated.

2.6 Conclusion learned from gas conversion

The main teachings we can learn from procedure used to convert appliances from town gas to natural gas is "*the earlier compatible appliances are put on the market; the cheaper and more efficient conversion will be*". So, the quick elaboration and publication of EN standards that include H_2NG testing is of uttermost importance.

With the disappearance of public national gas companies, it is nowadays unthinkable to go and pick appliances in customer's homes in order to prepare them in a dedicated workshop (re-drill holes without certifying them) for conversion and then convert them the day a new gas will come. The technique consisting in performing an inventory of appliances and work with manufacturers to validate their compatibility and/or changes to perform on appliances in order to make them compatible with a new gas seems the best approach. This will probably be one of the most complex challenges for the conversion/validation of existing appliances for H_2NG.

It should be also noted that the main difference between L gas → H gas conversion and NG → H_2NG conversion is that, for the L to H conversion, all appliances were compatible with the final state (or not, but at least, it was clearly identified) since they were all certified for use with H gas. **In the case of hydrogen injection in the gas network, the situation is more complex.**

In situ testing of appliances to check safety with fuels they were not certified for is an option, but it has been showed that it is time consuming. Although it could prove necessary, not all appliances can be tested that way and a careful choice of appliances to be tested is required.

An alternative option could be to build a database of appliances compatible with H_2NG (most probably 20%H_2) and perform tests of the other ones with limit gases that leave a certain safety margin to take into account production dispersion, pressure variations and wear of appliances.

3. H_2NG demonstration projects

3.1 AMELAND

Between year 2008 and 2011, the “Sustainable Ameland” project demonstrated the feasibility of injecting up to 20% H_2 into a small gas grid [13]. Natural gas used was Groningen natural gas (L gas). A small network feeding an apartment complex of 14 families was used.

Before injection began, several components of gas network were tested: pipes, joints, regulators, gas meters, boilers and cooking devices. Gas appliances were not designed specifically for the project. They were stock appliances which were tested with natural gas/hydrogen mixtures up to 30% H_2 in order to have a safety margin in case of an overshoot of the mixing unit. Gas grid and domestic gas installations were subjected to an extensive maintenance and inspection programme. The apartments were equipped with safety sensors for detection of gas leakages and carbon monoxide.

<u>Note:</u> *It was not specified in the document* [13] *whether boilers were field-adjusted or if factory settings were kept.*

During the initial phase of the project, hydrogen was mixed to the natural gas from 0% to 20% by steps of 5%. Afterwards, %H_2 did vary substantially.

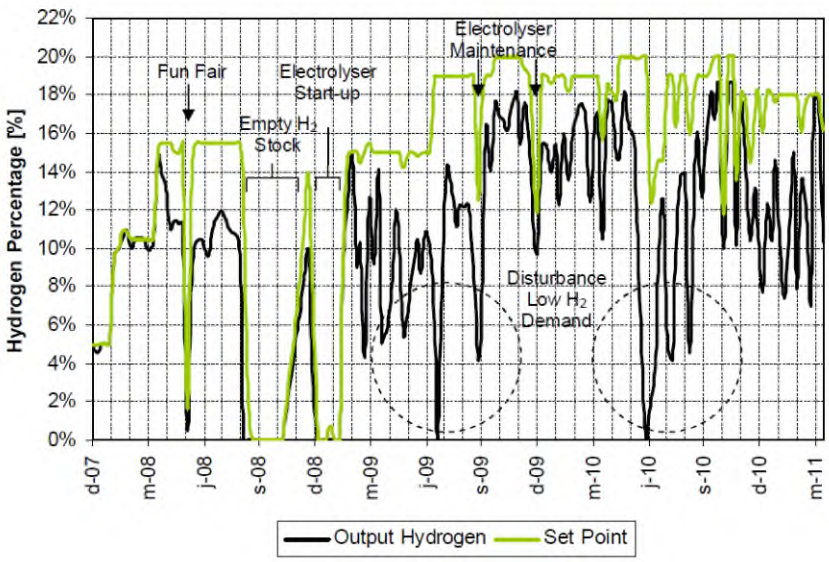


Figure 6 : hydrogen proportion in the gas during the Ameland project (source: [13])

During the four years of the project, no safety problems have occurred, thus proving that initial safety measures were well dimensioned for the project.

This project was the first to demonstrate that, for a duration of 4 years, with new and carefully tested appliances, with substantial %H_2 variation in the gas feed, it is possible to operate safely gas appliances with % H_2 up to 20% without specific modification to the appliances.

As it was the first demonstration project on H_2NG mixtures, extra safety measures were taken: apartments were equipped with safety sensors for detection of gas leakages and carbon monoxide.

3.2 GRHYD

Spiritual son of the AMELAND project, the French GRHYD project tested the injection of up to 20% H_2NG mixtures in a dedicated local network between year 2018 and year 2019. Two brands of condensing boilers and two brands of gas cooking stoves, previously tested in the laboratory, were installed in about hundred homes.

A commercial establishment equipped with two collective boilers was also supplied by natural gas / hydrogen mixtures.

Prior to injecting H_2NG mixture:

- Appliances (2 boilers and 2 gas cooking stoves) were lab tested up to 30% H_2. Boilers were marked I2Esi: they require a change of gas injectors or an adjustment when switching from H to L natural gas.
- Leakage rates of several gas components was lab-tested with helium. No leakage rate was higher than the reference of 6 l/h (defined as not critical anomaly A1 in French standard NF P 45 500)

The injection was carried out in successive stages, with rates of 6%, 10% and then 20%, then with variable levels of hydrogen, within the limit of 20%.

During hydrogen injection phases, boilers and gas cooking stoves were tested on site. A change in emissions, heating power and efficiency was measured, but no safety issue was found. In one case the cooking stove was replaced by a new one by the new tenant of the apartment.

During the two years of the project, no safety problems have occurred.

Compared to the Ameland project, all appliances were also previously lab tested with 30%H_2 and hydrogen was introduced progressively by increasing steps. The difference was in the use of extra gas leakage/CO detectors that were not required.

3.3 Hydeploy – used appliances and safety check

The HyDeploy project is a demonstration project for injecting 20% hydrogen into the gas network.

He was initiated very recently in the United Kingdom. It aims to supply 101 housing units and some tertiary buildings. As part of this project, several devices were tested in the laboratory to check their compatibility with hydrogen.

These devices have been tested with the standard gases of EN 437 as well as with a gas composed of CH_4 and 28.4% hydrogen [14]:

- **Gas fireplaces** functioned without problems. However, a slight decrease in brightness was noted. The flue gas backflow preventers were tested by obstructing the combustion products exhaust duct. The devices tested were AS type (and not BS as on boilers): they detect an oxygen deficiency in the room in order to prevent the CO level from reaching 200 ppm (in a standardized test room), during the certification process. All devices worked correctly except one. For the associated fireplace, the average CO concentration in the room was 180 ppm before the test. The authors conclude that it will be necessary to continue investigations on decorative combustion fireplaces equipped with AS-type devices.
- **Gas hobs**. Tests have shown that the temperatures of the main components of the burners remained within tolerable values not liable to cause degradation of the components.

- **Boilers**. As with gas hobs, temperatures of the main components of the burners remained within "tolerable values not liable to cause degradation of the components". The ionization currents have undergone a slight decrease without compromising the operational safety of the devices. For the minority of boilers that use the ionization probe to adjust the aeration rate (self-adapting boilers), the authors observed a slight operating drift (the same phenomenon was observed in a GERG study on self-adapting boilers [15]). The authors suggest studying how these devices work in more detail.

The authors concluded that the devices selected could operate without problems up to 28.4% hydrogen.

In the second phase of the project, **H_2NG mixture was injected in an existing gas network where existing (used) devices were installed**. This is the main difference compared to previous projects where new devices, previously lab-tested, were used. Before H_2NG was injected in the gas network, **a safety check was performed in every home** of the demonstration project [16]. Several verifications were performed:

- check of the gas network and gas appliances, to make sure they are up to current gas safety standards and appliances are operating safely with current delivered gas.
- a series of tests with a reference gas
- a second series of tests with two H_2NG at different concentrations.

Tests with reference gas and bottled H_2NG gases were used to check that gas appliances could operate properly with normal gases and H_2NG, but also to identify differences between lab test results and appliances in homes.

Gases were brought by the engineers and plugged to the home gas network after the flowmeter.

The **operation was performed by two engineers in two hours**.

Note: In comparison, in the Netherland, for a 100%H_2 demonstration project in the city of Uithoorn, STEDIN estimated that the conversion from natural gas to hydrogen, which included a safety check and change of appliance took one day per home by an installation worker [17].

3.4 Conclusion concerning demonstration projects

During the first H_2NG injection projects new appliances were used. Most of the projects aimed a maximum of 20% H_2 mixed with natural gas. Before being installed in homes, appliances were tested with a limit gas with about 30% H_2 in case there is a mixing overshoot.

In all cases, hydrogen was introduced progressively, generally by step of about 5% with a stable proportion of H_2. Afterwards, H_2 proportion was left to vary.

With the growing will to use natural gas/hydrogen mixtures in the gas grid, demonstration projects have recently taken a new step: the use of existing appliances (for example, the project HyDeploy, in UK, has developed a method for testing existing appliances on site).

This is one of the critical points in the use of H_2NG in gas networks as it will take place in a mixed environment with appliances certified for H_2NG and older appliances not certified for:

- How to check existing appliances in order to ensure a safe operation of these appliances with a gas mixture they were not certified for?

- Can existing appliances operate properly with H_2NG mixtures if the gas used is inside the Wobbe index range of certification? What if the Wobbe Index of the delivered gas goes below the current limits?
- Which tests could be used to check the safe operation of appliances with H_2NG? Is it economically feasible ?

4. Burner design / aerodynamics

Burner design has a strong impact on the capacity of a gas appliance to accommodate to different gases. Although burners designed at the beginning of the 20th Century were meant to be compatible with gas containing hydrogen (town gas), the swap to natural gas in the gas grid has required drastic changes in burner conception that could prevent them to operate properly with high amounts of hydrogen.

As flashback is generated from a rupture of equilibrium between the speed of fresh gases and the laminar flame velocity, this problem could be mitigated by changing several burner specifications:

1. **Air/fuel ratio** (or air excess) has a strong impact on flame speed (Figure 7). Increasing air/fuel ratio of a premixed flame or decreasing the one of a partially premixed one can decrease flame velocity. This can be performed by several way.
    a. For premixed burners, adjusting the **speed of the fan that brings air** to the gas appliance is one way to treat the problem.
    b. For partially premixed appliances, a **change in the injector/venturi design (shape, diameters, distance)** is a way to change primary air/fuel ratio, and, thus, to avoid flashback.

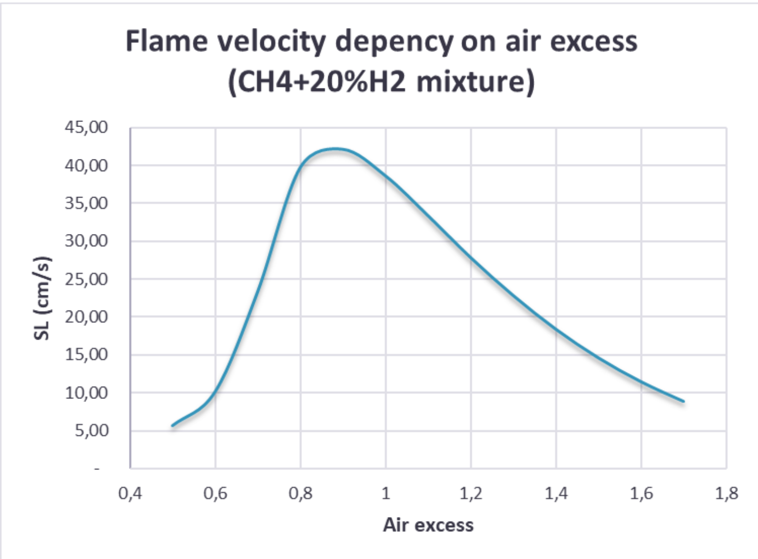


Figure 7: Laminar flame velocity dependency on air excess.

2. Gas inlet pressure
    a. an **increase in inlet gas pressure** increases the gas flowrate and, thus it is a way to **mitigate the decrease of heating power** of an appliance fed with H_2NG. However,

some it should be noted that gas appliances could be equipped with a pressure regulator. For these appliances, increasing gas distribution pressure has no effect.

   b. **Increasing gas pressure** can also increase its velocity in order to counterbalance the increase of flame velocity. However, the dependency of gas speed to pressure is only proportional to the square root of relative pressure. Thus, it **has less impact on flashback than a change of air excess**.

3. Size of burner port:
   a. It has been known for more than a hundred years that **flashback can be prevented by adjusting the size of the burner port to the composition of the gas burnt** [18]. The phenomenon responsible for stopping the flame is called quenching. It is the ability of the burner surface to cool down the flame up to a point when the flame goes out. Flame quench is used for safety purpose in gas arrestors, but it can also be applied to burners to prevent flashback [19].
   b. The size of flame ports also affects fresh gas velocity: when port size decreases, fresh gas velocity increases. Thus, it becomes more difficult for the flame to go up flow to cause flashback.
   c. The **depth of burner ports** has also an impact on flame quench [20]. The deeper the port, the harder for the flame to move upward. Port depth has a thermal effect on the flame, but it also changes velocity profile at port exit.
   d. The main drawback of **reducing flame port diameter** is that it **favours the lift off** of the flame [20]. Thus, either a compromise has to be found or other parameters have to be changed (port spacing, ports sharpness, use of pilot or auxiliary flames…).

5. Usable sensors in existing appliances

As more and more electronics are present in gas appliances, the use of sensors could be a way to mitigate the impact of gas quality variation, including %H_2 fluctuations.

5.1 Solutions for industry sector

Industry is probably the main sector of activity where appliances sensible to gas quality can be found. Some of them are able to operate in open loop mode (no controller) with a few regular human interventions to adjust the process to varying input parameters (gas quality, outside air temperature and moisture, raw materials…). Other appliances require a specific attention.

Many solutions to compensate for fuel (gas) quality variations or oxidant (air temperature/humidity) fluctuations have been developed during the past decades for these situations. These solutions can be separated into two categories:

1. **Feedback loop control** when a sensor is positioned in the furnace, or in the flue gases to adjust air and gas flowrates for optimal combustion/operation.
2. **feed forward loop control** when gas quality is measured before entering the thermal equipment.

These two options are detailed below.

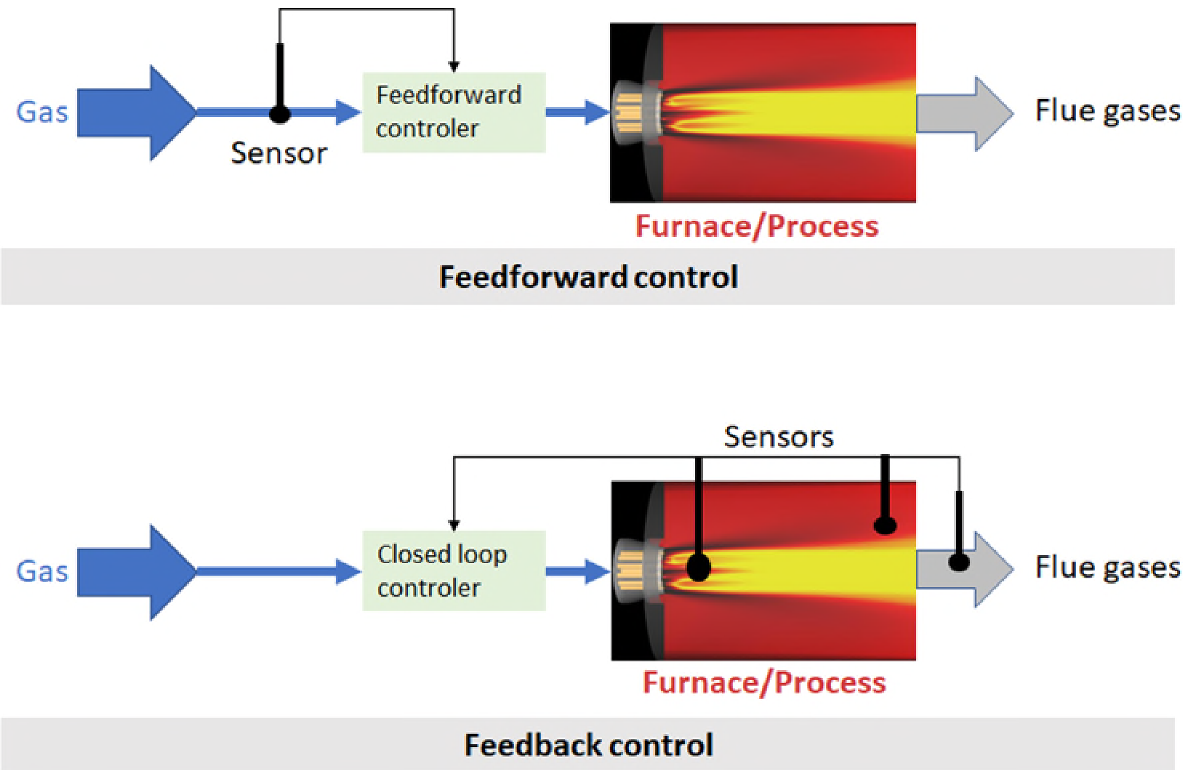


Figure 8: Principles of feedforward & feedback control loop.

5.1.1 Feedback loop control

Feedback-loop control related to gas quality is **mainly based on the measurement of the combustion products of natural gas (CO_2, O_2 or CO contents)**. These measurements are compared to reference parameters and translated into corrective actions on the gas and / or the air flow.

Closed loop control is particularly **well suited for cases where the combustion chamber is airtight**: boilers, airtight furnaces and controlled atmosphere furnaces.

The instruments required for feedback loop control are most often in-situ oxygen probes or "Zirconia probes" which make it possible to know the excess air and therefore the combustion aeration rate. This information is translated into an analog signal to the control system. Although most industrial furnaces are not strictly airtight, they use lambda control with a sensor in flue gases, anyway.

There are many feedback loop control configurations, combining the control of process-specific parameters (chamber temperature, vapor pressure, etc.) and that of maintaining excess air or the air factor.

Advantages and limitations:

- Used to correct the operating parameters of the equipment regardless of the nature of this disturbance (gas HCV, air temperature, operator disturbance, etc.).
- The best accuracy available.
- Longer reaction time than in feedforward loop".
- Theoretically limited to airtight combustion chambers.

If sensors used rely on O_2 or CO measurement, they will perform well in the presence of H_2 in the fuel.

Conclusions: for cost reasons, it could be difficult to use such kind of sensors for domestic use for the moment.

5.1.2 Feedforward control

In many processes, feedback control is not suitable, too slow or too complex to set up.

This is particularly the case when the product from the industrial process in contact with the burnt gases can changes their composition or in the case of air intakes in non-airtight furnaces. In that case, gas analysis does not make it possible to reliably link burnt gases composition to the combustion parameters. Moreover, the nature of the flue gases can also lead to a measurement that is too complex to implement or maintain (high temperatures, aggressiveness of combustion products, etc…).

In these cases, feedforward control is the solution: depending on gas quality variations, the measurements are translated into corrective actions on the combustion control devices (air and / or gas flow control valves).

For this, two types of devices can be used:

- A gas chromatograph, where the measurement of the main gas components is translated into relevant gas characteristics (Ws, lower or higher calorific value, air volume required…)
- An indirect measurement of gas quality, where gas properties are measured (thermal conductivity, sound speed, viscosity, density…) and translated into combustion characteristics through a correlation.

Currently, these two kinds of devices are not fitted to treat gases with hydrogen. Gas chromatographs require additional H_2 measurement system and indirect measurement stations require a change in correlation formulas and usually an additional property sensor dedicated to hydrogen.

Some of these sensors can be combined with gas quality regulators in order to stabilize gas characteristics at inlet point of industrial sites. This is, for example, the Indelis® system developed by ENGIE, which is able to keep the Wobbe number of natural gas constant thanks to injection of compressed air.

The problem of these gas analysers is that their current cost is prohibitive for domestic use. For example, an ATEX gas chromatograph used in the industry costs about 50-60k€. A correlation gas analyser costs about 10-20k€.

<u>Conclusions</u>: *Although these latter gas analysers are too expensive to be used for one single user, it is possible to imagine their implementation on an isolated gas branch of a gas network in order to transmit gas composition information to downstream appliances or to a gas technician in order to adjust properly appliances*.

5.2 Flame detection with a thermocouple

The thermocouple safety system is present on certain models of water heaters and most gas hobs. This simple and effective device cuts off the gas supply when the pilot flame of the appliance goes out, thus preventing any risk of unburnt gas release when the flame disappears. The thermocouple ensures that the flame or the pilot flame is always on and cuts off the gas if the flame goes out.

The operation of the thermocouple is based on its composition, which is made of two different metals. When the thermocouple is placed in the pilot flame, a current is created. This current is broken when the flame goes out and the safety valve connected to the thermocouple automatically closes.

In the presence of a hydrogen mixture, the flame tends to be hotter but shorter. Thus, if the thermocouple is well positioned, its efficacity as a flame detector is not affected by the presence of hydrogen.

In the past decades, the thermocouple + pilot flame combo has been replaced by ionization probes in boilers because ionization probes react faster than a thermocouple. However, it is expected that, at high H_2 percentages (>60%H_2), ionization current could decrease below the threshold limit and prevent the appliance from functioning properly.

As a consequence, *for high percentages of hydrogen in the gas, thermocouples could be re-introduced in some gas appliance. However, this will only be possible if they are compatible with the speed of detection of flame extinction required in EN standards*.

5.3 Flame detection and combustion control with an ionization probe

The simplest, most widely used and most economical method of combustion control on residential and commercial gas burners is the measurement of the ionization current of the flame. It strongly depends on the air factor, which is impacted by gas quality for burners without specific control. Keeping an optimal air factor is essential in order to have a maximum combustion efficiency and minimum pollutant (CO, NOx) emissions.

The signal from the ionization probe reacts quickly to variations in the air excess ratio, so quick that an efficient combustion control is achievable. The drawback is that the absolute value of the ionization signal also depends on the temperature of the flame, on the location as well as the age of the probe and the boiler,... The latter point has been resolved by the manufacturers via software check that includes a recalibration mechanism.

Unfortunately, the ionization signal also depends on the nature of the gas : the ionization of the flame increases with the number of carbon atoms per molecule as well as the number of multiple chemical bonds [21]. As the hydrogen molecule does not contain any carbon atom, its combustion produces ions by less efficient paths.

As a consequence:

- A 100% hydrogen flame does not produce enough ions to be detected by an ionization-based flame supervision device (at least with the detection limit used for natural gas). Other sensors must be used.
- Adding hydrogen to natural gas has an impact on flame detectors based on ionization currents and on automatic combustion control in boilers. For the moment, **literature review has not revealed any safety problems with ionization-based flame detection devices for natural gas/hydrogen mixtures**.

Concerning boilers with adaptative combustion control functions (ACCF boilers), it has been shown that the introduction of hydrogen into natural gas tends to disturb air/fuel control. In a GERG funded project on combustion controlled condensing boilers [15], several boilers have been tested with gases of varying Wobbe indices; some with hydrogen, some without. **It has been shown that, for gases containing hydrogen, ACCF boilers operate like traditional boilers**: lambda air factor increases when Wobbe Index decreases due to the presence of hydrogen. This phenomenon is illustrated on Figure 9.

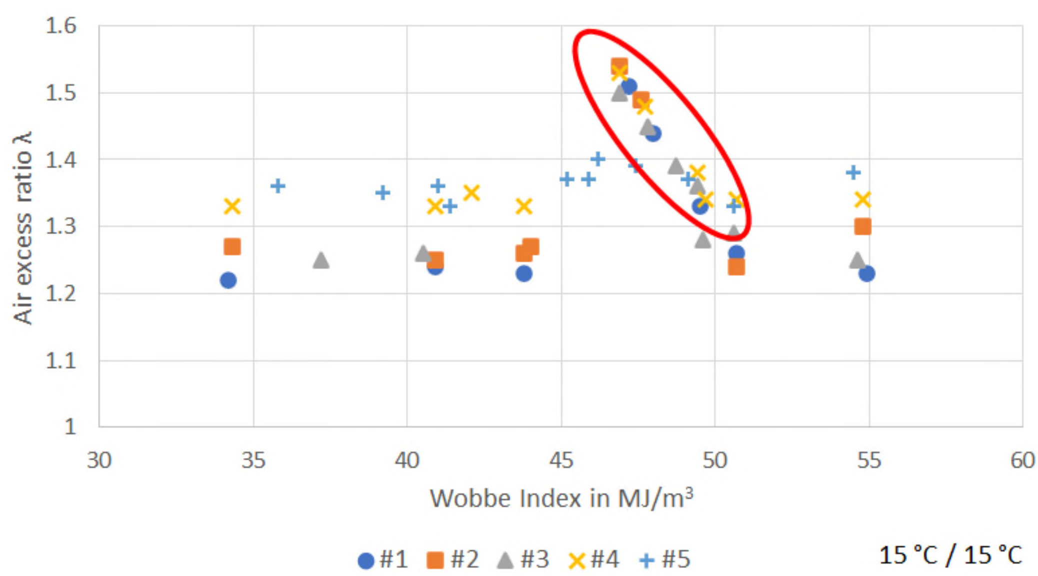


Figure 9: ACCF Boilers tested are able to adjust air factor to gas quality except for gases containing hydrogen (red circles on the figure). Recreated from [15]

5.4 CO sensor

In the past, some boilers (for example boilers from Vaillant) were equipped with a CO sensor to adjust air/fuel ratio [15]. For a boiler, when CO emissions are expressed in terms of air excess or %O_2 in the burnt gases, U shape curve appears:

- if air excess is too small, combustion takes place too close to the stoichiometry. Some CO molecules formed during the partial oxidation of methane are not able to find the final oxygen required in the hot zone of the flame.
- On the contrary, if air excess is too high, the flame becomes unstable and generates CO too.

The optimum air/fuel ratio is located between these two extremes where CO emissions are minimal.

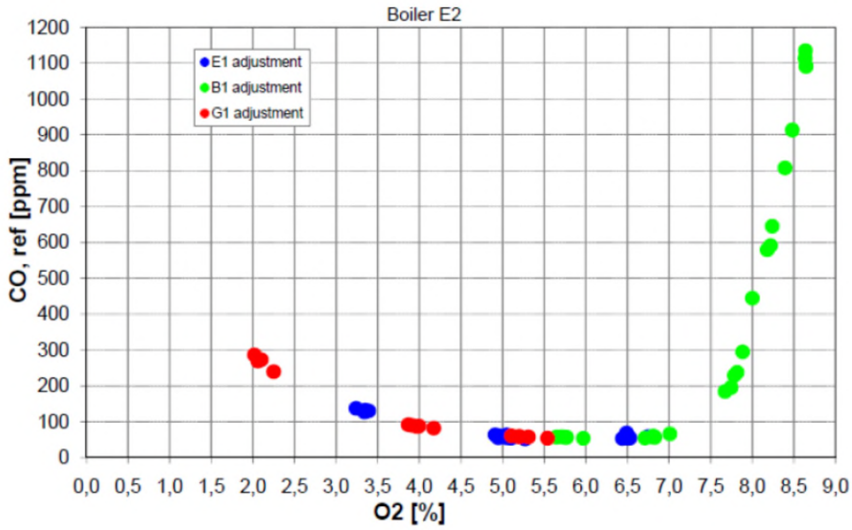


Figure 10: Example of a U shape curve for CO as a function of %O_2 (source: GASQUAL project [22]).

Document [15] mentions two CO sensors for boilers:

- One of them, developed by Steiner/Vaillant is a semiconductor whose resistivity is changed by an oxidation-reduction on its surface (CO reacts with oxygen to form CO_2). By monitoring resistivity, it is possible to deduce the level of CO.
- The second one was developed by Lamtec (CarboSen 1000 probe). It is a modified zirconium probe that is able to detect CO, H_2 and CxHy.

<u>Conclusions</u>*: This kind of CO sensor may be a solution for closed loop control of boilers to be used with high percentages of hydrogen. However, no study on the impact of the presence of hydrogen on these sensors has been found*. A test of this kind of boiler could bring some new information on how they operate with H_2NG.

5.5 Boiler adjustment and combustion analysers

The more test results are produced during the THyGA project, the clearer it becomes that field adjustment of gas appliances will be a problem when a high proportion of H_2 is mixed with natural gas and when this proportion will vary[4].

Portable gas combustion analysers, even if they can display CO_2 concentration in burnt gases, are not equipped with an actual CO_2 sensor. The majority of them is based on an O_2 sensor. CO_2 is calculated by a mathematical formula adjusted according to the kind of fuel used (see for example ref [23–25]).

$$CO_2 = \frac{CO_{2max} \times (O_{2ref} - O_2)}{O_{2ref}}$$

Where:

- O_2 is the measured value of oxygen in %
- O_{2ref} is 21%
- And CO_2max is dependent on the kind of fuel

For example, for all natural gases, the manufacturer Testo uses a value of CO_2max=11.9%.

Based on the theory detailed in the Work Package 2 of THyGA [1], some calculations were performed to check the accuracy of this method:

- It was considered that the **reference gas** used by TESTO is a mixture of 95% CH_4 and 5% C_3H_8 in order to have a CO_2max of 11,92% (close to 11.9% specified in the TESTO user manual).
- Burnt gases composition calculation were performed for several gases (THyGA EU low, THyGA EU high, DVGW 260-Biomethane H, BT104-Groningen gas (L gas), reference gas with 20% H_2) with a Lambda of 1.3.

These results concerning the accuracy of measurement are summed up in Table 5.

Table 5 : Accuracy of CO_2 calculation with a portable combustion analyser.

L=1,3	Ws (kWh/m3)	%O2 (dry)	CO2 (dry)	Calculated CO2max	CO2max programmed in gas analyser	CO2 displayed by gas analyser	Delta
CH4+5%C3H8	14,53	5,24%	**8,94%**	11,92%	11,90%	**8,93%**	-0,10%
EU high (93.4%CH4+6,6%C3H8)	14,67	5,24%	**8,99%**	12,00%	11,90%	**8,93%**	-0,66%
EU Low (95.6%CH4+4,4%N2)	13,26	5,22%	**8,70%**	11,62%	11,90%	**8,94%**	2,78%
DVDW 260-Biomethane H	13,17	5,23%	**8,99%**	11,98%	11,90%	**8,94%**	-0,60%
BT104 - Groningue gas	12,16	5,17%	**8,86%**	11,81%	11,90%	**8,97%**	1,25%
(CH4+5%C3H8) with 20%H2	12,56	5,27%	**8,49%**	11,35%	11,90%	**8,91%**	4,99%

It appears that the CO_2 concentrations displayed by the portable gas analyser is overestimated compared to the real CO_2 concentration for most fuel gases. This can be considered as beneficial for

[4] See especially chapter 8 of ThyGA report D2.2 "Impact of hydrogen admixture on combustion processes – Part I: Theory"

appliance adjustment because it prevents the fuel/air mixture from being too rich and produce too much CO.

When hydrogen is involved (reference gas (CH_4+5%C_3H_8) mixed with 20% H_2), the displayed CO_2 concentration is overestimated by about 5%. This can have two consequences for a boiler adjusted with this gas, one is a drawback, but the other one is a benefit:

1. Firstly, **it could lead to an excess air higher than the upper limit suggested by the manufacturer**. In the worst conditions, this could lead to a blow out of the flame. It has no impact on safety (no flame = boiler shut off) but could have an impact on the proper operation of the appliance. *Some tests could be done in THyGA WP5 to check the appearance of this phenomenon.*
2. Secondly, when a boiler is adjusted with a gas with 20% H_2 and used, afterwards, without H_2, its higher air excess (caused by O_2 to CO_2 conversion in the analysers) **delays the risk of CO appearance compared to an adjustment performed with a real CO_2 analyser**.

For example, considering figures of Table 5, a boiler should be adjusted to 8.91% CO2 when it is fed with the reference gas with 20% H_2. Now, we check what happens when hydrogen is removed afterwards.

1. With a portable analyser, the real lambda during adjustment is 1.3. When hydrogen is removed and the appliance is fed with the reference gas, lambda decreases down to 1.11.
2. With a laboratory analyser that measures the real CO_2 value, the real lambda after adjustment is 1.24. When hydrogen is removed and the appliance is fed with the reference gas, lambda decreases down to 1.06.

These calculations confirm that the use of a **combustion analyser with O_2 sensor** (case 1) is a better option than an analyser with a real CO_2 sensor (case 2) when hydrogen levels in the gas are fluctuating because it **reduces the probability to produce CO due to a too rich air/fuel mixture**. However, due to a low difference in air excess, it cannot be considered as a full mitigation solution to prevent CO emissions when hydrogen is removed from the gaseous fuel and combustion became close to stoichiometry.

Conclusions:

- *It could be of interest to check, within THyGA WP5, if portable sensors could contribute to the reduction of CO emissions of gas appliances with fluctuating %H_2.*
- *It could also be of interest to introduce corrections to the %CO_2max value used in portable combustion analyser to better reflect the locally delivered gas composition.*
- *It could also be of interest to check the way an appliance should be adjusted in case of fluctuating proportion of %H_2. Supposing the %H_2 is known, how to adjust the appliance? at 0%H_2, %H_2/2 or at the maximum %H_2? Is the knowledge of %H_2 enough or is it necessary to know the full gas composition?*

5.6 Patents/projects under development

Some manufacturers are more advance on hydrogen-compliant appliances than others and have already filed some patents.

Patent WO2020/181902A1 from Bekaert Combustion Technology (BCT) describes a **method for modulating a burner when the combustible gas** supplied to a premixed surface burner which **comprises at least 20% of hydrogen**. In order to avoid flashback during ignition, the lambda value is set to 1.2 times the lambda value used during normal operation (for example, if lambda is 1.3 at full load, it is set to 1.2x1.3=1.56 during ignition). By doing this, they reduce the flame velocity of the gas/air mixture, thus preventing flashback during ignition. It should be noted that igniting a methane/air mixture with such an excess air is not possible because hydrocarbons badly combust in these conditions. The lambda value at full power is kept at its nominal value not only because the risk of flashback is lower but also because it keeps a high level of efficiency.

Patent WO2020/182902A1 from Bekaert Combustion Technology (BCT) describes a method for starting a surface burner with natural gas/hydrogen mixtures above 50% H_2 without having a risk of flashback. The method described consists in increasing the lambda value (air excess) above 1.85 during ignition. Afterwards, a second lambda value, lower than the ignition value, is set during operation mode in order to maximize the efficiency of the appliance.

Patent WO2020/19791A1 from BDR THERMEA describes a method for air/fuel ratio adjustment at low heating power in order to avoid flashback. It mentions ways of estimating air/fuel ratio with the use of correlations programmed in a calculator and indirect means of measuring air and fuel flowrates, such as fan speed, valve command signal, ionization probe…). This patent also describes means of detecting and fighting flashback, such as using a temperature sensor on the gas injector (when flashback, a sharp rise of its temperature is detected), a pressure sensor or a sound sensor.

6. Appliance environment

6.1 Draught

When gas composition varies, it has an impact on combustion, but also on the nature of burnt gases. This can have an impact on the draught of gas appliances on two aspects:

1. The **volumetric flowrate**, which could increase or decrease the pressure loss
2. Gas density that affects **buoyancy**

6.1.1 Volumetric flowrate of flue gases

The volumetric flowrate of flue gases depends on several parameters such as fuel gas flowrate, air excess, the volume of burnt gases generated by combustion, their temperature, etc…

Concerning fuel gas flowrate, it is usually admitted that, for a constant inlet pressure, the volumetric flowrate Q_{vol} at the outlet of a gas injector only depends to the relative density through the formula:

$$Q_{vol} \approx \mathrm{A}\sqrt{\frac{\mathbf{2}\,\boldsymbol{\Delta P}}{\boldsymbol{\rho_{air}}}} \cdot \frac{\mathbf{1}}{\sqrt{\boldsymbol{d}}}$$

Where:

- A is a constant
- ΔP is the fuel gas relative pressure
- ρ_{air} is the air density
- d is the relative density of the fuel gas

The relative density of hydrogen is smaller than the relative density of methane/natural gas. When hydrogen is added to natural gas, its density decreases. Thus, fuel volumetric flowrate increases.

The air excess varies according to the following formula:

$$\lambda_{H2NG} = \lambda_{NG} \cdot \frac{Va_{NG}}{Va_{H2NG}} \cdot \sqrt{\frac{d_{H2NG}}{d_{NG}}}$$

Where:

- λ is the air excess
- Va is the volume of air required for a stoichiometric combustion
- d is the relative density
- Subscript
    - NG is for natural gas
    - H_2NG is for hydrogen / natural gas mixtures

The volume of gases generated by the combustion of 1 m^3 of fuel gas can be calculated using the chemical equation of combustion. In stoichiometric conditions, this volume, $V_{f'0}$ (humid conditions) is 10.56 m^3 of burnt gases for 1 m^3 of fuel for CH4 but only 2.89 m^3/m^3 for H_2.

While adding hydrogen, the gas flowrate and air excess tend to increase, but the volume of burnt gases generated tends to decrease.

In order to calculate the impact of hydrogen on flue gas flowrate, we have considered a boiler operating at 10 kW with an air excess of 1.35 with CH_4 as an initial fuel. When this fuel is switch to CH_4+20%H_2, the burnt gases flowrate will decrease from 13.26 to 11,19 m^3/h (15°C).

Thus, adding hydrogen to natural gas decreases flue gas flowrate (which means that it would not be required to be mitigated by larger exhaust ducts.

6.1.2 Buoyancy

On modern boilers, the release of combustion product outside is helped by a fan that either pulls fresh air into gas appliance or pushes combustion products from the appliance. The list of possible configurations is detailed in European standard EN 1749 [26]. Old gas appliances, gas appliances with low heating power, gas ranges or gas fires where the flame has a decorative function have no fan included and rely on natural draught only.

Natural draught pressure is given by the buoyancy formula for gases:

$$\Delta P = (\rho_{air_{ext}} - \rho_{flue\ gases})$$

Where:

- ΔP is the pressure of natural draught that pulls flue gases outside the smokestack
- $\rho_{air_{ext}}$ is the outside air density
- $\rho_{flue\ gases}$ is the density of flue gases

Under the same conditions as in chapter 6.1.1, flue gases density was calculated. Considering flue gases at a temperature of 15°C, flue gases density for pure methane is 1,2513 kg/m^3 and flue gas density of CH_4+20%H_2 is smaller: 1,2389 kg/m^3 (factors taken into account in this calculation include the decrease of CO_2 concentration compensated by an increase of H_2O percentage, but also the increase of air excess that moderates the decrease of density).

The decrease of flue gases density when hydrogen is mixed with natural gas favours natural draught. However theoretical calculations mentioned above were performed for gases at the same temperature (15°C was used as a reference).

In real life, hydrogen increases the air excess. The increase of air excess decreases flue gas temperature, which, this time has a negative impact on draught.

Equilibrium flame temperature were calculated with a dedicated software (CANTERA [27]). For methane, with a lambda of 1.35, equilibrium flame temperature is 1896 K while it drops down to 1832 K for a lambda of 1.44 for CH_4+20%H_2.

As a consequence, natural draught could be less efficient when hydrogen is present in the fuel due to a decrease of temperature of the flue gases. However, as flue gases pass through the heat exchanger, temperature difference will not be so extreme. Only tests could measure the real impact of H_2NG composition on flue gases temperature.

The solution to prevent this kind of problems could be either to adjust the fuel/air ratio or to monitor flue gas temperature.

6.1.3 Conclusions

Addition of hydrogen to natural gas tends to decrease the volumetric flowrate of flue gases. As a consequence, it is not an obstacle to the evacuation of flue gases, neither for natural draught nor for fan assisted appliances.

Hydrogen changes the chemical composition of flue gases: while the proportion of CO_2 decreases, the proportion of H_2O increases, causing a decrease of density. This is also in favour a decrease of the pressure drop in exhaust ducts of gas appliances. This phenomenon, however, is moderated by the increase of air excess cause by density and stoichiometric air requirement changes.

However, a third phenomenon has to be considered. It is the decrease of gas temperature due to the increase of air excess when hydrogen is added. The drop of temperature is far from being negligible (the drop of temperature before heat exchanger has been estimated to be from 2010 °K for methane to 1962 °K for CH_4+20%H_2).

Some tests should be performed to measure how hydrogen affects natural draught, and to check if combined effects do cause draught problems on extreme cases (weak draught with methane). The impact of the efficiency of heat exchangers on flue gas temperature should be investigated.

Some mitigations measures could be to make the appliance work with lower excess air if CO limit is not close, to use adaptative combustion measure to keep excess air constant or to limit the efficiency of heat exchanger

6.2 Condensates

6.2.1 Does hydrogen addition increase condensates?

While the combustion of a molecule of methane produces one molecule of CO_2 and two molecules of H_2O, the combustion of hydrogen only produces H_2O. This has an impact on the amount of condensates produced by gas appliance.

Two cases should be considered:

- Standard boilers where the air excess changes with gas quality

- Boilers with adaptative control function (*ACF boilers*) that are able to keep air excess constant

6.2.1.1 ACCF boilers

ACCF boilers are Adaptative Combustion Control Function boilers. Their control function can maintain air excess constant when air or gas characteristics vary in time.

Let's consider a gas appliance which operates with methane at λ=1.3. Then, the proportion of water in flue gases will increase in the proportion shown in Table 6. This will generate an increase of the dew point of a few degrees. It will increase water condensation in the boiler, but it could also generate some condensation in the flue gas pipe.

Table 6: percentage of water generated by gas combustion.

%H2 in fuel (CH4/H2)	Lambda	%H2O in exhaust gases
0%	1,30	14,9%
20%	1,30	15,7%
40%	1,30	16,8%
60%	1,30	18,6%
80%	1,30	21,5%
100%	1,30	27,7%

When gas quality changes, very few appliances can keep a constant air excess. Concerning domestic appliances, only combustion controlled condensing boilers can perform this way. However, as shown previously [15], combustion control is usually not effective in presence of hydrogen in the fuel gas. So, the behaviour of current ACF boilers is somewhere between a standard boiler and a boiler able to keep a constant air excess.

6.2.1.2 PGS controlled boilers

PGS, Pneumatic Gas Supply controlled boilers are boilers where the gas flowrate is pneumatically driven by the gas relative pressure.

Most of gas appliances have their air excess increase when hydrogen is added to the fuel gas. This parameter is taken into account in Table 7. In this case, the water produced is diluted in a larger volume of air and, up to 60% H_2 in the fuel gas, the concentration of water does not increase in the flue gases, thus reducing the risk of increase of condensation in the exhaust duct.

Table 7: percentage of water present in flue gases when the lambda increase is taken into account

%H2 in fuel (CH4/H2)	Lambda	%H2O in exhaust gases
0%	1,30	14,9%
20%	1,39	14,8%
40%	1,50	14,8%
60%	1,63	15,1%
80%	1,78	16,2%
100%	1,84	20,4%

The flowrate of H_2O in the exhaust gases can be calculated by taking into account V_{H20}, the volume of water produced by the combustion of 1 m^3 of gas (Table 8). Between 0% and 60% H_2, the flowrate of water remains almost constant.

Table 8: Evolution of the flowrate of water when hydrogen is added to methane

%H2 in G20	Momentum conservation (heating power proportional to Ws, gas flowrate to 1/sqrt(d)		
	Gas flowrate	VH2O (m3H2 O/m3 of gas)	H2O flowrate
Units -->	m3/h	m3H2O /m3gas	m3/h
0%	1,00	2,00	2,00
20%	1,10	1,80	1,98
40%	1,24	1,60	1,98
60%	1,45	1,40	2,03
80%	1,83	1,20	2,19
100%	2,81	1,00	2,81

The critical point that could increase the amount of condensed water is the decrease of flue gases temperature. For example, considering a boiler operating at λ=1.3 and considering the increase of air excess due to the change of density and stoichiometric air requirement, there is a sensible decrease of flue gas temperature (

Table 9). This has an impact on the dew point temperature and the efficiency of the natural draught.

Table 9: impact of H_2 addition on equilibrium temperature (variable air excess).

%H2 in fuel (CH4/H2)	Lambda	Equilibrium temperature (°C)
0%	1,30	1 776
20%	1,39	1 727
40%	1,50	1 680
60%	1,63	1 649
80%	1,78	1 663
100%	1,84	1 834

However, due to the presence of the heat exchanger that extracts both heat and condensation from the flue gases, it is not possible to estimate the risk of an increase of condensation in the exhaust conduit. As a consequence, only test could provide some information on whether or not hydrogen enhances condensation in the exhaust ducts.

Thus, in order to avoid condensation in the flue duct when hydrogen is added to natural gas, it is necessary to check that flue gas temperature stays above the dew point. A careful adjustment of the air excess or a temperature probe in the fuel gases could be a mitigation solution.

6.2.2 Does hydrogen addition increase acidity of condensates?

Little is known about how the admixture of hydrogen influences the acidity of condensates.

Condensates acidity is usually caused by the dilution into water of NOx, CO_2 and sulfur components.

- NOx reacts with water to produce nitric acid (HNO_3)
- CO_2 reacts with water to produce carbonic acid (H_2CO_3)
- Sulfur components react with water to produce sulfuric acid (H_2SO_4)

Although natural gas contains some sulfur components, it is commonly agreed that the main sources of acidity of condensates are carbonic and nitric acids. The pH of the condensates seems to range from 3 to 4 [28] [29]. As a comparison a pH of 3 corresponds to vinegar while rainwater acidity is between 4 and 5.

Thus, addition of water into natural gas could act on several factors:

- Increase of flame temperature, a more compact flame → increase of NOx
- Increase of air excess → dilution of CO_2 and NOx
- Increase / decrease of the amount of condensate
- Decrease of CO_2 emissions

These factors could influence the pH of condensate in one direction or another. As some of them strongly depend on the technology used, it is not possible to anticipate if pH will increase or decrease with hydrogen admixture.

Thus, experimental tests are required to check tendencies. The measurement of condensate

6.2.3 Conclusion

On most gas appliances, the addition of hydrogen into methane up to 60% will not change the concentration of water in exhaust gases. The water flowrate in flue gases will also remain constant. What will change is that, due to an increase of air excess, the temperature of flue gases will decrease and, consequently, will favor the appearance of condensation.

However, it is difficult to go further through calculation as it is not possible to estimate the behavior of heat exchangers**.** Especially, the risk of fumes condensing in pipes not designed for it needs to be assessed, to avoid CO migrating to lodgings.

As a consequence, to check the impact of the proportion of hydrogen on condensation, tests should be carried out.

7. Conclusion: How to mitigate the effect of a new gas on appliances?

7.1 Gas quality

In future years, the increase in LNG imports, biomethane injection and hydrogen addition to the gas will lead to an increase of the effective Wobbe Index (WI) bandwidth of gases at entry points. On the other side, at exit points, manufacturers require narrow WI bandwidth in order to optimize the performances of their appliances (Figure 11).

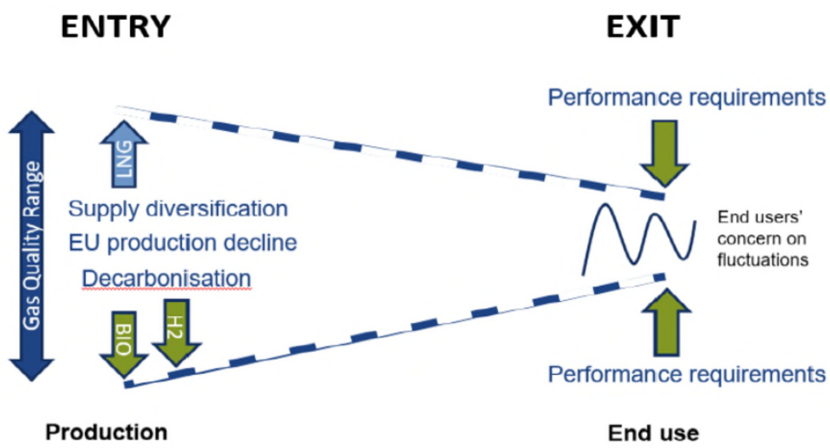


Figure 11: Illustration of competing requirements on the Wobbe Index range for the gas entering and exiting the system. Source: [30].

A first mitigation measure could be to use means of reducing the WI bandwidth of gases at entry points. In the past, mixing stations have been used to handle this problem by introducing inert gases or high WI gases. However, although adding new gases cand improve gas properties on one point, it could also degrade them on others. Calculations can discriminate impacts, but only tests could quantify them and validate the approach.

7.2 New appliances

The study of sensors is a good way to start.

Two groups of sensors can be used depending on control loop: feedforward or feedback loop control.

- With feedforward control, the behaviour of appliances is adjusted according to gas quality.
- With feedback loop regulation, flue gases are analysed and then, the behaviour of the appliance is adapted accordingly.

There are already correlation-based gas sensors available in the industrial gas applications. Technically, they have the potential to be adapted for domestic use. However, they are still very expensive (about one to several thousand euros). Currently, it is not possible to use them in each appliance. However, it could be an interesting perspective for the future.

For the moment, a few sensors exist in domestic appliances.

- Ionization probes are the most widespread. They operate properly as a safety sensor with H_2NG gases up to 60% (according to THyGA tests) and maybe above, but they do not work well for combustion control purpose.
- In the past, Vaillant has manufactured an adaptative combustion controlled domestic (ACCF) boiler based on a CO sensor. This could be a mitigation solution to explore in WP5 in order to optimize combustion.

Concerning safety sensors: if one wants to build an appliance that could operate with natural gas or pure hydrogen, there could be a renewed interest for thermocouple as a flame detector. However, the response time of this sensor is slow and may not match current safety requirements, especially for the more powerful appliances. Otherwise, ultraviolet sensors like those used in the industry for flame detection could be an alternative, however costly, solution.

Some patents have also been published concerning the mitigation of the flashback problem. What they suggest is to increase the air/fuel ratio when operating conditions could generate flashback (ignition). One patent describes a method to detect flashback using different kind of sensors on the injector (temperature sensor for example). However it should be noted that increasing air/fuel ratio to avoid flashback could also bring other problems (blow off, no or delayed ignition) if the air/fuel ratio goes outside the recommended range.

7.3 Existing appliances

What to do with existing appliances in order to check that they are suitable for operating with H_2NG mixtures?

This point was investigated in the past during conversion projects:

- From town gas to natural gas
- From pipe gas to LNG

- From L gas to H gas

It is also interesting to cross this information with demonstration projects on H_2NG to see how they have guaranteed safety for users as well as a safe operation of appliances.

When town gas was replaced by natural gas in the 60's, gas interchangeability rules were not clearly established. Switching from a low calorific value gas containing hydrogen to a high calorific value gas led to several transformations in gas network. Distribution pressure was raised by about 10 mbar and the design of injector/burner holes were adapted. The impact of the burner design is briefly described in the report. However, re-designing a burner can be a complex work as improvements in some areas can lead to drawback in others (ex: improving flashback behaviour is usually compensated by worse blow off behaviour). Increasing distribution pressure for H_2NG could be a way to mitigate the loss of heating power for high proportion of H_2. However, this solution would not work for appliances with a pressure regulator. This solution could be tested in WP5, if necessary.

Recent conversion projects from L gas to H gas gave a better view on how a modern conversion is performed. It involves creating an inventory of appliances in each home and the classification in several segments where appliances could operate with both gases without changes or must be changed or require some conversion work. In France, an exhaustive appliance database was built with help of manufacturers in order to classify all encountered appliances in different segments. A similar database could be built for H_2NG with the help of manufacturers: suitable for H_2NG, not suitable, and in-between.

Experimental / demonstration projects on H_2NG is another source of information on how to mitigate the impact of H_2NG on gas appliances. Most of them used new appliances and only performed lab-testing with onsite measurement to check their behaviour in time.

However, recently the project HyDeploy has initiated a safety check work on gas appliances and installations before the injection of 20% H_2 in the gas grid. Based on this work, a method of safety check of gas appliances could be initiated and tested in WP5 in order to discriminate used appliances unable to operate with H_2NG from the others.

7.4 Grey areas

Some grey areas might require some more investigations in order clear some unknown issues.

On site adjustment will be a major problem if, in the future, the proportion of hydrogen varies on a wide range. In the labs of THyGA partners, adjustment tests are carried out with lab CO_2 analysers (with a CO_2 sensor). However, field adjustment is performed with combustion analysers equipped with O_2 sensors. The analysers convert O_2 data into CO_2 data using a predefined natural gas composition. The impact of this was not measured in THyGA. Preliminary calculations show that the use of field analysers could be beneficial regarding H_2, but it has also some drawbacks. More interesting, an adjustment based on O_2 levels in flue gases could reveal more adequate for H_2NG mixtures. Detailed tests/analysis of this situation should be performed, with gas analysers and with a specific O_2 range calculated from CO_2 range given in instruction manuals. This could eventually mitigate adjustment problems.

Natural draught should not be an issue on most appliances. Preliminary calculations show that increasing the proportion of H_2 decreases the volume of flue gases and its density (at constant temperature). However, increasing the proportion of hydrogen also increases the air excess, and thus, can also decrease flue gases temperature. As lower flue gases temperature means less natural draught, this point has to be investigated, mainly in extreme conditions, when a boiler is at the limit of a malfunction (partially blocked flue stack to generate pressure loss, for example).

8. List of Illustrations

9. List of tables

10. REFERENCES

[1] Leicher J, Schaffert J, Carpentier S, Albus R, Görner K. [THyGA D2.2] Impact of hydrogen admixture on combustion processes – Part I: Theory. GWI/CRIGEN; 2020.

[2] Schaffert J, Flayyih M, Burmeister F, Albus R, Görner K, Milin P, et al. [THyGA D2.5] Testing programme for hydrogen tolerance tests of domestic and commercial natural gas appliances. 2021.

[3] Flayyih M, Schaffert J, Burmeister F, Görner K, Milin P, Carpentier S, et al. [THYGA D2.1] Market segmentation of domestic and commercial natural gas appliances. 2021.

[4] Schweitzer J. [THyGA D3.5] Intermediate report on the test of technologies by segment – Impact of the different H2 concentrations on safety, efficiency, emissions and correct operation. 2022.

[5] Wakrim A. Historique des changements de gaz en France (1957-1986). DRI - GDF SUEZ; 2013.

[6] Delbourg P, Lafon J. Interchangeabilité des gaz. Association Techniques de l'Industrie du Gaz; 1971.

[7] Schneck H. La combustion et l'interchangeabilité des gaz - Problèmes actuels et futurs. Direction de la Recherche de Gaz de France; 1975.

[8] GRDF. Réaliser l'autoinventaire. Changement de gaz dans les Hauts de France n.d. https://sites.grdf.fr/web/changement-de-gaz-dans-les-hauts-de-france/autoinventaire (accessed February 17, 2022).

[9] Singer B, Apte M, Black D, Hotchi T, Lucas D, Lunden M, et al. Natural gas variability in California: environmental impacts and device performance - Experimental evaluation of pollutant emissions from residential appliances. 2009. https://doi.org/10.2172/980736.

[10] CEN. EN 16726 - Gas infrastructure - Quality of gas - Group H 2018.

[11] Types of gas and the corresponding supply pressures according to Article 4(1) of Regulation (EU) 2016/426 of the European Parliament and of the Council on appliances burning gaseous fuels and repealing Directive 2009/142/EC 2018.

[12] CEN. EN 437 - Gaz d'essais - Pressions d'essais - Catégories d'appareils 2021.

[13] Kippers MJ, Overdiep JJ. [AMELAND Project] Hydrogen injection in natural gas on island of Ameland in the Netherlands. 2011.

[14] Isaac T. HyDeploy: The UK's First Hydrogen Blending Deployment Project. Clean Energy 2019;3:114–25. https://doi.org/10.1093/ce/zkz006.

[15] Carpentier S, Milin P, Mostefaoui N, Nitschke-Kowsky P, Schweitzer J, Sadegh N, et al. Self-regulated gas boilers able to cope with gas quality variation - Lab Reports. GERG Project; 2018.

[16] Safety Checks - HyDeploy. HyDeploy Project Website n.d. https://hydeploy.co.uk/hydrogen/safety-checks/ (accessed February 23, 2022).

[17] Final technical report Uithoorn conversion project (Technisch eindrapport ombouwproject Uithoorn). Stedin; 2021.

[18] Berry W, Brumaugh LV, Moulton GF, Shawn GB. Design of atmospheric gas burners (Technologic Papers of the Bureau of Standards) 1921.

[19] Couto HS, Duarte JB, Bastos-Netto D. Domestic Range Burner Design Procedure, Hong Kong: 2004.

[20] Gattei L. A study on the fluid dynamics of domestic gas burners. PhD. Universita' di Bologna, 2008.

[21] Association Technique de l'Industrie du Gaz en France. La combustion du gaz et les flammes - Propriétés électriques des flammes n.d.

[22] Schweitzer J. GASQUAL D6.1 - Conclusions on domestic appliances and annex 6 "impact by country". Adopted version. GASQUAL; 2012.

[23] testo 340 - Flue gas analyser - Instruction manual 2014.

[24] ECOM B ONE - Analyseur de combustion 2017.

[25] Wöhler - Mode d'emploi Analyseur de Combustion - Wölher A 450 2022.

[26] FD CEN/TR 1749 - European scheme for the classification of gas appliances according to the method of evacuation of the combustion products (types) 2010.

[27] Goodwin D, Speth R, Moffat H, Weber B. Cantera: An object-oriented software toolkit for chemical kinetics, thermodynamics, and transport processes. 2021.

[28] Condensing boiler. Wikipedia 2022.

[29] Managing Condensate for Condensing Boilers. Automatic Heating n.d. https://www.automaticheating.com.au/solutions/condensing-boilers-explained/managing-condensate-condensing-boilers/ (accessed April 1, 2022).

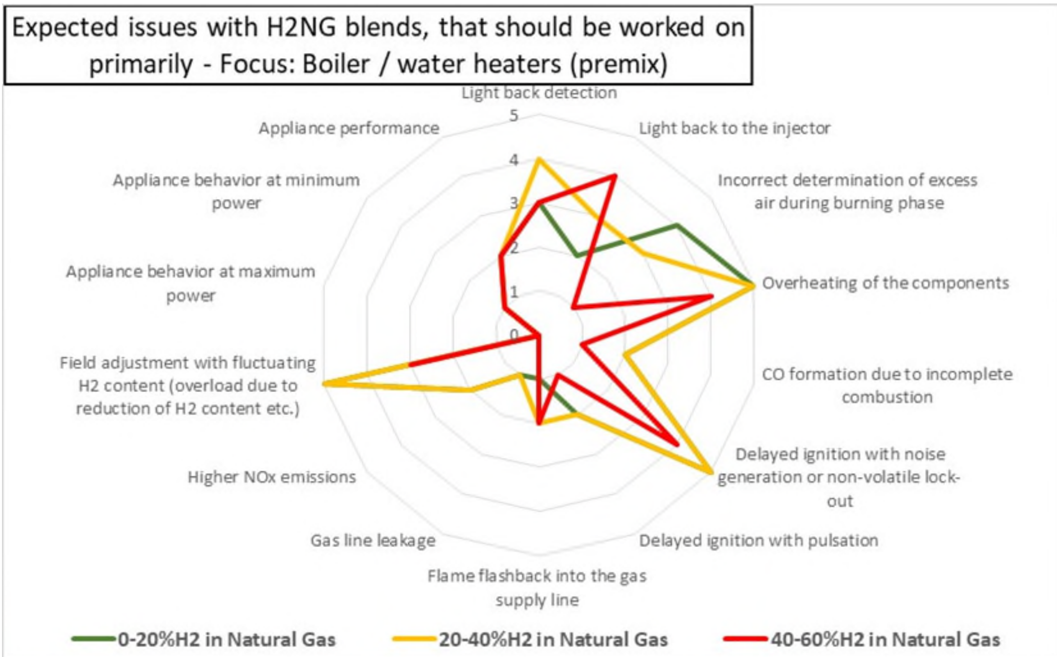
[30] SFG-Infrastructure, SFG-Utilisation. CEN SFGas GQS — Recommendations and considerations on Wobbe Index aspects related to H-gas — Final report 2021.

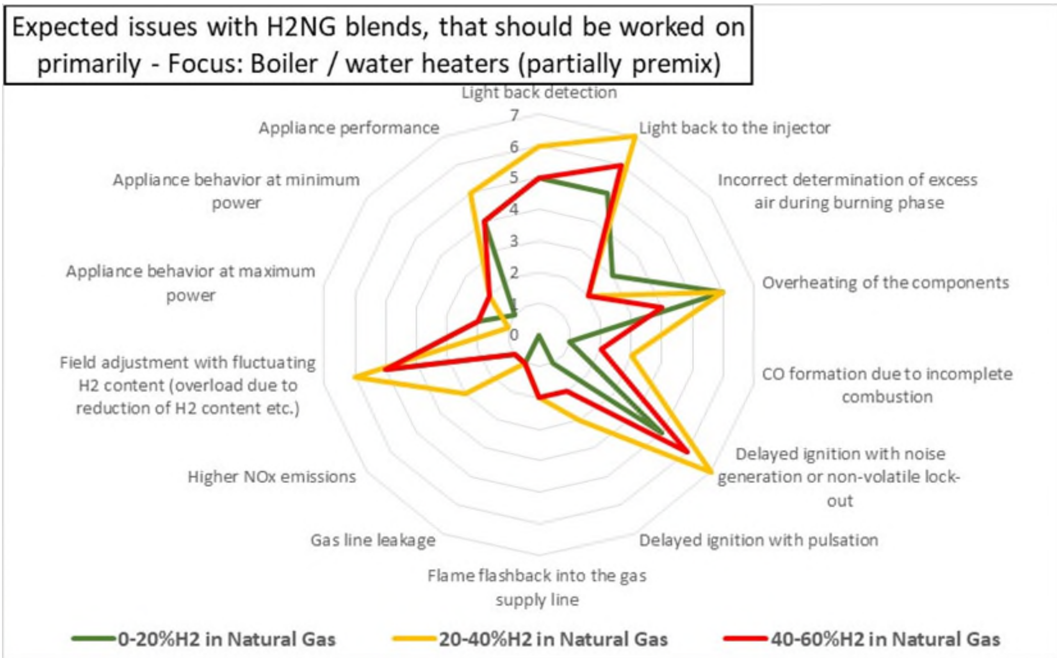
Appendix 1: results from the THyGA survey on mitigation

This appendix contains data analysis from the THyGA project survey on mitigation, gathering inputs from 15 respondents (manufacturers, associations or research center).

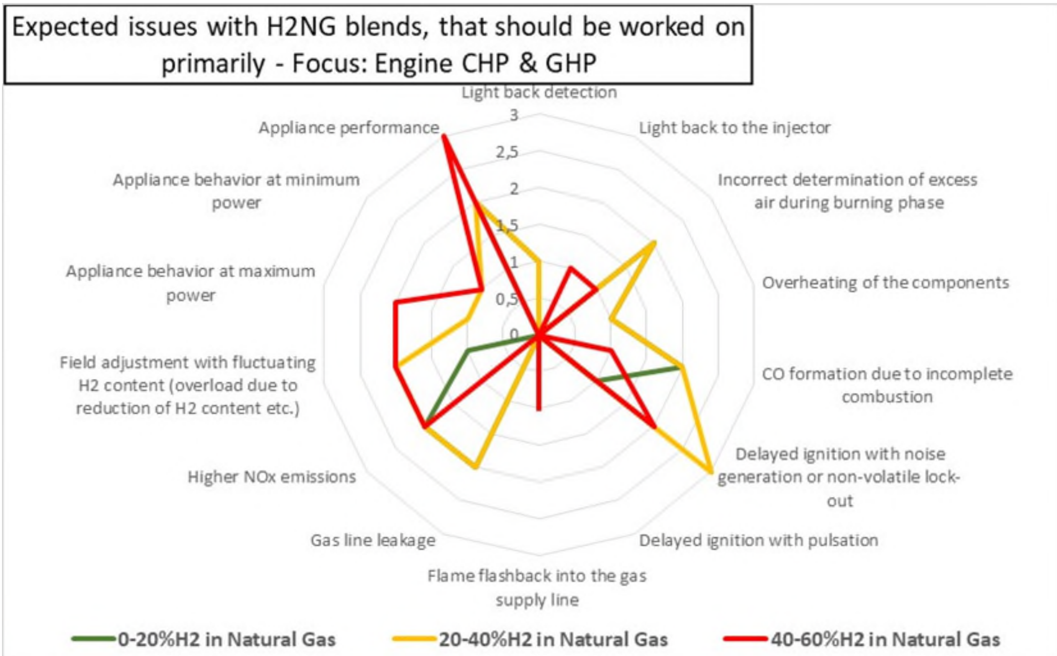
Note: the scale of the figures is voluntarily different from one to another because the goal was to assess the expected impact type of appliance per type of appliances, and not relatively (different number of answers per type of appliances).

Expected issues from H_2NG blends that should be worked on, in priority

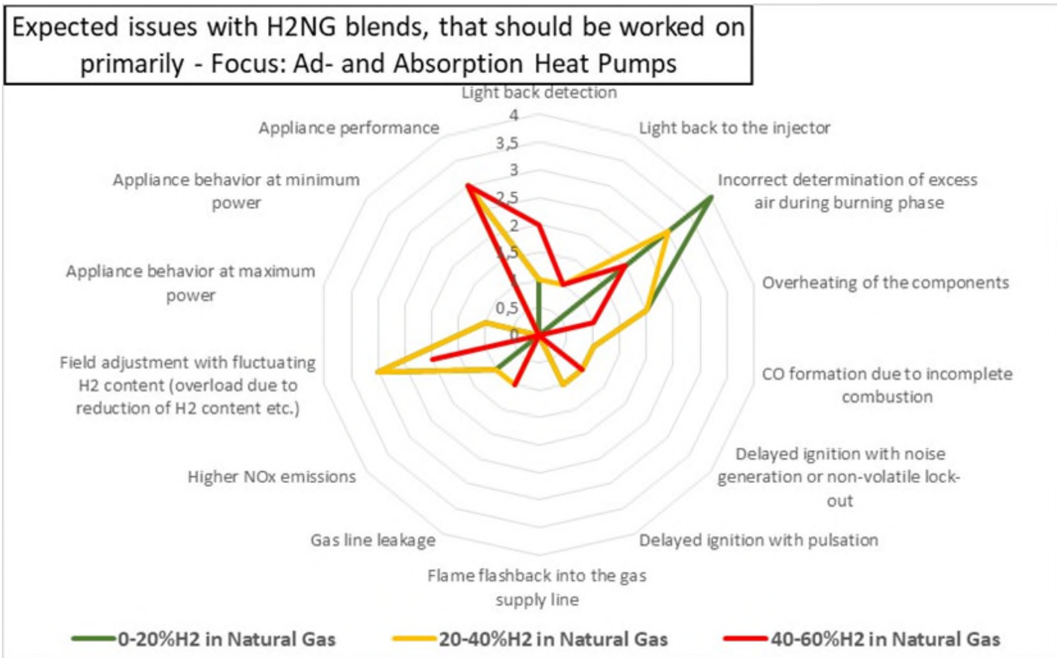


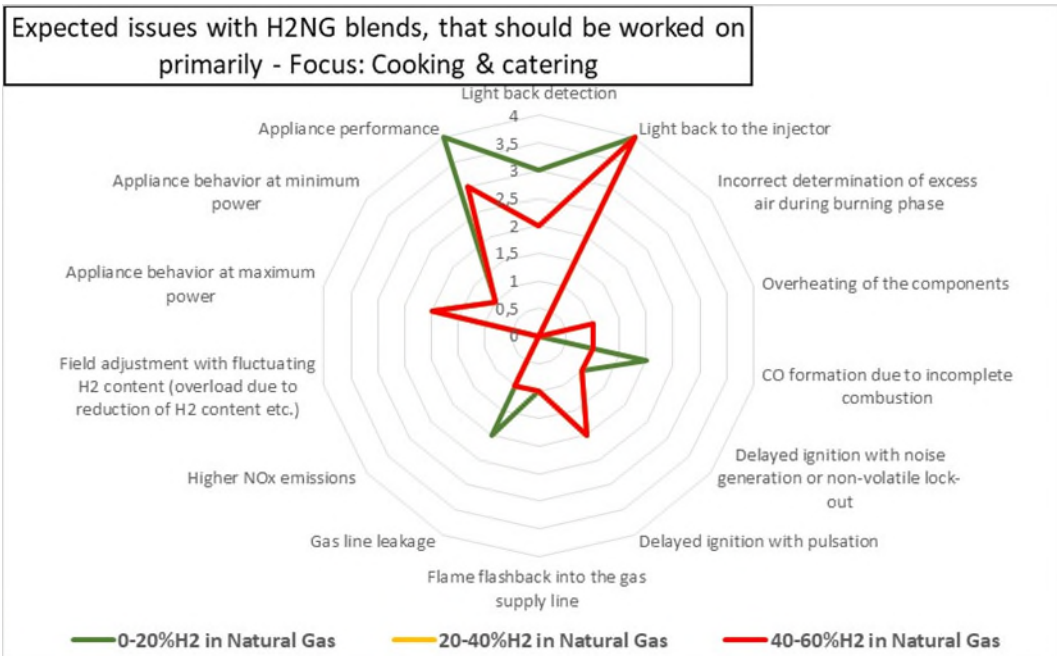


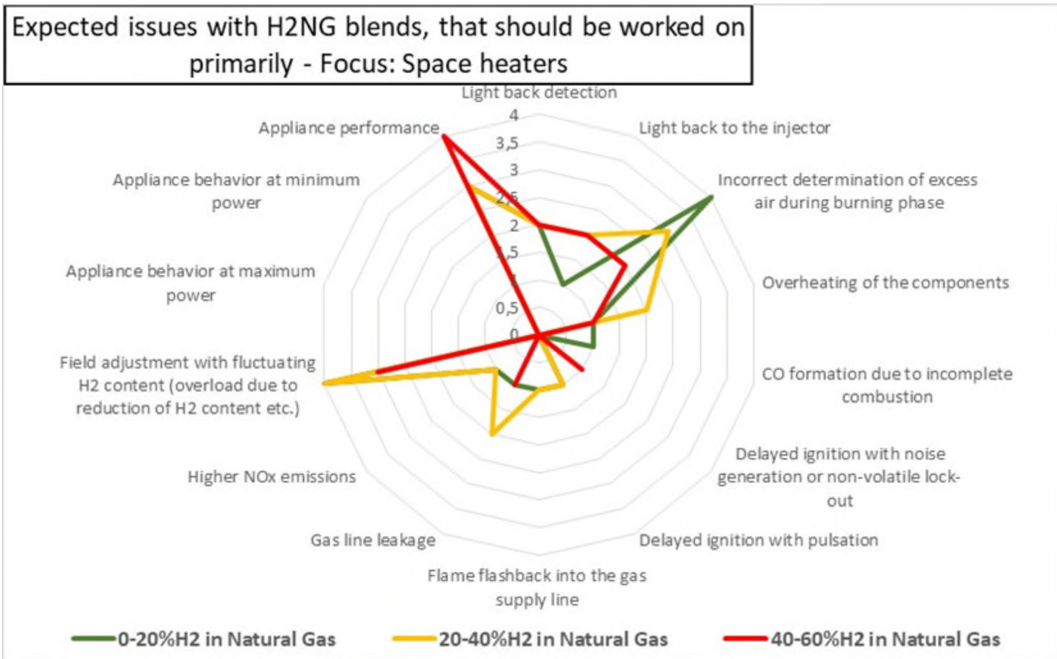
Expected issues with H2NG blends, that should be worked on primarily - Focus: Boiler / water heaters (partially premix)
Light back detection
Light back to the injector
Incorrect determination of excess air during burning phase
Overheating of the components
CO formation due to incomplete combustion
Delayed ignition with noise generation or non-volatile lock-out
Delayed ignition with pulsation
Flame flashback into the gas supply line
Gas line leakage
Higher NOx emissions
Field adjustment with fluctuating H2 content (overload due to reduction of H2 content etc.)
Appliance behavior at maximum power
Appliance behavior at minimum power
Appliance performance
0
1
2
3
4
5
6
7
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas



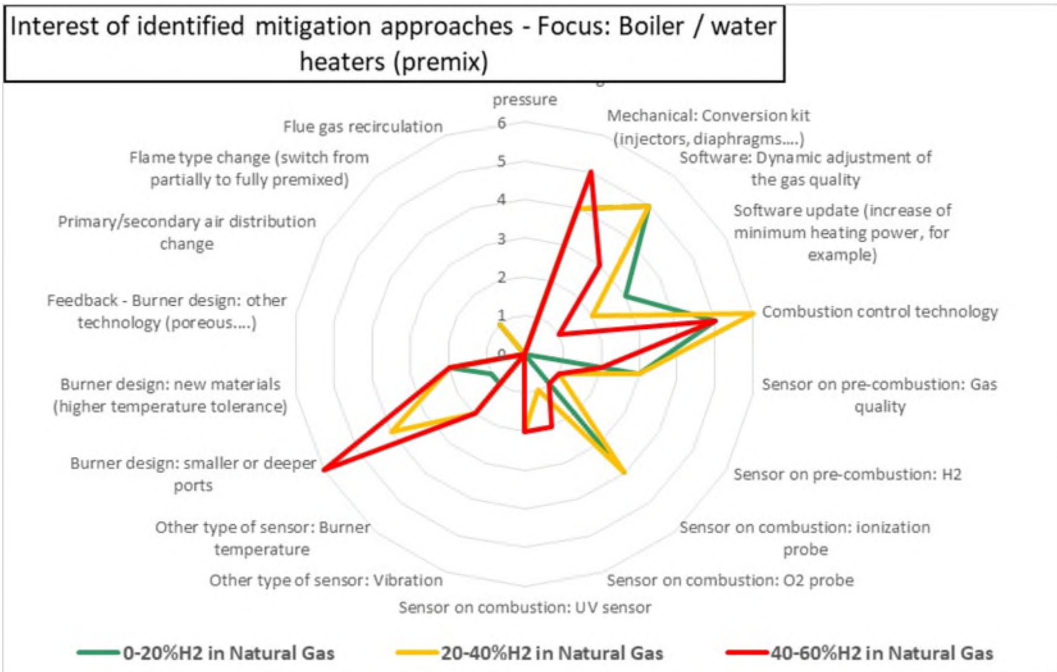
Expected issues with H2NG blends, that should be worked on primarily - Focus: Engine CHP & GHP
Light back detection
Light back to the injector
Incorrect determination of excess air during burning phase
Overheating of the components
CO formation due to incomplete combustion
Delayed ignition with noise generation or non-volatile lock-out
Delayed ignition with pulsation
Flame flashback into the gas supply line
Gas line leakage
Higher NOx emissions
Field adjustment with fluctuating H2 content (overload due to reduction of H2 content etc.)
Appliance behavior at maximum power
Appliance behavior at minimum power
Appliance performance
0
0,5
1
1,5
2
2,5
3
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas

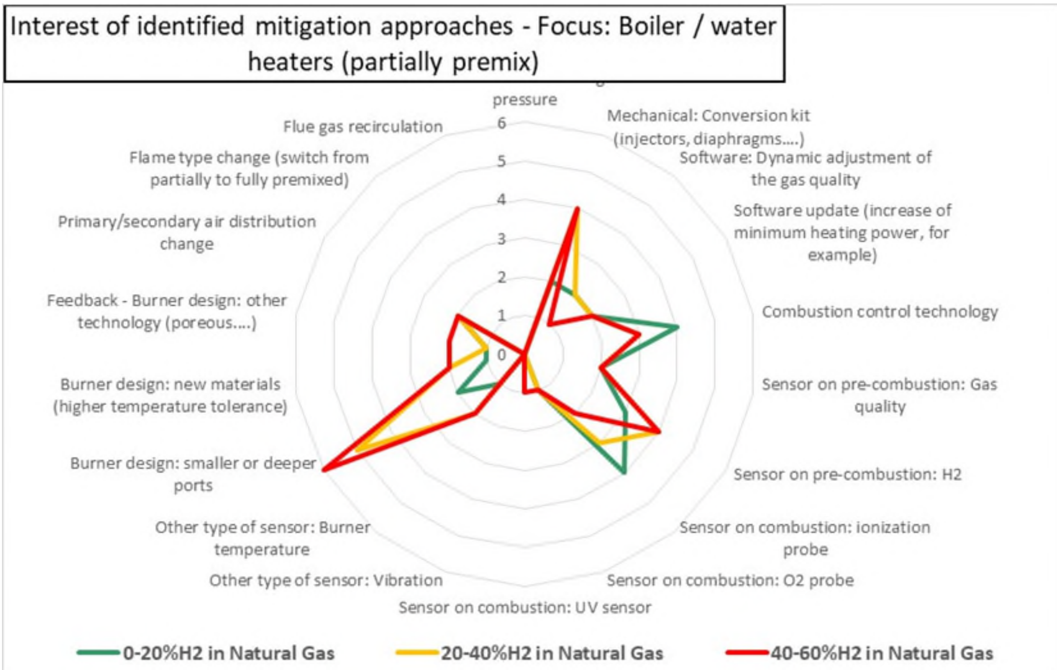

Expected issues with H2NG blends, that should be worked on primarily - Focus: Ad- and Absorption Heat Pumps
Light back detection
Light back to the injector
Incorrect determination of excess air during burning phase
Overheating of the components
CO formation due to incomplete combustion
Delayed ignition with noise generation or non-volatile lock-out
Delayed ignition with pulsation
Flame flashback into the gas supply line
Gas line leakage
Higher NOx emissions
Field adjustment with fluctuating H2 content (overload due to reduction of H2 content etc.)
Appliance behavior at maximum power
Appliance behavior at minimum power
Appliance performance
4
3,5
3
2,5
2
1,5
1
0,5
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas

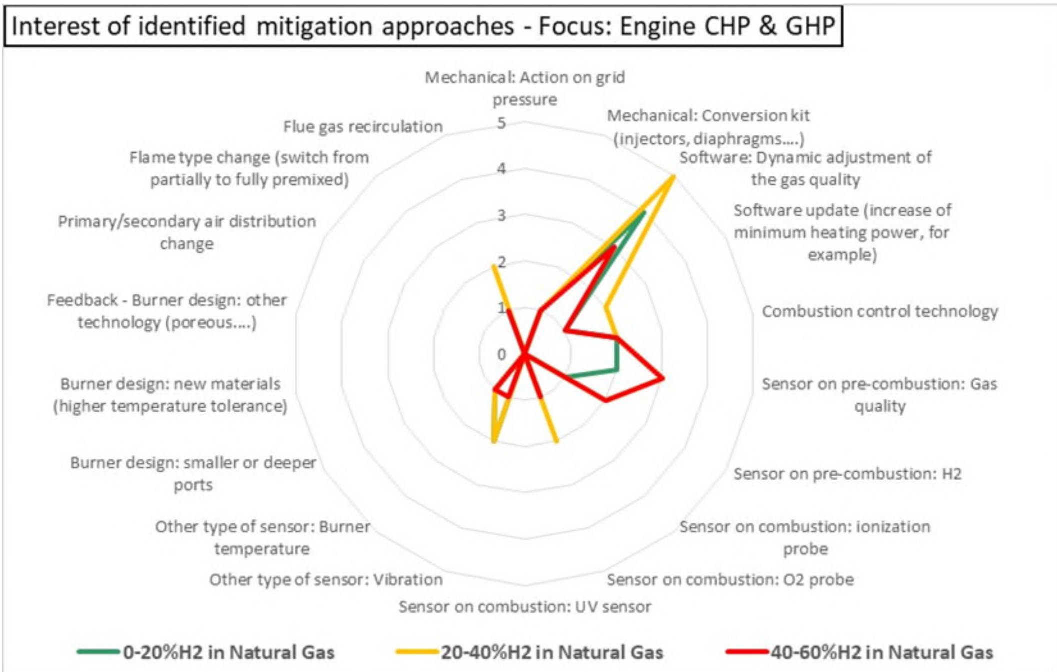

Expected issues with H2NG blends, that should be worked on primarily - Focus: Cooking & catering
Light back detection
Light back to the injector
Incorrect determination of excess air during burning phase
Overheating of the components
CO formation due to incomplete combustion
Delayed ignition with noise generation or non-volatile lock-out
Delayed ignition with pulsation
Flame flashback into the gas supply line
Gas line leakage
Higher NOx emissions
Field adjustment with fluctuating H2 content (overload due to reduction of H2 content etc.)
Appliance behavior at maximum power
Appliance behavior at minimum power
Appliance performance
4
3,5
3
2,5
2
1,5
1
0,5
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas

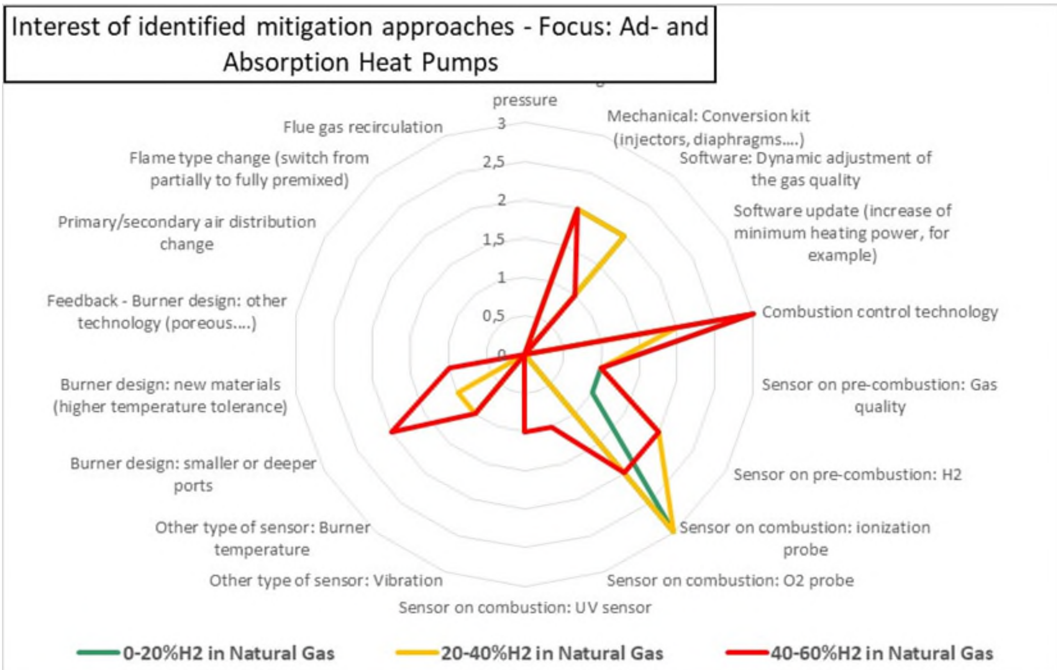

Expected issues with H2NG blends, that should be worked on primarily - Focus: Space heaters
Light back detection
Light back to the injector
Incorrect determination of excess air during burning phase
Overheating of the components
CO formation due to incomplete combustion
Delayed ignition with noise generation or non-volatile lock-out
Delayed ignition with pulsation
Flame flashback into the gas supply line
Gas line leakage
Higher NOx emissions
Field adjustment with fluctuating H2 content (overload due to reduction of H2 content etc.)
Appliance behavior at maximum power
Appliance behavior at minimum power
Appliance performance
4
3,5
3
2,5
2
1,5
1
0,5
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas

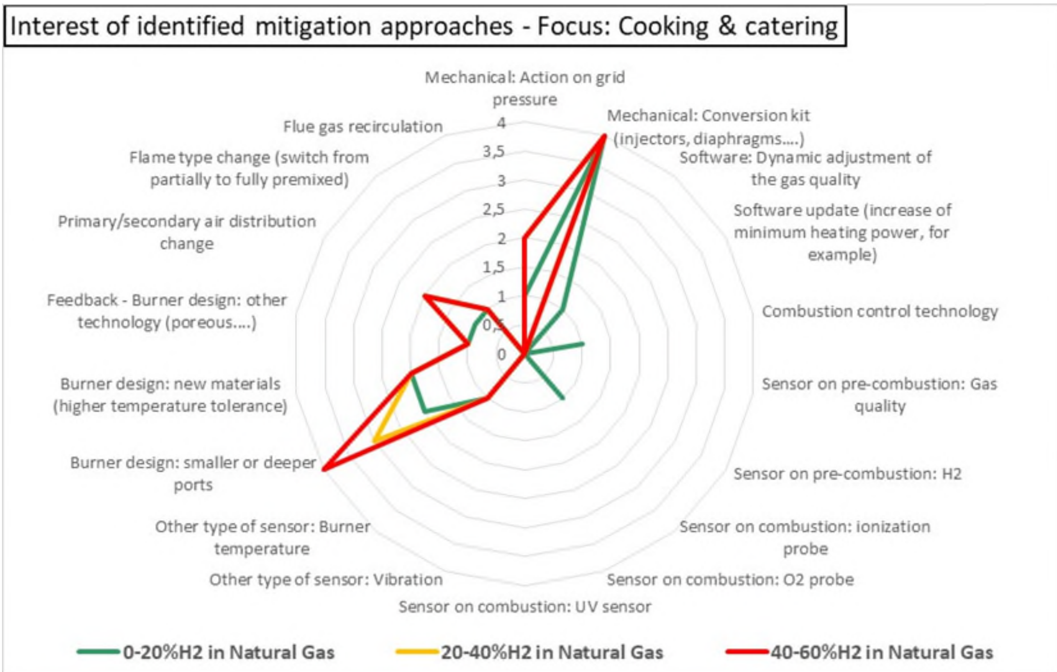
Interest of the different mitigation approaches identified in WP5

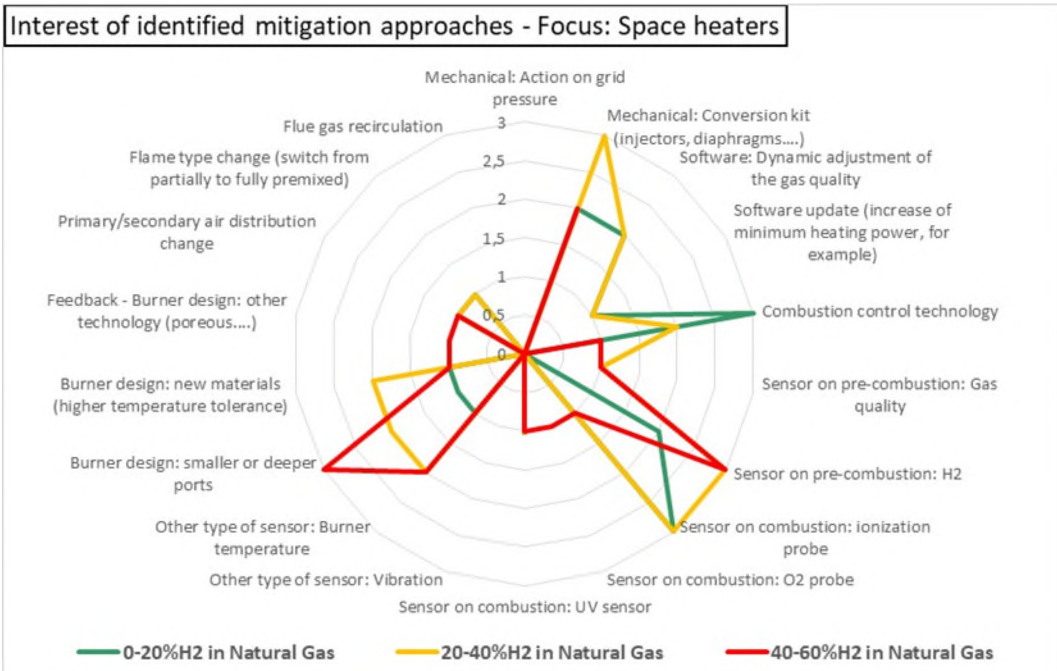


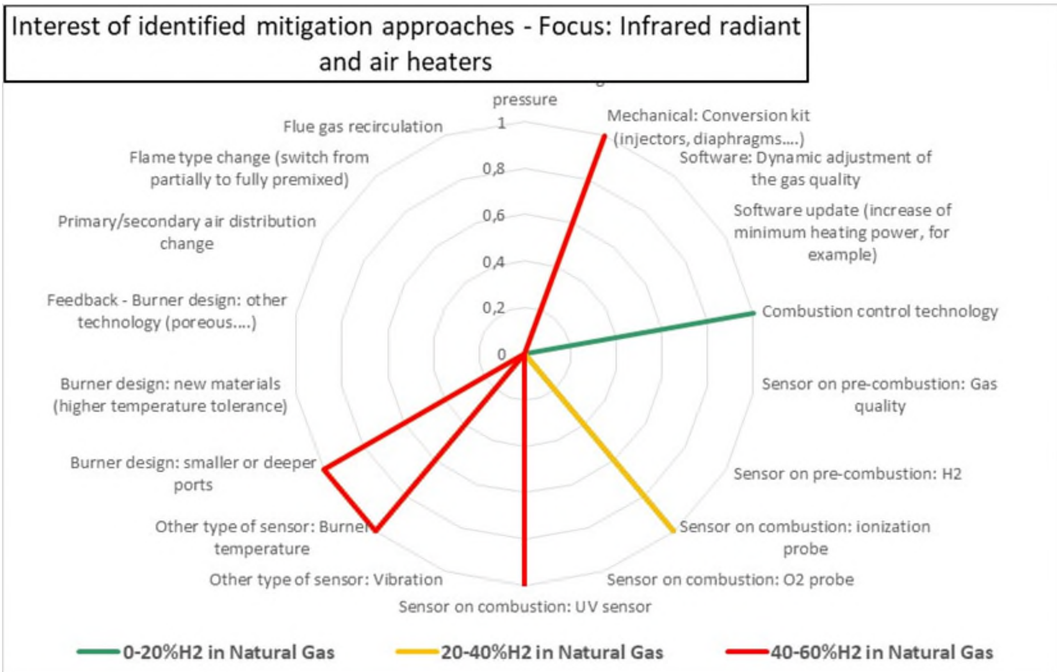



Interest of identified mitigation approaches - Focus: Engine CHP & GHP
Mechanical: Action on grid pressure
Mechanical: Conversion kit (injectors, diaphragms....)
Software: Dynamic adjustment of the gas quality
Software update (increase of minimum heating power, for example)
Combustion control technology
Sensor on pre-combustion: Gas quality
Sensor on pre-combustion: H2
Sensor on combustion: ionization probe
Sensor on combustion: O2 probe
Sensor on combustion: UV sensor
Other type of sensor: Vibration
Other type of sensor: Burner temperature
Burner design: smaller or deeper ports
Burner design: new materials (higher temperature tolerance)
Feedback - Burner design: other technology (poreous....)
Primary/secondary air distribution change
Flame type change (switch from partially to fully premixed)
Flue gas recirculation
5
4
3
2
1
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas


Interest of identified mitigation approaches - Focus: Ad- and Absorption Heat Pumps
pressure
Mechanical: Conversion kit (injectors, diaphragms....)
Software: Dynamic adjustment of the gas quality
Software update (increase of minimum heating power, for example)
Combustion control technology
Sensor on pre-combustion: Gas quality
Sensor on pre-combustion: H2
Sensor on combustion: ionization probe
Sensor on combustion: O2 probe
Sensor on combustion: UV sensor
Other type of sensor: Vibration
Other type of sensor: Burner temperature
Burner design: smaller or deeper ports
Burner design: new materials (higher temperature tolerance)
Feedback - Burner design: other technology (poreous....)
Primary/secondary air distribution change
Flame type change (switch from partially to fully premixed)
Flue gas recirculation
3
2,5
2
1,5
1
0,5
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas


Interest of identified mitigation approaches - Focus: Cooking & catering
Mechanical: Action on grid pressure
Mechanical: Conversion kit (injectors, diaphragms....)
Software: Dynamic adjustment of the gas quality
Software update (increase of minimum heating power, for example)
Combustion control technology
Sensor on pre-combustion: Gas quality
Sensor on pre-combustion: H2
Sensor on combustion: ionization probe
Sensor on combustion: O2 probe
Sensor on combustion: UV sensor
Other type of sensor: Vibration
Other type of sensor: Burner temperature
Burner design: smaller or deeper ports
Burner design: new materials (higher temperature tolerance)
Feedback - Burner design: other technology (poreous....)
Primary/secondary air distribution change
Flame type change (switch from partially to fully premixed)
Flue gas recirculation
4
3,5
3
2,5
2
1,5
1
0,5
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas


Interest of identified mitigation approaches - Focus: Space heaters
Mechanical: Action on grid pressure
Mechanical: Conversion kit (injectors, diaphragms....)
Software: Dynamic adjustment of the gas quality
Software update (increase of minimum heating power, for example)
Combustion control technology
Sensor on pre-combustion: Gas quality
Sensor on pre-combustion: H2
Sensor on combustion: ionization probe
Sensor on combustion: O2 probe
Sensor on combustion: UV sensor
Other type of sensor: Vibration
Other type of sensor: Burner temperature
Burner design: smaller or deeper ports
Burner design: new materials (higher temperature tolerance)
Feedback - Burner design: other technology (poreous....)
Primary/secondary air distribution change
Flame type change (switch from partially to fully premixed)
Flue gas recirculation
3
2,5
2
1,5
1
0,5
0
0-20%H2 in Natural Gas
20-40%H2 in Natural Gas
40-60%H2 in Natural Gas



Suggested sources of information

Additional sources of information related to actual works on mitigation have been identified through the survey:

- Projects AVACON[5] and Thüga Westküste 20 % H_2 (DVGW) in Germany
- Intergas (Netherlands) retrofitted one of their NG boilers to a H_2 boiler.
- Bekaert and DNV GL/GasTerra independently developed a hydrogen demonstration boiler by adapting an existing domestic boiler.
- In Italy a project on retrofitting has been approved in June 2021 and will start in few months. In a small area in the north of Italy (Modena area) a blend with increasing percentage of H_2 will be injected to serve about 50 end-users (mostly domestic users). The H_2 % will be: 2%-5%-10% in 2022, up to 20% by 2023. The objective is to check on the field the behaviour of the whole chain and to identify possible issues in any segment of the chain (including appliances).
- US initiatives (UC Irvine "Implications of Increased Renewable Natural Gas on Appliance Emissions and Stability", Gas Technology Institute "Fuel Interchangeability Test on Appliances") or technical documents "design of atmospheric gas burners[6]"
- DVGW Project Roadmap Gas 2050 which investigates (among other things) the impact of H_2 admixture in the grid on residential and commercial gas appliances.

[5] https://www.avacon.de/de/ueber-uns/newsroom/pressemitteilungen/erstmalig-bis-zu-20-prozent-wasserstoff-in-einem-deutschen-gasve.html

[6] https://nvlpubs.nist.gov/nistpubs/nbstechnologic/nbstechnologicpaperT193.pdf