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

WP3: Report on the impact of H2 concentrations on safety, efficiency, emissions, and correct operation for different segments of appliances

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Executive summary

The present report is presenting all WP3 short-term tests and analyses.

About 100 appliances have been tested in different segments, defined in the task 2.1 with H2 up to 60%. The results show that the main observations and analyses from the literature (Tasks 2.2 and 2.3) are confirmed, and new findings are also made.

Limitations of our conclusions

As for any study, the conclusions made on the work done will have natural limitations and uncertainties.

One of the main limitations is the number of appliances tested; 100 appliances were tested when more than 200M are installed, and this leads especially to uncertainties for the segments where only few (sometimes only one) appliances were tested.

Safety and operational

Some appliances designed for natural gas may have issues with providing the purpose they are intended for because of the change in flame colour (can impact decorative space heaters) or because of reduction of power leading to longer cooking duration or comfort (sanitary hot water).

Performances & emissions

The impact of H2NG blends on appliances' NOx emissions is for the vast majority positive (decrease of measured emissions).

The impact on appliance efficiency is generally very modest and can be either positive or negative.

Recommendations for future testing

The tests done for the project has enabled us to be conclusive on many aspects. For some other aspects it would be highly recommended to have more extensive testing to be more conclusive. Especially the delayed ignition should be more widely investigated.

Acknowledgments

The authors of the present report wants to express their special gratitude to

- Appliances manufacturers having kindly provided their appliances for testing in WP3 or help with support.

  AGA Rangemaster, AO Smith, AristonThermo, ATAG, Bosch, Broetje, BSH, Carlieuklima, Carrier, Ebmp-papst, EC Power, Electrolux professional, Gogas, Groupe Atlantic, GWM, Immergas, Kalfire, Lacanche, MEMS, MKN, MTT, Nortek, Qtec, Percy Doughty, Remeha, Schwank, Senertec, SolidPower, Systema, Vaillant, Viessmann, Weishaupt, Wolf

- Appliances manufacturers partners in this project BDR Thermea and Electrolux) having helped with the analysis of the results with their deep expertise and knowledge.

- External (to the project) laboratories having tested appliances with the same protocol as developed in the project and shared their results with the project team: Applus and some manufacturers

- Experts from associations and CEN TCs which provided their advises on the test protocol and our analysis (adjustment etc.)

Table of contents

List of abbreviations

Non-Technical

AP	Advisory Panel Group
CBP	Common Business Practices are “standards, procedures and/or protocols commonly used throughout the gas industry in Europe”
FCH 2 JU	Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership)
GA	Grant Agreement
GAR	Gas Appliances Regulation
MS	Milestone
TC	Technical Committee (of CEN)
WP	Work Package

Gases

CH_4	Methane
CNG	Compressed Natural Gas
EU low	Lowest real gas specifications for the Wobbe distributed in the EU (H gas)
EU high	Highest real gas specifications for the Wobbe distributed in the EU (H gas)
H gas	Family of gases of “High calorific value” distributed in EU having specification close to methane (G20) by opposition to L gas (Family of gases of “Low calorific value”)
G20	G20 is pure CH_4
G23	G23 is a limit gas containing CH_4 and N_2, it has a Wobbe Index below EU low
Limit gases:	EN437 defines limit gases as "*test gas representative of the extreme variations in the characteristics of the gases for which appliances have been designed*". Limit gases are used for the certification of gas appliances. The following gases are generally used for the certification of appliances using of H gas: • *G21 → incomplete combustion + sooting* • *G222 → light back* • *G23 → flame lift* • *G24 → overheating*
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas (usually propane or butane), not considered as a “natural gas”

Technical

A/F ratio	Air/Fuel ratio, linked to the air excess
λ	Air excess (see above) is the ratio (air used/air needed for a stoichiometric combustion)
CHP	Combined heat and power
CO	Carbon monoxide
CO_2	Carbon dioxide
DAF: “dry, air free”.	This is used in boilers and other appliances standards to express pollutant emission concentrations (CO, NOx, etc.) values in the flue gases. The concentration of pollutant species is measured and then corrected to “dry- air free” which is the same as “dry- 0% O2”.
FB	Flashback
FC	Fuel Cell
GHP	Gas Heat Pump
H2	Hydrogen
H2NG	Hydrogen / Natural Gas blend
HE	Hydrogen Embrittlement
HP	Heat Pump
Hi or Hs	Heating value (Hi: inferior; Hs: superior) (net, gross)
ICE	Internal Combustion Engine
MN	Methane Number
N_2	Nitrogen
O_2	Oxygen
P.C.B.	Printed Circuit Board
Qmin	Minimum heat input of an appliance (kW)
Qmax	Maximum heat input of an appliance (kW)
ROC	Rate of change (of percentage of H2, increasing or decreasing rate). ROC test is performed by changing rapidly the gas composition flowing to the tested appliance.
s_L	Laminar combustion velocity (Flame speed or Specific Velocity)
TTB	Combustion Product Discharge Safety Device (TTB)
UHC	Unburned hydrocarbons
UH	Unburned hydrogen
Wi or Ws	Wobbe Index (Wi: inferior; Ws: superior) (net, gross)

Controls

PGS	Pneumatic gas supply
PGAR	Pneumatic gas air ratio
eGAR	Electronic gas air ratio
ACCF	Adaptive combustion control function

Definitions

Stoichiometric combustion: Combustion with exactly the quantity of air needed to burn all the gas /fuel.

Cold start / Hot start: Testing conditions where appliances are cold or hot, respectively. Cold tests are generally carried out as a first test in the morning after a night where the appliance is not running. Hot start conditions are obtained when the appliance is restarted after few minutes after it was stopped. The main objective of the test is to check the operation of the appliance: can it restart without troubles or not (e.g. does it need several ignition attempts etc.?)?

%H2 is the volume percentage of hydrogen blended with natural gas

Introduction

This report gathers the results from the THyGA "short-term" test campaign, over almost 3 years of laboratory activity.

Short-term tests are carried out to observe how appliances react during a small duration (few minutes to few hours) on different H2NG mixtures, while long-term tests are designed to evaluate behaviour over several weeks.

The analysis is based on the test of 102 appliances (burners), it covers almost all the segments identified at the beginning of the project /4/ according to their type (boiler, water heater…) and combustion specificities (partially premix, fully premix…).

Deliverable situation for WP3

Table 1 gives the public deliverables listed in the Grant Agreement for WP3. The present report is the deliverable D3.8 "Segment of technologies by segment report on the impact of the different H2 concentrations on safety, efficiency, emissions and correct operation" within Task 3.2 of the THyGA project. It includes the results from the short-term tests realized on appliances selected by the project (selection done within WP2) and completes intermediate report D3.5.

Deliverable D3.9 covers the results of the long-term tests.

Table 1: List of public deliverables from the THyGA project 's WP3

D3.5	Intermediate segment of technologies by segment report on the impact of the different H2 concentrations on safety, efficiency, emissions and correct operation	Report
D3.6	Intermediate long-term effect of H2 on appliances tested	Report
D3.7	Testing done on components (new and taken from existing installation) from different countries including statistics on results obtained for the leakage testing	Report
D3.8	Segment of technologies by segment report on the impact of the different H2 concentrations on safety, efficiency, emissions and correct operation	Report
D3.9	Long term effect of H2 on appliances tested	Report
D3.10	Compiling of results from all tasks and development of further statistics at EU and country level	Report

1 Work carried out in WP3 for short term testing and working method

1.1 WP3 – Experimental Work

The main goals of the WP3 as defined in the project's Grant Agreement[1] are:

1. To define a **detailed test protocol** based on WP2 input in order to define accurately the details of the testing procedures and to guarantee the best possible reproducibility of testing and to make sure that all elements needed for the analysis are included in the reports.
2. To **execute short- and long-term tests** on as many appliances as possible to achieve conclusions on sensitivity to H2 by segments of technologies.
3. To **check the tightness of present indoor installation and appliance components** to H2NG admixture.

The present report covers the short-term tests of point 2, long-term tests are dealt with in D3.9 and leakage tests in D3.7. /5/

1.2 Elaboration of the protocol

The testing procedure in WP3 is based on a protocol that was developed in the early stage of the project, conjointly with WP2 (Task 2.5). The steps of elaboration and interactions with the stakeholders are more precisely described in the public deliverable D2.5 /6/ ("Testing programme for hydrogen tolerance tests of domestic and commercial natural gas appliances").

It is important to note that:

- the project tried to elaborate a test protocol as accurate as possible (for the test description), to achieve a **high reproducibility** between labs.
- All aspects related to identified hydrogen impact on appliances are subject to testing, described and integrated in the protocol, so that we can be **as conclusive as possible** at the end of the project.

To reach these two objectives, a lot of efforts was made to describe as accurately as possible the methodology, and a wide range of stakeholders have been involved in the formulation of the testing protocol, to make sure we integrate all existing experience on the topic. Several phases of implementations were needed for a stabilized version of the test protocol.

Phase 1. Preliminary (experimental) protocol (Jan - May 2020)

This phase was based on:

1. Initial analysis of past/previous projects, which tested gas appliances with H2NG blends.
2. An extended analysis of the effect of H2, based on a simple calculation tool (laminar flame velocity calculation) in order to determine the most crucial situations for H2NG blends.

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[1] https://cordis.europa.eu/project/id/874983

3. The integration of the conclusions of a similar project (GASQUAL, impact on gas quality on domestic appliances).
4. First discussions with all partners (end of January 2020) during the Kick-off meeting.

The preliminary protocol was the subject of several discussions within THyGA consortium and was later sent to the stakeholders (mainly manufacturers and associations in the advisory panel group of the project).

Phase 2. Protocol discussion with the stakeholders (May 2020 and later)

The protocol was presented during a first public event workshop (1st THyGA public Workshop, 6th of May 2020) before being discussed again in further detail in a second workshop including only stakeholders from the advisory panel group (19th of May 2020). The document had previously been sent to this group and also to CEN Technical Committees, to gather as much feedback as possible. Some specific points were also discussed with stakeholders in various bilateral meetings. The protocol was improved and updated following the feedbacks and comments gathered.

Phase 3. Protocol for real use (June 2020 and later)

The testing protocol was implemented as a practical tool for testing (test sheets & reports) developed in Excel and used as a basis for the tests. The first tests started before the summer 2020 at DGC and GAS.BE and later at GWI for testing/validation of the protocol.

The results were discussed between the labs, and several improvements and corrections were brought to the protocol in order to consider the reality of testing and the first findings.

During this phase, each new test was analysed, and the new information was used to optimise and further improve the protocol in order to get the most results from the resources allocated. This resulted typically in removing part of some tests that were not contributing very much information and replacing them by others that brought more added value to the tests and to the project.

However, the project team stated that the testing procedure could only be considered stable by M12; this version was also described and shared with 10 "external labs"[2]. Since then, minor changes and corrections have been added in the light of regular laboratory discussions (every month).

Phase 4. Protocol further improvements (from December 2020 – March 2022)

Each analysis of a new test result sheds light on how appliances' safety, emissions and performance are impacted by H2 (one of the main goals of WP3). The test results and exchanges with manufacturers on the results also raised new questions.

Therefore, to treat the question of tolerance to H2 extensively, it was needed to be open to further adaptation of the protocol: mostly minor modifications of the existing protocol and developments of operational details on some tests were needed, especially for new appliances not yet tested in the THyGA test programme. Most of the changes implemented were improvements of the reporting tools (Excel sheets) used for capitalization and comparison of results. In practice, we have made only slight

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[2] « External Labs »: independent laboratories interested in putting in practice the THyGA protocol within their facilities; their results could be added to the THyGA's tests to improve the final analysis of the project.

changes to the protocol until March 2022 (but also added new tests needed for WP4 and WP5 at a later stage).

Some additional information regarding the test protocol

- Given the strategy proposed by most DSO/TSOs, the injection to levels higher than 30% H2 seems unlikely technically and economically, from a grid perspective. **Thus, in agreement with the FCH 2 JU** (now Clean Hydrogen Partnership), **THyGA proposed to focus on hydrogen rates below 30% at the beginning of the project**, while still investigating up to 60% (according to the Grant Agreement).
- The test protocol has been challenged by partners and external stakeholders, it **covers all points from the Grant Agreement, but also includes optional tests,** providing complementary information, and was carried out according to project needs and possibilities (agreement from the manufacturer, availability from the lab, budget, etc.).

Many meetings and communication meetings both within and outside the project were organised: this large number of interactions was very positive for sharing knowledge and dissemination, very useful input was received from the industry (manufacturers and TCs) and implemented in the work programme.

WP3 has also organised a specific informal workshop on UHC (Unburned Hydrocarbon) measurements, that were part of the testing programme. This was done in synergy with other projects and has helped laboratories to measure those emissions in a harmonised way.

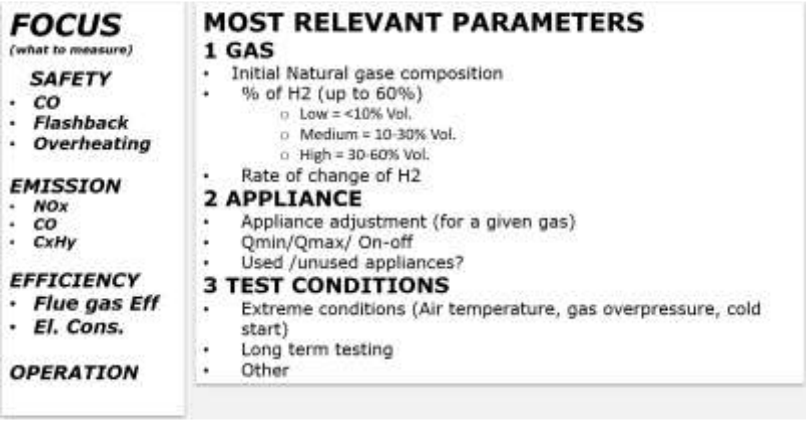
1.3 Content of the protocol & test program

THyGA is looking at four main aspects of H2 injection in natural gas:

1. Impact on appliance safety.
2. Impact on appliance emissions.
3. Impact on appliance performance.
4. Impact on appliance operation.

In practice, we organised the tests in a way to optimise the costs and gathered set points where we could find synergies (for example, some of the safety tests could be combined with performance and emissions tests).

In order to assess these four aspects, we defined the gases relevant for the tests, but also all other operation and test conditions that would allow us to make conclusions on the ability of appliances to deal with H2NG blends.



FOCUS
(what to measure)

SAFETY
- **CO**
- **Flashback**
- **Overheating**

EMISSION
- **NOx**
- **CO**
- **CxHy**

EFFICIENCY
- **Flue gas Eff**
- **El. Cons.**

OPERATION

MOST RELEVANT PARAMETERS

1 GAS
- Initial Natural gase composition
- % of H2 (up to 60%)
  - Low = <10% Vol.
  - Medium = 10-30% Vol.
  - High = 30-60% Vol.
- Rate of change of H2

2 APPLIANCE
- Appliance adjustment (for a given gas)
- Qmin/Qmax/ On-off
- Used /unused appliances?

3 TEST CONDITIONS
- Extreme conditions (Air temperature, gas overpressure, cold start)
- Long term testing
- Other

Figure 1: Overall THyGA Test program.

The details of the protocol are given in deliverable D2.5, but for a good understanding of the present report, the main aspects of the testing protocol and test programme are summarized in the next section.

1.4 Test gases for the short-term tests

Short-term tests were carried out to observe how appliances reacted in the short term (few minutes to few hours) to different H2NG blends. The evaluation covers safety, energy efficiency, emissions as well as operational aspects (checking that the appliance is fit for the purpose).

The range of gases chosen for the testing is taken from a statistical analysis of a JRC/ENTSOG study of 2019[3] on distributed natural gas qualities (H-Gas) in the EU. The idea is to test appliances within the extrema of observed ranges of gases transported in Europe.

- *"The data source for the sensitivity analysis is public, gas quality data for 2015 and 2016 were provided by ENTSOG for the CEN, FGas study on natural gas quality. These data sets correspond to a limited subset of all points. The numbers on the graph are the measured 99th percentile Superior Wobbe Index (15C/15C) of each individual data set. The 1-99th percentile of data was analyzed, as decided upon by SFGas TF1 of the study on gas quality.*
- *The distributed gas quality conformed to national specifications. The size of the markers corresponds to capacity, not actual flow rates."*

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[3] Pre-normative study of H-gas quality parameters" Survey 2 Information on the currently distributed natural gas quality in different European member states, JRC Zaccarelli, N., Weidner

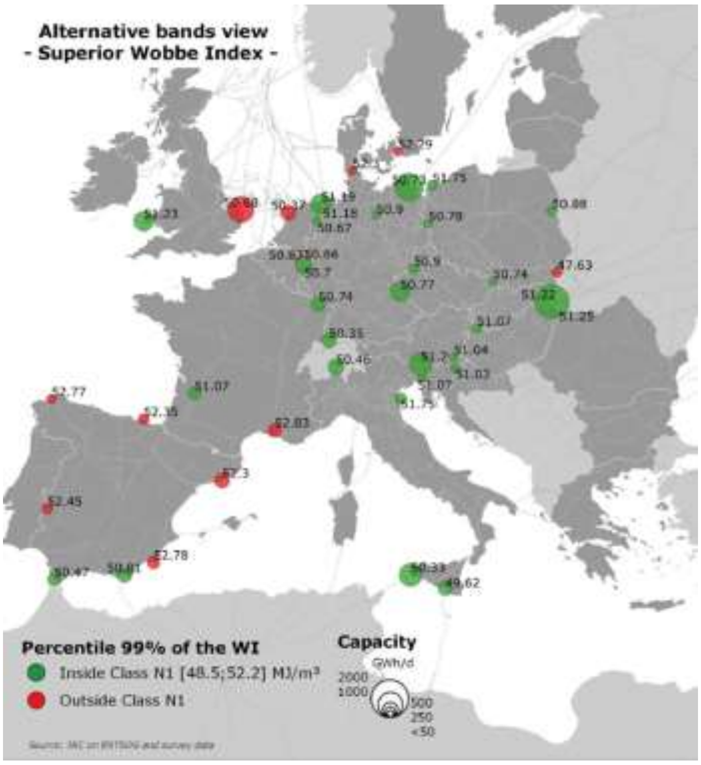


Figure 2: Range of Wobbe Index (superior) transported in Europe from SFGas WG "Pre-normative study of H-gas quality parameters" Survey 2 Information on the currently distributed natural gas quality in different European member states, JRC Zaccarelli, N., Weidner.

According to this study,

- The actual gas specifications for the Wobbe (Ws) distributed in the EU are between = 47,63 (EU LOW) to 52,78 (EU HIGH) MJ/m3 (15/15) (dWobbe= 5,15 MJ).
- The two limits (EU LOW and EU HIGH) were used for the project.

In THyGA,

- **EU HIGH is defined as a combination of a binary blend of $CH_4 + C_3H_8$**
- **EU LOW as a binary blend of $CH_4 + N_2$.**

Adding hydrogen to these two gases will bring variation in both Wobbe (Ws) and relative density as shown on Figure 3.

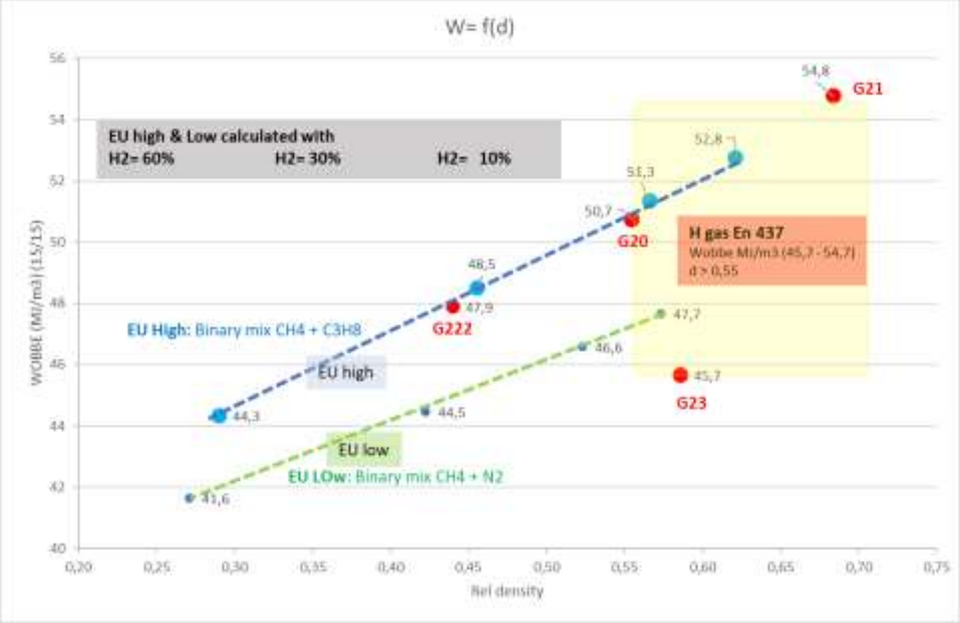


Figure 3: Wobbe (Ws) and Density variations for "EU low" and "EU high" with hydrogen (0, 10, 30, 60%).

The yellow area defines the specifications of the H gas (gross Wobbe index and density) according to the EASEE-gas CBP. The Wobbe has a range from 46.44 to 54.00 MJ/m3 and the relative density from 0.555 to 0.70.

Nominal gases chosen for the tests are CH_4, EU LOW, EU HIGH combined with H2. In addition, tests included various scenarios of adjustment with these gases (with/without H2) and the use of gases at the other extreme of the range (with and without H2), as described in 2.1.

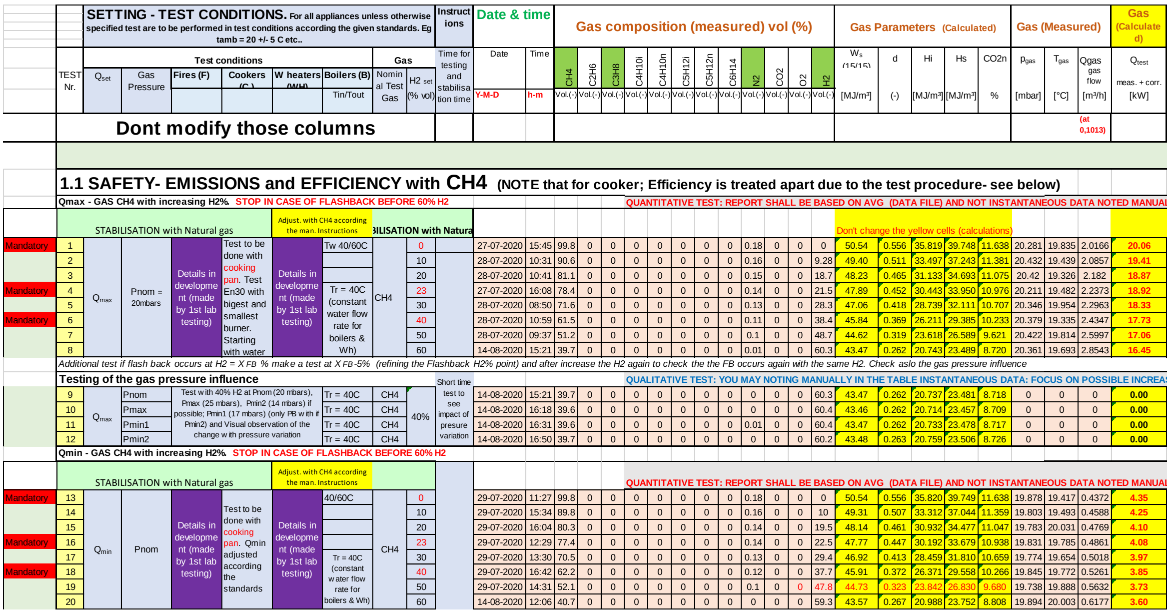
Gas composition (measured) vol (%)												Gas Parameters (Calculated) REF 0/0				
CH4	C2H6	C3H8	C4H10	C4H10i	C5H12	C5H12i	C6H14	N2	CO2	O2	H2	Ws	d	Hi	Hs	CO2n
Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	[MJ/m³]	(-)	[MJ/m³]	[MJ/m³]	%
With CH4 as initial gas																
100											0	53,47	0,555	35,818	39,840	11,638
90											10	52,17	0,507	33,314	37,135	11,360
80											20	50,87	0,458	30,810	34,430	11,031
77											23	50,48	0,443	30,058	33,618	10,920
70											30	49,58	0,409	28,306	31,724	10,634
60											40	48,30	0,361	25,802	29,019	10,148
50											50	47,08	0,312	23,298	26,314	9,538
40											60	45,96	0,264	20,793	23,609	8,749
With EU low as initial gas																
95.6								4.4			0	50,30	0,573	34,242	38,087	11,637
86.04								3.96			10	49,17	0,523	31,896	35,557	11,347
76.48								3.52			20	48,04	0,473	29,549	33,027	11,004
73.61								3.388			23	47,71	0,457	28,845	32,268	10,888
66.92								3.08			30	46,94	0,422	27,203	30,497	10,592
57.36								2.64			40	45,87	0,372	24,856	27,967	10,088
47.8								2.2			50	44,87	0,321	22,510	25,438	9,459
38.24								1.76			60	44,00	0,271	20,163	22,908	8,650
With EU high as initial gas																
93		6.6									0	55,51	0,621	39,472	43,759	11,850
84		5.94									10	54,04	0,566	36,602	40,662	11,692
75		5.28									20	52,55	0,511	33,733	37,565	11,384
72		5.082									23	52,10	0,495	32,872	36,636	11,280
65		4.62									30	51,05	0,456	30,863	34,468	11,011
56		3.96									40	49,56	0,401	27,994	31,371	10,551
47		3.3									50	48,10	0,346	25,124	28,274	9,967
37		2.64									60	46,72	0,290	22,255	25,176	9,204

Figure 4: Various gas compositions for the test gases for THyGA project (THY_WP3_019_DataSheet oct 2020c D4) and indicative values for the Wobbe, calorific values and density.

1.5 Reporting methodology

The report is based on a spreadsheet that laboratories were asked to fill with data and comments about the results obtained.

- The spreadsheet file includes several sheets each having a specific function.
- The data sheet is identical for all appliances (and therefore a bit bulky (400 lines X 240 columns)), it provides all details on the tests and includes all data, text fields, instructions and calculations (gas parameters based on composition, emissions under reference conditions etc.).



		SETTING - TEST CONDITIONS. For all appliances unless otherwise specified test are to be performed in test conditions according the given standards. Eg tamb = 20 +/- 5 C etc..								Instructions	Date & time		Gas composition (measured) vol (%)												Gas Parameters (Calculated)					Gas (Measured)			Gas (Calculated)
	TEST Nr.	Test conditions						Gas		Time for testing and stabilisation time	Date	Time	CH4	C2H6	C3H8	C4H10i	C4H10n	C5H12i	C5H12n	C6H14	N2	CO2	O2	H2	W_s (15/15)	d	Hi	Hs	CO2n	p_{gas}	T_{gas}	Qgas gas flow	Q_{test} meas. + corr.
		Q_{set}	Gas Pressure	Fires (F)	Cookers (C)	W heaters (WH)	Boilers (B)	Nominal Test Gas	H2 set (% vol)																								
							Tin/Tout				Y-M-D	h-m	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	Vol.(-)	[MJ/m³]	(-)	[MJ/m³]	[MJ/m³]	%	[mbar]	[°C]	[m³/h]	[kW]
		Dont modify those columns																														(at 0,1013)	
	1.1 SAFETY- EMISSIONS and EFFICIENCY with CH4 (NOTE that for cooker; Efficiency is treated apart due to the test procedure- see below)																																
	Qmax - GAS CH4 with increasing H2%. STOP IN CASE OF FLASHBACK BEFORE 60% H2														QUANTITATIVE TEST: REPORT SHALL BE BASED ON AVG (DATA FILE) AND NOT INSTANTANEOUS DATA NOTED MANUAL																		
		STABILISATION with Natural gas				Adjust. with CH4 according the man. Instructions		BILISATION with Natura																	Don't change the yellow cells (calculations)								
Mandatory	1	Q_{max}	Pnom = 20mbars	Details in development (made by 1st lab testing)	Test to be done with cooking pan. Test En30 with bigest and smallest burner. Starting with water	Details in development (made by 1st lab testing)	Tw 40/60C	CH4	0		27-07-2020	15:45	99.8	0	0	0	0	0	0	0	0.18	0	0	0	50.54	0.556	35.819	39.748	11.638	20.281	19.835	2.0166	20.06
	2								10		28-07-2020	10:31	90.6	0	0	0	0	0	0	0	0.16	0	0	9.28	49.40	0.511	33.497	37.243	11.381	20.432	19.439	2.0857	19.41
	3								20		28-07-2020	10:41	81.1	0	0	0	0	0	0	0	0.15	0	0	18.7	48.23	0.465	31.133	34.693	11.075	20.42	19.326	2.182	18.87
Mandatory	4						Tr = 40C (constant water flow rate for boilers & Wh)		23		27-07-2020	16:08	78.4	0	0	0	0	0	0	0	0.14	0	0	21.5	47.89	0.452	30.443	33.950	10.976	20.211	19.482	2.2373	18.92
	5								30		28-07-2020	08:50	71.6	0	0	0	0	0	0	0	0.13	0	0	28.3	47.06	0.418	28.739	32.111	10.707	20.346	19.954	2.2963	18.33
Mandatory	6								40		28-07-2020	10:59	61.5	0	0	0	0	0	0	0	0.11	0	0	38.4	45.84	0.369	26.211	29.385	10.233	20.379	19.335	2.4347	17.73
	7								50		28-07-2020	09:37	51.2	0	0	0	0	0	0	0	0.1	0	0	48.7	44.62	0.319	23.618	26.589	9.621	20.422	19.814	2.5997	17.06
	8								60		14-08-2020	15:21	39.7	0	0	0	0	0	0	0	0.01	0	0	60.3	43.47	0.262	20.743	23.489	8.720	20.361	19.693	2.8543	16.45
	Additional test if flash back occurs at H2 = X_{FB} % make a test at X_{FB}-5% (refining the Flashback H2% point) and after increase the H2 again to check the the FB occurs again with the same H2. Check aslo the gas pressure influence																																
	Testing of the gas pressure influence									Short time test to see impact of presure variation					QUALITATIVE TEST: YOU MAY NOTING MANUALLY IN THE TABLE INSTANTANEOUS DATA: FOCUS ON POSSIBLE INCREA																		
	9	Q_{max}	Pnom	Test with 40% H2 at Pnom (20 mbars), Pmax (25 mbars), Pmin2 (14 mbars) if possible; Pmin1 (17 mbars) (only PB with if Pmin2) and Visual observation of the change with pressure variation			Tr = 40C	CH4	40%		14-08-2020	15:21	39.7	0	0	0	0	0	0	0	0	0	0	60.3	43.47	0.262	20.737	23.481	8.718	0	0	0	0.00
	10		Pmax				Tr = 40C	CH4			14-08-2020	16:18	39.6	0	0	0	0	0	0	0	0	0	0	60.4	43.46	0.262	20.714	23.457	8.709	0	0	0	0.00
	11		Pmin1				Tr = 40C	CH4			14-08-2020	16:31	39.6	0	0	0	0	0	0	0	0.01	0	0	60.4	43.47	0.262	20.733	23.478	8.717	0	0	0	0.00
	12		Pmin2				Tr = 40C	CH4			14-08-2020	16:50	39.7	0	0	0	0	0	0	0	0	0	0	60.2	43.48	0.263	20.759	23.506	8.726	0	0	0	0.00
	Qmin - GAS CH4 with increasing H2%. STOP IN CASE OF FLASHBACK BEFORE 60% H2																																
		STABILISATION with Natural gas				Adjust. with CH4 according the man. Instructions									QUANTITATIVE TEST: REPORT SHALL BE BASED ON AVG (DATA FILE) AND NOT INSTANTANEOUS DATA NOTED MANUAL																		
Mandatory	13	Q_{min}	Pnom	Details in development (made by 1st lab testing)	Test to be done with cooking pan. Qmin adjusted according the standards	Details in development (made by 1st lab testing)	40/60C	CH4	0		29-07-2020	11:27	99.8	0	0	0	0	0	0	0	0.18	0	0	0	50.54	0.556	35.820	39.749	11.638	19.878	19.417	0.4372	4.35
	14								10		29-07-2020	15:34	89.8	0	0	0	0	0	0	0	0.16	0	0	10	49.31	0.507	33.312	37.044	11.359	19.803	19.493	0.4588	4.25
	15								20		29-07-2020	16:04	80.3	0	0	0	0	0	0	0	0.14	0	0	19.5	48.14	0.461	30.932	34.477	11.047	19.783	20.031	0.4769	4.10
Mandatory	16								23		29-07-2020	12:29	77.4	0	0	0	0	0	0	0	0.14	0	0	22.5	47.77	0.447	30.192	33.679	10.938	19.831	19.785	0.4861	4.08
	17						Tr = 40C (constant water flow rate for boilers & Wh)		30		29-07-2020	13:30	70.5	0	0	0	0	0	0	0	0.13	0	0	29.4	46.92	0.413	28.459	31.810	10.659	19.774	19.654	0.5018	3.97
Mandatory	18								40		29-07-2020	16:42	62.2	0	0	0	0	0	0	0	0.12	0	0	37.7	45.91	0.372	26.371	29.558	10.266	19.845	19.772	0.5261	3.85
	19								50		29-07-2020	14:31	52.1	0	0	0	0	0	0	0	0.1	0	0	47.8	44.73	0.323	23.842	26.830	9.680	19.738	19.888	0.5632	3.73
	20								60		14-08-2020	12:06	40.7	0	0	0	0	0	0	0	0	0	0	59.3	43.57	0.267	20.988	23.752	8.808	19.894	20.003	0.6177	3.60

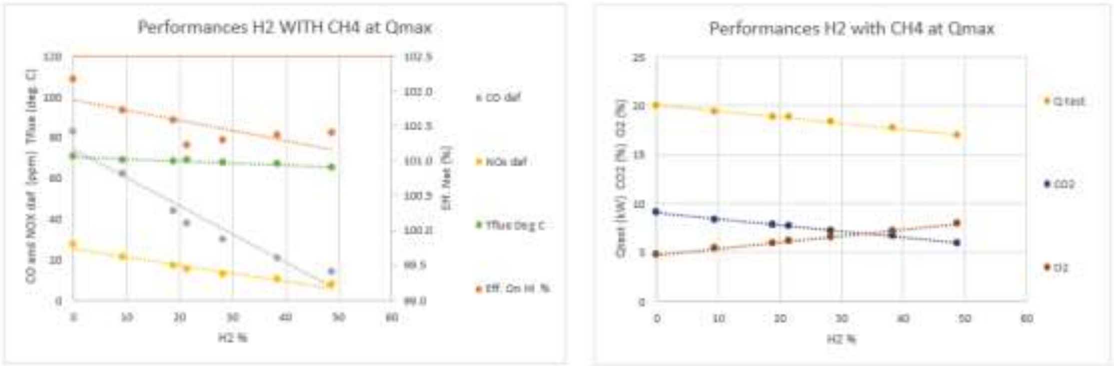
Figure 5: Extract from the "test sheet"

The sheet was improved in the light of the first tests and was regularly corrected and improved when new questions and observation were made by partners. **The document evolved until March 2022, to get the highest benefit from the test carried out.**

The data sheet also includes a report tab that is partly automated with the data extracted from the data tab. The main information is included in the "report" tabs with a sufficient level of detail for the analysis of the results. This report allowed the labs to see the results at a glance and possibly resolve visible issues and was used for meta-analysis of the results when specific questions on some results raised.

2.1 & 2.2 PERFORMANCES with CH4 (Qmax) test at 60/40 C (for the first test)

	H2	Wobbe (Ws)	Eff	CO daf	NOX daf	Qtest (input)	Tfluegas	CO2	O2
	%	[MJ/m³]	% on Hi	ppm	ppm	kW	[°C]	[%]	[%]
1	0.0	50.54	102.2	83	28	20.06	70	9.1	4.8
2	9.3	49.40	101.7	62	21	19.41	69	8.3	5.4
3	18.7	48.23	101.6	44	17	18.87	68	7.8	6.0
4	21.5	47.89	101.2	37	15	18.92	69	7.7	6.2
5	28.3	47.06	101.3	30	13	18.33	68	7.3	6.6
6	38.4	45.84	101.4	21	10	17.73	67	6.7	7.3
7	48.7	44.62	101.4	14	8	17.06	65	6.0	8.0
8	60.3	43.47		11	8	16.45	0	5.3	8.4



Performances H2 WITH CH4 at Qmax

Performances H2 with CH4 at Qmax

Figure 6: Example of data table and figures extracted from the test report.

1.6 Control of the report

Before finalisation, the report was **controlled by a third party** (another THyGA laboratory) in a Q/A process. The objective is double:

1. **Control & discuss the test results** and check that no important point was missed and that there were no mistakes.
2. **Having the third party learn how the other labs performed the test.** The objective was to reach a better harmonisation of practice and reproducibility of the test between the labs. From mid- 2022, it was decided that DGC would take-over all controls to optimize the analysis. This was done in several stages:
    a. Initial reading of the **test report**. Comments and questions to the labs.
    b. Meeting-Brainstorming of THyGA partners with manufacturers to check the compiled **data results** by segment family (mainly on the most highly represented segments for boilers and cookers). This method allowed to spot irregular trends or outlying data for further check of mainly emissions and efficiency tests.
    c. Meeting-Brainstorming of THyGA partners with manufacturers to check the compiled **safety test results** by segment family (done for all segments). This method allowed to spot irregular results and to ensure that the reporting was done in a single harmonised way.

1.7 THyGA appliance ID

The testing covers a wide variety of appliances of different types and different burner or combustion technologies. The list of appliances tested is given in the section 4 (results), segment by segment.

In order to make it easy to visualize the tolerance to H2NG admixture, the project created a "THyGA appliance ID card" (Figure 7), where the main results can be seen at a glance, without reading a long report.

- The first line gives the report short name *Lab. short name/Chrono number Segment*, the segment being the type of appliance tested as defined in the segmentation from WP2 (Task 2.1, see list in ANNEX2).
- Comb Control indicated if the appliance is equipped with combustion control or not.

THyGA Appliance ID card for	EB08_SEGM_303							
Appliance	C							
Burner	Atmospheric multi ring burner (dual wok burner)							
Origin	Spain							
Segment	303							
Max. power input (net) (kW)	5							
Min. power input (net) (kW)	0							
SAFETY ASSESMENT. H2 % tested	0	10	20	23	30	40	50	60
1.1 SAFETY- with CH4	X			X		X		
1.2 SAFETY- with EULOW	X				X			
1.3 SAFETY- with G23								
1.4 Cold start.						X		
1.5 Hot start.				X		X		
1.6 Low air temperature (- 10 C)								
1.7 Flue gas pipe length	NA	NA	NA	NA	NA	NA	NA	NA
1.8 ROC (PLUGG FLOW)						X		
1.9 Impact of H2 on flame detection.								
1.10 Flash back analyse.						X		
3.1 ADJUSTMENT A	NA	NA	NA	NA	NA	NA	NA	NA
3.2 ADJUSTMENT B	NA	NA	NA	NA	NA	NA	NA	NA
3.3 ADJUSTMENT H	NA	NA	NA	NA	NA	NA	NA	NA
3.4 ADJUSTMENT G	NA	NA	NA	NA	NA	NA	NA	NA
4.1 Delayed ignition test.								
4.2 Soundness								
4.3 Quick variation Qmin-Qmax Shut-off					X			
4.4 Overheat. Meas. of temp.								
4.5 Cooker hob test with 4 burners on						X		
4.6 Influence of wind								
4.7 Long term (limited time)						X		
4.8 Fluctuation of the aux. energy								
4.9 Fluctuation of pressure						X		
4.x Other test								
OVERALL	In general, the dual wok burner does not have flashback but had flame instability with 40% H2 which might cause to flashback. The flame instability extended from inner ring to outer ring over hours.							

Figure 7: Example of THyGA ID card (NA = not applicable).

Safety characterisation

The advantage of using such cards is to have an easy way to compare results and see at a glance where are the issues with H2 for different or similar appliances.

The card was designed in a way to represent **most safety-related aspects** and to gather the information about which levels of H2 were tested and which results were obtained.

- The green colour indicates that we have not detected a safety risk during the tests according to the protocol adopted.
- The red colour indicates that we have detected a safety risk during the tests according to the protocol adopted.
- The yellow colour indicates that we have open questions or **potential safety risk**.
- Orange indicates operational issues (not having safety consequences)
- "X" indicates which test was performed since not all % of H2 were compulsory within the THyGA protocol.

The cell colour is interpolated between two points of the same colour, but not in case the colour is different. In this case, the colour is left blank, which means that we cannot conclude (= interpolate between cells of different colours).

THyGA Appliance ID card for GA3_SEGM_407

SAFETY ASSESMENT. H2 % tested

OVERALL

THyGA Appliance ID card for GA4_SEGM_406

SAFETY ASSESMENT. H2 % tested

OVERALL

Figure 8: Example of comparison of results from 2 different THyGA ID card (NA = not applicable).

Generally, a safety risk will be declared when appliances no longer behaved as we would expect for a CE certification test. This means, for example, that flashback or CO emissions above 1000 ppm (dry - air free) are considered as safety risks.

A **potential safety risk** signifies that we assumed that a situation could develop into a safety risk in the long run. For example, this can be an unstable low flame position (flame close to the burner port) which may deteriorate a burner in the long run, due to the increase of temperature. This is of course a more subjective assessment.

There is a large variety of tests that can be done, but not all of them could be performed due to the budget and capacity constraints of the labs (for example, the delayed ignition can only be performed by two laboratories).

2 Important reminder and information for some of the main tests

2.1 Adjustment

2.1.1 Introduction

In practice, most of appliances in the category H are adjusted by the manufacturers with G20 before being sold on the market. Some appliances are also re-adjusted **in the field** according to manufacturer instructions, either during the commissioning or after a service or a reparation. This is done with the gas distributed locally and not G20.

What we call adjustment in THyGA is the operation of field adjustment to reach a certain air excess according the O_2 or CO_2 value that is given by the boiler manufacturer in technical instructions. This is common practice for fully premix appliances, for which the air excess is fixed by the manufacturers and specified in the appliance installation instructions.

Previous investigations about gas quality impacts on appliances (Gasqual) /7/ have already concluded that the adjustment of gas appliances is critical for the safety of appliances. The main issue identified was CO emissions due to air excess changes with evolution of gas quality. Adding fluctuating % of hydrogen to an already fluctuating (in composition) natural gas makes things even worse.

- Today, some appliances like premixed condensing boilers are set manually by an installer at a given gas quality (Wobbe index) and may be used later with very different gas quality (different Wobbe index).
- Tomorrow, when injecting hydrogen in the gas grid, the adjustment may occur at a time when there is (or not) hydrogen (depending on the supply situation), and later the appliance may (or not) be used with gas with or without hydrogen as well.

The adjustment of appliances with gas containing hydrogen can in principle lead to:

- High CO emissions mainly due to variations of the air excess.
- Increased flashback risk in some circumstances.

2.1.2 Reminders on adjustment

Field adjustment of appliances is **routinely carried out in a number of European countries** on appliances such as condensing boilers with fanned premixed burners. The procedure is not allowed in all countries, however, as far as the manufacturers' instructions mention an adjustment procedure of the air/gas ratio when commissioning or maintaining the appliances, it is possible that some installers do adjust the appliances based on the locally available natural gas at the time of commissioning, even if it is not done on a general basis.

The reason for appliance field adjustment is that commissioning, routine maintenance and replacement of gas train components require **air/gas ratio tuning** (based on O_2 or CO_2 measurement) to meet combustion performance criteria (such as CO, NO_x) as stated in manufacturers' installation and maintenance procedures.

The appliance field adjustment of air/gas ratio is carried out according to possible national regulations and to manufacturers' instructions. It typically consists of adjusting the air/gas ratio to reach the CO_2 or O_2 concentration in the combustion products specified by the manufacturer. Thus, the final air/gas ratio adjustment will depend on the distributed gas quality and the ambient conditions on the moment of adjustment. Furthermore, to our knowledge, there is no harmonised requirements regarding the minimum metrological requirements and accuracy of the instruments used by installers to control the CO_2 or O_2 concentrations. This may also influence the final adjustment.

The appliances adjusted for air/gas ratio are typically modern, condensing boilers with premix burners. In general, these appliances have fully modulating controls on both air and gas to enable part-load efficiency and emission targets to be met[4]. The market for this type of appliance increases across

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[4] Ecodesign directive requirements

Europe and other boiler technologies are more or less banned today. Other appliances identified as requiring field adjustment of their air/gas ratio are appliances with forced draught, jet burners, but also some catering equipment.

Other boilers, water heaters, cookers and space heaters, mostly with partially premixed burners, generally do not have requirements for field adjustment. If adjustments are needed, it concerns only the burner pressure that does not depend on the gas quality distributed.

2.1.3 Expected impact of the change of Wobbe index

As demonstrated in the project GASQUAL /7/, scenarios of field adjustment of air excess are not H2 specific and are done with natural gas without H2, but H2 increases the potential amplitude of Wobbe Index variations (Figure 3), which we know may bring issues on some appliances when adjusted. For more details see also the Section 8 of REF/2/

This is especially true when an appliance is adjusted with a lean gas with H2 (low Wobbe Index) and then used with a rich gas (high Wobbe Index). In this case, the main issue observed is CO due to the decrease of air excess, as seen in GASQUAL.

- Therefore, the main concern with the adjustments including gases with H2 is not the flashback, but CO emissions due to changes in air excess.
- In general, premixed burners show a U-shaped curve of CO over λ, the bottom of the curve being for air excess for which the burners offer the best compromise between efficiency and emissions (e.g., λ =1.3).
    - CO emissions are typically low (around 10 ppm to 50 pm DAF).
    - Coming closer to stoichiometry (λ = 1), CO emission increases strongly up to several 1000 of ppm.
- The same also happens on the other side of the U curve, starting with very high air excess (e.g., λ =1.8) then decreasing, also resulting in high CO values.

The Figure 9 (from GASQUAL) illustrates the above explained concept, but the air excess is here replaced by O_2% (O_2 concentration in the combustion products).

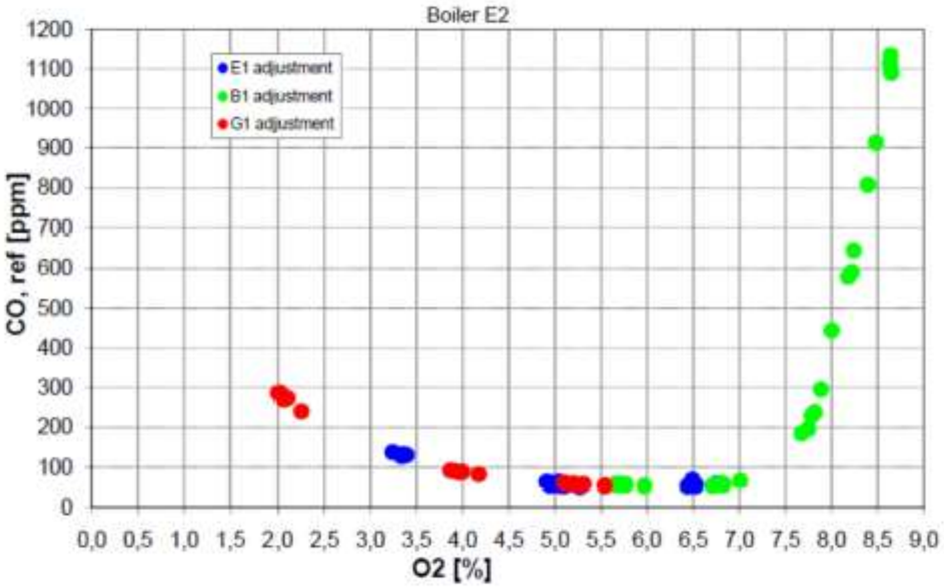


Figure 9: GASQUAL/7/ test results showing the variation of CO emissions with O_2. Variations are created by testing appliances with gases of different Wobbe and for 3 different initial adjustments (high range, CH_4, low range).

2.1.4 Objectives of the THyGA adjustment tests

This part of test is aimed at studying what happens when appliances are adjusted to a given gas and used afterwards with different gases. This test is only feasible for the appliances that can be adjusted with CO_2 or O_2 values given by the manufacturers (e.g., premix condensing boilers), it is not applicable for:

- Appliances with automatic combustion controls that are designed to be automatically adjusted.
- Most of appliances with atmospheric burners.

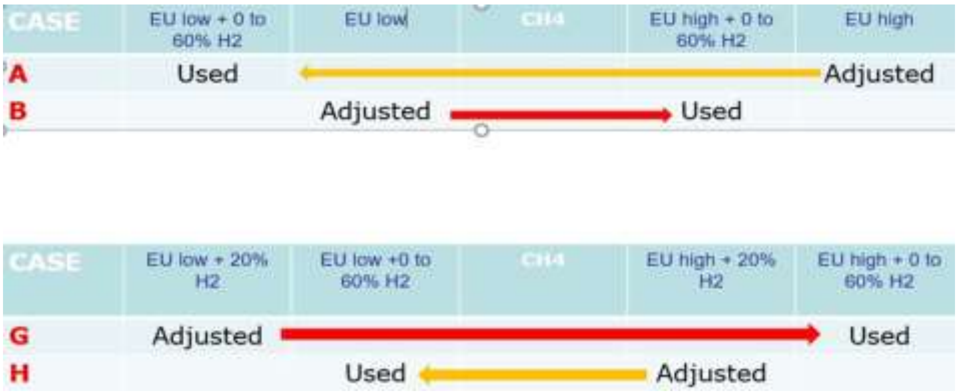
If appliances can be adjusted over the whole range of H gas, to which up to 60% H2 can be added and after that be used with any H gas, to which up to 60% H2 can be added, we already know that there will be no appliance that will be safe! However, such a situation is not realistic and testing this would have a limited added value. Consequently, it was assumed for these test campaigns that there would not be more than 20% H2 in the grid when appliances are field adjusted.

The first tests results showed that one of **the most critical situations is an adjustment with a low Wobbe Index gas with some hydrogen and a switch later on to a high Wobbe index gas without hydrogen** (adjustment G in the test protocol), the main consequence is a very strong increase of CO emissions levels.

2.1.5 Adjustment tested

We have selected four adjustment scenarios based on the analysis of the impact of each of them on the flame speed and air/gas ratio.

- Adjustment A: appliances are adjusted with EU high and tested with EU low, and EU low + H2 (10%, 30%, 60%)
- Adjustment B: appliances are adjusted with EU low and tested with EU high, and EU high+ H2 (10%, 30%, 60%)
- Adjustment G: appliances are adjusted with EU low + 20% H2 and tested with EU high, and EU high + H2 (10%, 30%, 60%)
- Adjustment H: appliances are adjusted with EU high + 20% H2 and tested with EU low, and EU low + H2 (10%, 30%, 60%)



CASE	EU low + 0 to 60% H2	EU low	CH4	EU high + 0 to 60% H2	EU high
A	Used	←	←	←	Adjusted
B		Adjusted	→	Used	

CASE	EU low + 20% H2	EU low +0 to 60% H2	CH4	EU high + 20% H2	EU high + 0 to 60% H2
G	Adjusted	→	→	→	Used
H		Used	←	Adjusted	

Figure 10: Adjustments within THyGA test program.

The four adjustments were studied in detail in the preparation phase (see D2.5). The evolution of the flame speed was calculated for the 4 different scenarios.

The theory and the first tests have shown that test G with 20% H2 in "EU Low" was the most challenging and, therefore, the test was extended to 2 new test gases 10 and 30 % H2 to check what would be the influence of other H2 concentrations in the gas used for adjustment.

As seen on Figure 11, this situation will also result in the increase of flame speed, for the testing point with high Wobbe index.

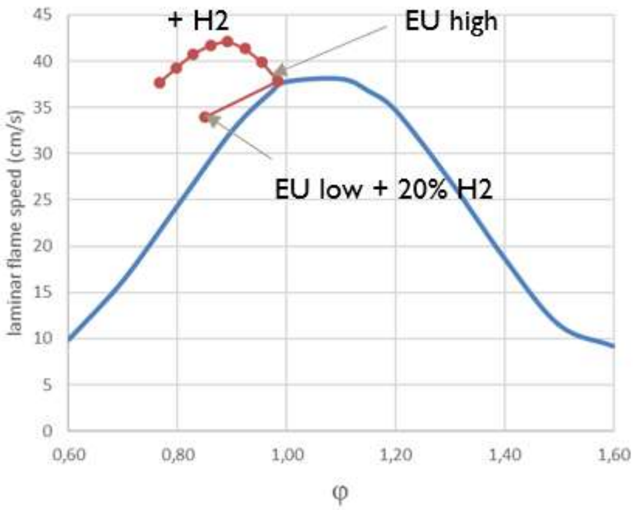


Figure 11: Variation of the flame speed with equivalence ratio (inverse of air gas ratio).

2.2 Interpretation of the test in view of laboratory measurement aspects

The use of test data should always be considered together with metrology aspects linked to the testing procedure.

It is well known that measurement data are subject to uncertainties that are linked to laboratory instruments, test procedures and test conditions. Errors can also be made during testing due for example to a sudden drift on a meter or a wrong operation (e.g. calibration with a wrong reference) of the laboratory.

Therefore, the results of THyGA need to be interpreted with consideration of parameters, of which the most important are:

- The measurement uncertainty
- The measurement repeatability
- The possible outliers

The above points are defined and discussed in this section. Most of the input is from existing standards on metrology statistic. Reference /1/ was also used here as a basis of our work for assessing results including the existing knowledge about laboratories reproducibility as measured recently in the project ECOTEST.

2.2.1 Uncertainty

Uncertainty: Parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand.

Standard uncertainty: Uncertainty of the result of a measurement expressed as a standard deviation. The standard uncertainty is calculated from the experimental standard deviation(s).

Expanded uncertainty: Quantity defining an interval around the result of a measurement that may be expected to encompass a large fraction of distribution of values that could reasonably be attributed to the measurand.

Uncertainty given with a confidence level.

Unless otherwise indicated, one may assume that a normal distribution is used to calculate the quoted uncertainty, and if the confidence level is not given, we assume it is about 95% (see definition in Annex 3).

U(95%) = 1,96.s

Very often the following rounding is used: U(95%) = 2.s

2.2.2 Normal distribution

Calculations are generally based on a hypothesis of a normal or approximately normal distribution of the results. However, when another distribution is known, the appropriate formulas are to be used. Unless otherwise indicated, one may assume that a normal distribution was used to calculate the quoted uncertainty.

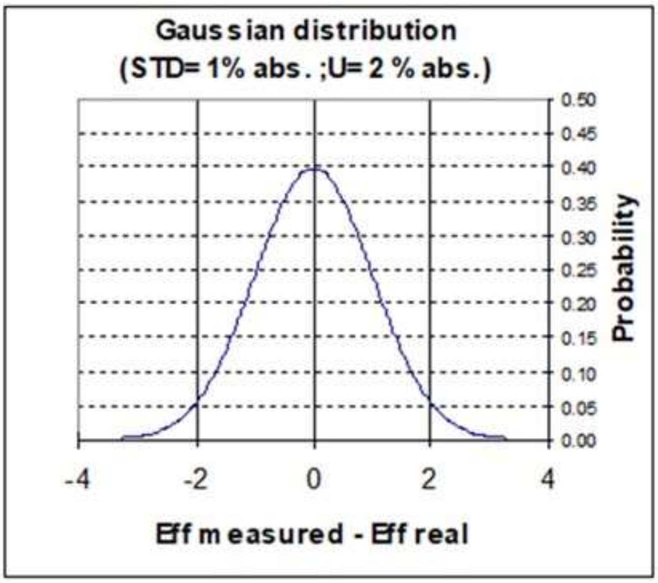


Figure 12: Normal distribution curve.

2.2.3 Repeatability (ISO 5725)

The repeatability (r) is the value, below which the absolute difference between two single test results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory, and short interval of time) may be expected to lie within a probability of 95%.

The repeatability is a value indicating how one single laboratory can reproduce the same measurement, for example when repeating the same efficiency test (e.g. in the morning and in the afternoon).

Note that the repeatability is an amplitude. It is not expressed as ± value as are the uncertainties.

The **reproducibility** (R) is somehow similar to the repeatability but is covering tests done in different laboratories. See in Annex3 for the definition from the standards.

2.2.4 Outliers and Stragglers (Extreme values)

Extreme values are defined as observations in a sample, so far separated in value from the remainder as to suggest that they may be from a different population, or the result of an error in measurement (ISO 3534-1993).

Extreme values can be subdivided into stragglers, extreme values detected between the 95% and 99% confidence levels, and outliers, extreme values at > 99% confidence level.

Outliers and Stragglers do not properly belong to the experiment and are corrected or discarded in keeping with the explanation obtained after investigations.

Outlier and straggler values can be investigated by using the Dixon tests, Grubb, Mandel's test (used in our project here) or other tests described in standards.

There can be different reasons for extreme values:

- **The value is a mistake.**
- The distribution is not Gaussian. Grubbs' test depends on that assumption. For distribution having a heavy tail, and it is easy to mistake extreme values as outliers.
- **The value may be the tail of a Gaussian distribution.**

2.2.5 What is the most important parameter for the THyGA evaluation?

Although it is preferable to have a high measurement accuracy to get accurate measurement, the most important for the project is to have a good **repeatability,** as we are more interested in having accurate information on variation of a given parameter like efficiency or emission and less interested in the absolute value of those.

We have no measurement data for the labs' repeatability, but we have data on reproducibility between labs achieved during a project, ECOTEST, with some of the labs present in THyGA.

The value of reproducibility between labs is much larger than the repeatability within a single lab. There is no relation that can be used to calculate repeatability from reproducibility, but it is not uncommon to have values for repeatability that are 1/3rd or 1/4th of the reproducibility or less, depending on the lab.

The range of **reproducibility** calculated between labs was as follows:

- Boiler Full load efficiency between 1,4 and 2,4 % (absolute)
- Micro-CHP Efficiency between 7 and 10 % (absolute)
- Boiler NO_x emissions between 12 and 17 mg/kWh
- Micro-CHP NO_x emissions between 50 and 70% (relative)

Note that NO_x reproducibility is very dependent on the level of emissions measured.

The repeatability is not a constant value and changes from test to test depending on a number of factors like time between two tests, calibration between two tests, etc.

As a result, there is no universal value that can be used here, but the following values are generally obtained:

- Boiler efficiency: 0.5% absolute, or better
- Boiler NO_x emissions (5 mg/kWh for emissions below 50 mg/kWh) and (20% relative above 50 mg/kWh) or better

The conclusion on test validity, in order to be able to conclude if H2 has a significative influence, shall consider both the repeatability expected and the number of tests carried out.

In this first example, four different situations are shown based on test of boiler efficiency

1. **GWI07:** Six tests were carried out and are all together in a ± 0.5 % range apart except one (Nr5. for 50% H2). WE consider Nr 5 as slightly outlying. With the above, we can state that hydrogen has no significant influence on efficiency for this boiler.
2. **D4 & GWI13**: The points all together are all close to a line which seems to indicate a good repeatability and a clear trend for the influence of hydrogen (increasing for GW13, decreasing for D4)

3. **D6,** shall be more carefully considered since only 2 points are measured. The variation of about 1% between the 2 measurements is higher than the reality expected for this measurement. The conclusion is that the efficiency increases with H2 for this boiler, but this conclusion is not as certain as for the two previous boilers.

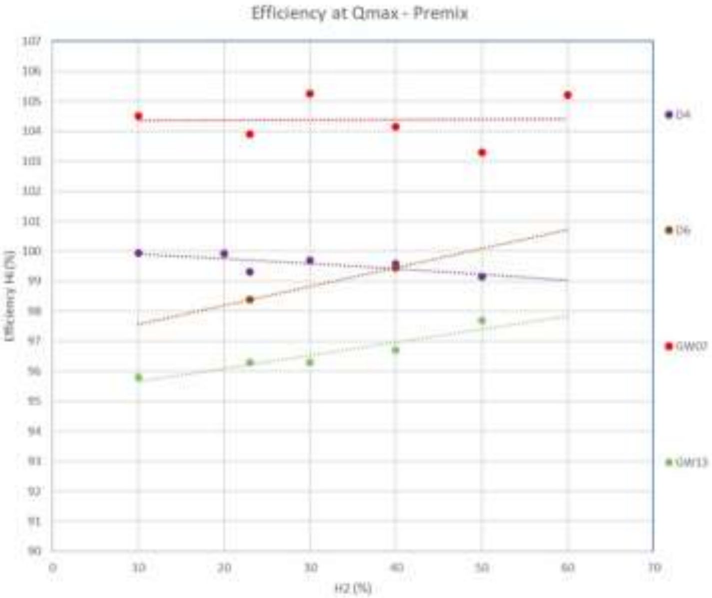


Figure 13: Example of efficiency results for 4 boilers.

Second example

1. **EN02**, based on 3 measurements, shows a rather strong decrease (more than 10%, from 0 to 60% H2) compared with the previous tests (Figure 13) showing about 3% variation of efficiency. The points are close to a line so we have no reason to suspect mistakes or problems for those tests, however, the linear model will not work here as the interpolated efficiency at 0% H2 will be impossible physically. So, we can use the data, but need to be cautious.
2. **AP02** shows rather high differences between test results, which look contradictory. One of the tests could be outlying here; it is not possible to tell which one and for which reason. In this case, we shall refrain from concluding on the test results.

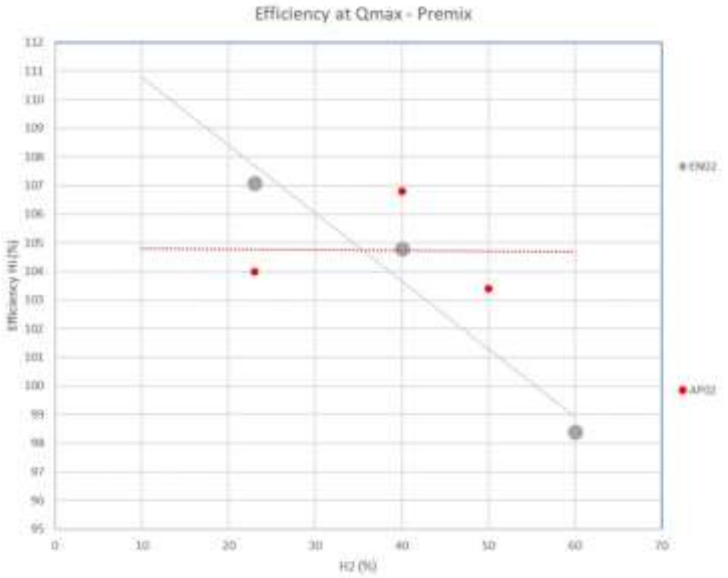


Figure 14: Example of efficiency results for 2 boilers.

2.2.6 How to determine if hydrogen has an influence on a given parameter

In order to be sure that variation of a parameter is due to H2 concentration, the measured variations should be larger than the repeatability.

Considering that laboratories have in general a repeatability of 0,5%, we can conclude from the following graph that hydrogen will increase the efficiency of premix boilers in most of the cases. In only one case we can conclude that the efficiency is decreasing.

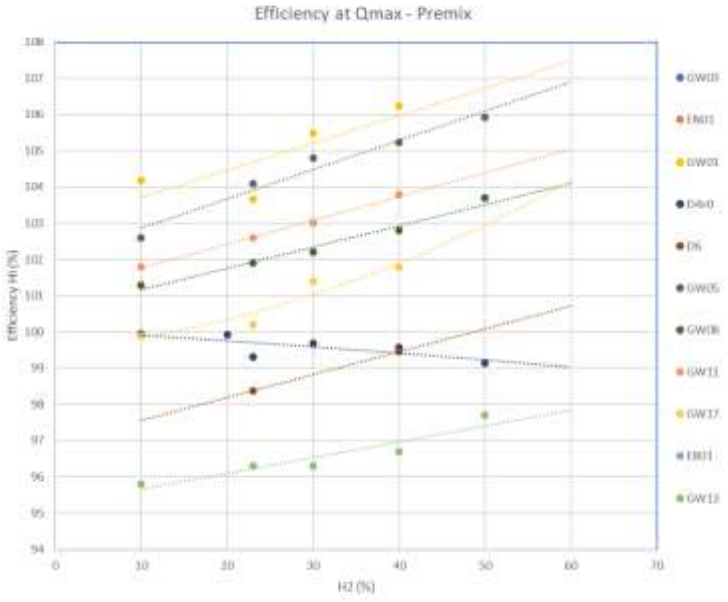


Figure 15: Example of efficiency results for several boilers

2.3 Analysis of the data. Methodology

2.3.1 Evaluation of the safety

The safety assessment is made through several tests where we evaluate if hydrogen is going to bring appliances in an increased safety risk compared to use with natural gas.

The following risk are considered:

1. The **flame stability and especially the flashback** (or light back) which is often considered one of the main risks because hydrogen generally increases the flame speed and therefore the probability of flashback appearance.
2. The **emissions of CO**.
3. The **increasing risk of explosion, detonation, fire etc.** because of a failure of flame detection, late ignition, leakage etc.
4. The **risk of deterioration** of components leading to the risk above.

The safety assessment is done through the following testing programme:

1.1 SAFETY- with CH4
1.2 SAFETY- with EULOW
1.3 SAFETY- with G23
1.4 Cold start
1.5 Hot start
1.6 Low air temperature (- 10° C)
1.7 Flue gas pipe length
1.8 ROC (PLUGG FLOW)
1.9 Impact of H2 on flame detection
1.10 Flashback analysis
3.1 ADJUSTMENT A
3.2 ADJUSTMENT B
3.3 ADJUSTMENT H
3.4 ADJUSTMENT G
4.1 Delayed ignition test
4.2 Soundness
4.3 Quick variation Qmin-Qmax Shut-off
4.4 Overheat. Meas. of temp.
4.5 Cooker hob test with 4 burners on
4.6 Influence of wind
4.7 Long term (limited time)
4.8 Fluctuation of the aux. energy
4.9 Fluctuation of pressure
4.x Other test

Some tests are irrelevant for some appliances and the allocated budget by test does not allow to look at all aspects. Therefore, in the course of the project, we have tried to have the most important points covered in a more or less systematic way, and have the other aspects distributed between labs and tests.

2.3.2 Emissions of CO, NOx and UHC.

For the type of appliances in the scope of this project, emissions or legal limits for pollutant species are given as dry and stoichiometric (or also called “air free”) flue gas concentrations for the given species, e. g. in [ppm].

The units we have used for the work and the present report are **ppm dry-air free**.

According to /9/, this puts hydrogen combustion at an inherent disadvantage if emissions for natural gas are compared to emissions with blends. Hydrogen combustion produces less flue gas per energy released (assuming a constant λ), and the flue gas contains more water vapor as well. Therefore, for comparability with natural gas, units like **mg/kWh** would be preferred for the application of limits.

Conversions from ppm to mg/kWh are given in the CEN technical document CR1404 /11/.

$$X\ (\text{mgkWh}) = 3.6 \bullet X\ (\text{ppm daf}) \bullet \rho \bullet V_{fd}/(H_i \bullet 288/273)\ \ = 3.413 \bullet X_1 \bullet \rho \bullet V_{fd}/H_i$$

with

X = NOx or CO Emissions (dry air free)

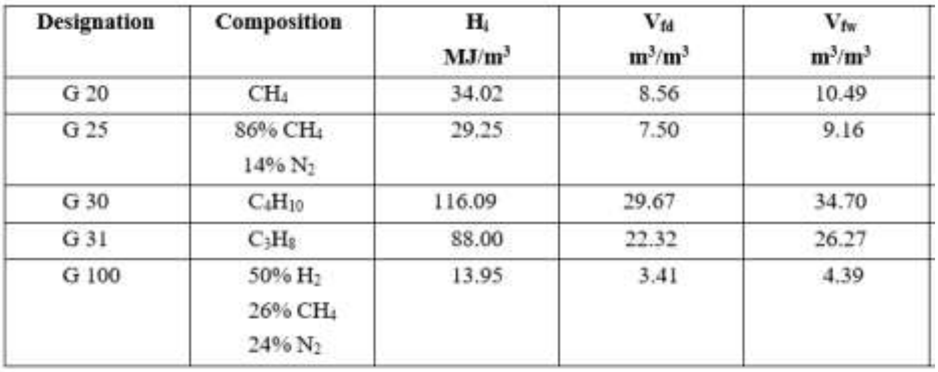
ρ = the density of component x.

density: (ρ) = **The weight of a particular gas per unit volume of dry gas at 0°C:**

CO:	**1.251 kg/m^3**
H_2O:	**0.830 kg/m^3**
NO:	**1.340 kg/m^3**
NO_x as NO_2:	**2.054 kg/m^3**

V_{fd}: **Volume of dry combustion products per unit of volume or mass of gas for stoichiometric (neutral) combustion m^3/m^3 or m^3/kg.**

Table 2: Composition, calorific power, and dry/wet volume of combustion products for different gases.



Designation	Composition	H_i MJ/m^3	V_{fd} m^3/m^3	V_{fw} m^3/m^3
G 20	CH_4	34.02	8.56	10.49
G 25	86% CH_4 14% N_2	29.25	7.50	9.16
G 30	C_4H_{10}	116.09	29.67	34.70
G 31	C_3H_8	88.00	22.32	26.27
G 100	50% H_2 26% CH_4 24% N_2	13.95	3.41	4.39

The CR1404 doesn’t include in its scope the blends of natural gas with hydrogen. However, the method could be updated using characteristics of combustion gases with hydrogen as a fuel mixed with CH4.

For H2 NG mix the V_{fd} is

- 8,6 m3/m3 for CH4

- 7,2 m3/m3 for CH4 with 20% H2
- 5,9 m3/m3 for CH4 with 40% H2

The above can be used to calculate the emissions of emissions for blends in mg/kWh.

Note that there has not been (to our knowledge) a real discussion within CEN on emissions from blends and therefore the present document is for the time based on stoichiometric emissions in ppm.

2.3.3 Some explanations on the method used for presenting the results (Table with overview of the results for safety).

Table 3 summarizes how the results obtained from individual test reports are combined to give an overview allowing to compare all appliances in the same family of segments.

Table 3: Overview of the results for the water heater segment.

	Appliance ID		GA05	GA10	GW14	GW19	GA09	EN04
	Segment		201	202	202	202	203	204
	Qmin (kW)		5.3	9	9.3	9.5	NA	13.5
	Qmax (kW)		10.5	26.2	22.6	30	7.7	57
	Combustion control feature (Y/N)		N	N	N	Y	N	N
At what level of H2 the problem may occur : reference gas + %H2 used	**%H2 in test gas**	**0**	X	X	X	X	X	X
		0-**10**	(*)		X	X		
		10-**20**						
		20-**23**		X	X	X	X	X
		23-**30**			X	X		
		30-**40**	X	X	X	X	X	X
		40-**50**			X			
		50-**60**			X			
EE	1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X	X	X
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2	X					
EE	1.3 Efficiency and emission G23	G23 + H2			X	X		
CS	1.4 Cold start	CH4+40%H2	X	X	X	X	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)		X	X	X	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2						
FGP	1.7 Flue gas pipe length	CH4+30%H2						
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X	X	X
FD	1.9 Impact H2 flame detection.		X	X	X		X	X
FB	1.10 Flash back		X	X	X	X	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA	NA	
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA	NA	
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	
DI	4.1 Delayed ignition test.	CH4+30%H2						
S	4.2 Soundness							
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X	X			X	X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2					X (40%)	
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA	NA	NA
W	4.6 Influence of wind		X (0%)	X			X	
LT	4.7 Long time (limited time)	depends on manufacturer		X			X	
AUX	4.8 Fluctuation of the aux.						NA	
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X	X	X
O	Other /Operational						X	X

(*) Issue with CH4 test and H2 test

The first part of the table "Appliance" is a short description of the appliance tested where:

- The "code" column discloses the name of the report with the following nomenclature Lab. short name/Chrono number.

- The “Segment” column gives the type of appliance tested as defined in the segmentation from WP2 (Task 2.1, see list in ANNEX2).
- Qmin & Qmax are the maximum and minimum heat input in kW, respectively.
- Comb Control indicates if the appliance is equipped with combustion control or not.
- Appliance category.

The second part of the table “H2 tested” indicates what % of H2 were used for the test.

The third part of the table “ELEMENTS TESTED (for which the problem did occur)” indicates what was tested and what are the results obtained. When an issue occurs, the percentage of hydrogen is written.

For that, we use a colour code:

Table 4: Color code to read the results overview.

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

- X indicates for which points tests were performed.
- If the results between two tests are showing no issues, the colour green is interpolated despite no test are done.
- If a test shows issue with X % H2, all tests with H2 > X are extrapolated and marked in RED.

Note that Delayed ignition is treated in section 3.3.

2.3.4 Reporting for other aspects (Efficiency & emissions)

The efficiency and emissions results are treated statistically and by figures /graphs.

Due to the large number of appliances tested we cannot give individual results; however, we will give typical examples and also will show outlying results when relevant.

2.3.5 Group of Segments

To get a clear overview of the results we have classified appliances by group of segments. When considering hydrogen impact on appliances, it makes sense to differentiate fully premix appliances from other appliances (partial premix or “atmospheric”) and forced draught burners which explains some “subgroups” (example: catering segments 400a and 400b).

Later on, in view of late results sent we have created more of those subgroups.

- Fully Premix boilers (Segm. 100a)
- Not fully premix boiler & Forced draught burner (Segm. 100b & 100c)
- Water heaters (Segm. 200)
- Domestic Cooker hobs and ovens (Segm. 300)

- Catering premix (Segm. 400a)
- Catering not-premix (Segm. 400b)
- Space heaters (Segm. 500)
- CHP (Segm. 600)
- Heat Pump (Segm. 700)
- Radiant heater & non dom. air heaters (Segm. 800)

2.4 Comments on the reporting (figures)

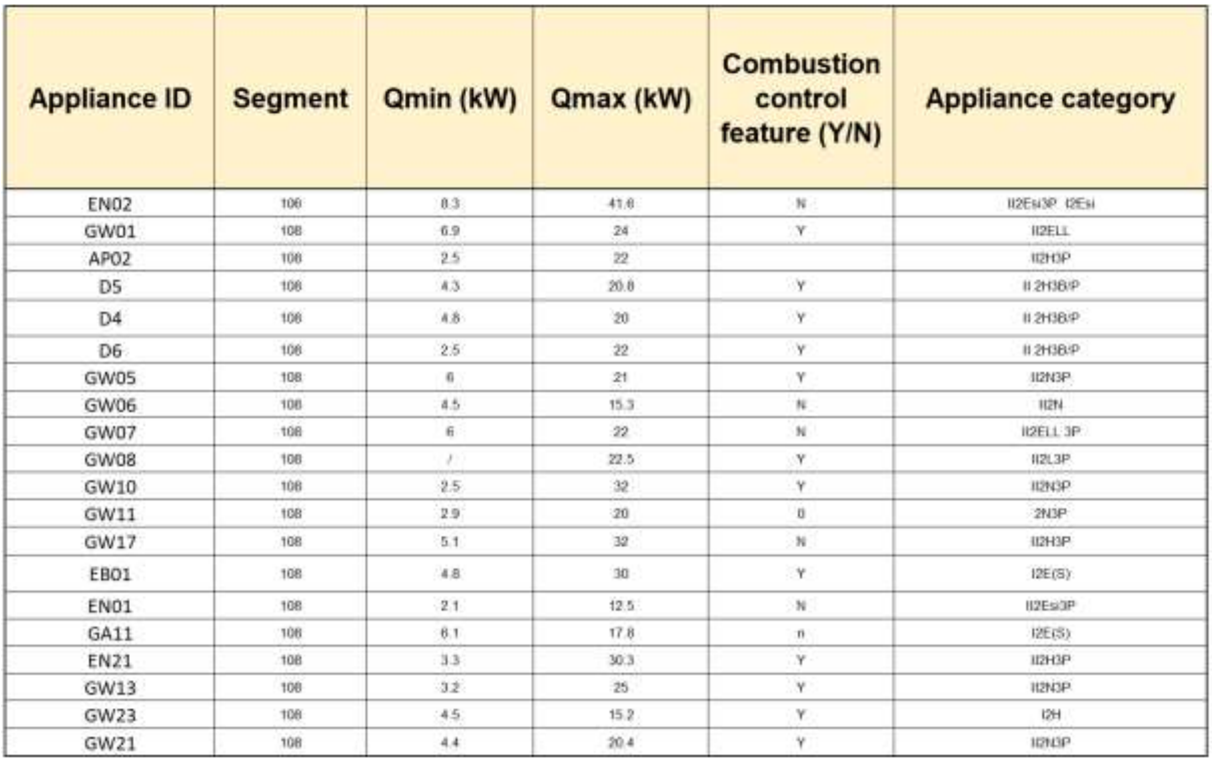
In the following, if a curve or figure is missing, it is because there is no data. Sometimes a curve is missing but still appears in the legend: it is because the data is bulk processed, so the name will be there, but the curve will only be there if there is any data for it to be drawn with.

2.5 Fully Premix boilers (Segm. 100a)

2.5.1 Appliances tested

Fully Premix boilers (Segm. 100a) include **THyGA segments 103, 106 and 108** (see Annex 2 for more details)

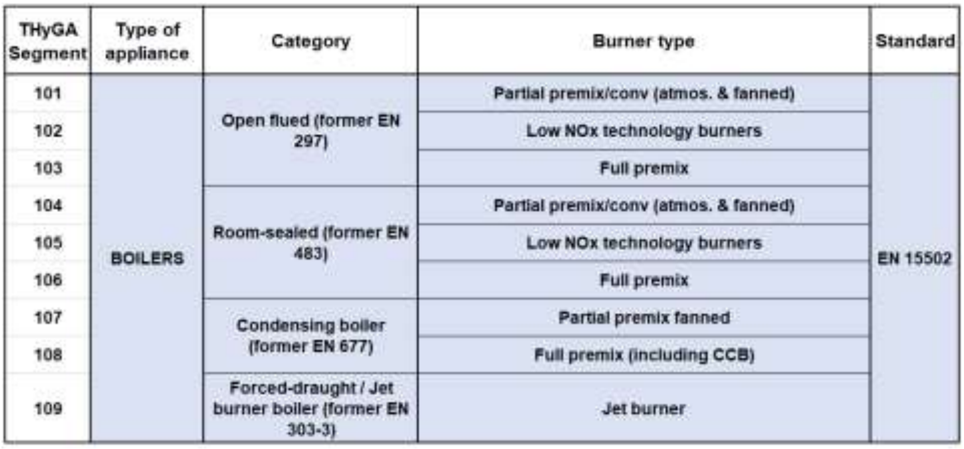
Table 5: Characteristics of the 20 fully premix boilers tested.



Appliance ID	Segment	Qmin (kW)	Qmax (kW)	Combustion control feature (Y/N)	Appliance category
EN02	106	8.3	41.6	N	II2Esi3P I2Esi
GW01	108	6.9	24	Y	II2ELL
AP02	108	2.5	22		II2H3P
D5	108	4.3	20.8	Y	II 2H3B/P
D4	108	4.8	20	Y	II 2H3B/P
D6	108	2.5	22	Y	II 2H3B/P
GW05	108	6	21	Y	II2N3P
GW06	108	4.5	15.3	N	II2N
GW07	108	6	22	N	II2ELL 3P
GW08	108	/	22.5	Y	II2L3P
GW10	108	2.5	32	Y	II2N3P
GW11	108	2.9	20	0	2N3P
GW17	108	5.1	32	N	II2H3P
EB01	108	4.8	30	Y	I2E(S)
EN01	108	2.1	12.5	N	II2Esi3P
GA11	108	6.1	17.8	n	I2E(S)
EN21	108	3.3	30.3	Y	II2H3P
GW13	108	3.2	25	Y	II2N3P
GW23	108	4.5	15.2	Y	I2H
GW21	108	4.4	20.4	Y	II2N3P

Note that the GW08 is declared “30% H2 certified burner”

Table 6: Segmentation of the boiler category.



THyGA Segment	Type of appliance	Category	Burner type	Standard
101	BOILERS	Open flued (former EN 297)	Partial premix/conv (atmos. & fanned)	EN 15502
102			Low NOx technology burners	
103			Full premix	
104		Room-sealed (former EN 483)	Partial premix/conv (atmos. & fanned)	
105			Low NOx technology burners	
106			Full premix	
107		Condensing boiler (former EN 677)	Partial premix fanned	
108			Full premix (including CCB)	
109		Forced-draught / Jet burner boiler (former EN 303-3)	Jet burner	

2.5.2 Safety

Table 7: Safety results for segment 100a - Part 1.

	Appliance ID		EN02	GW01	AP02	D5	D4	D6	GW05	GW06	GW07	GW08
	Segment		100	100	100	100	100	100	100	100	100	100
	Qmin (kW)		6.3	6.8	2.8	4.3	4.8	2.8	6	4.8	6	4.8
	Qmax (kW)		40.6	24	22	20.8	20	22	21	35.2	22	22.8
	Combustion control feature (Y/N)		N	Y		Y	Y	Y	Y	N	N	Y
	Appliance category		II2Er3P I2Ea	I2ELL	II2H3P	II2H3B/P	II2H3B/P	II2H3B/P	II2N3P	I2N	II2ELL 3P	II2L3P
At what level of H2 the problem may occur : reference gas + %H2 used	**%H2 in test gas**	**0**	X	X	X	X	X	X	X	X	X	X
		0-**10**	X	X		X	X	X	X	X	X	X
		10-**20**	X			X	X	X				
		20-**23**	X		X	X	X	X	X	X	X	X
		23-**30**	X	X		X	X	X	X	X	X	X
		30-**40**	X	X	X	X	X	X	X	X	X	X
		40-**50**	X		X	X	X		X		X	X
		50-**60**	X		X	X	X		X		X	X
EE	1.1 Efficiency and emission CH4	CH4 + H2	X	X	X 60%	X	X	X	X 60%	X	X	X 60%
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2		X			X					X
EE	1.3 Efficiency and emission G23	G23 + H2							X	X	X	X 23%
CS	1.4 Cold start	CH4+40%H2	X	X	X 60%	X	X	X 40%	(*) X 60%	X	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X		X 60%	X		X	(*) X 60%	X	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2		X						X		
FGP	1.7 Flue gas pipe length	CH4+30%H2		X				X				
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X 50%	X	X		X		X
FD	1.9 Impact H2 flame detection.		X	X		X	X	X	X		X	X
FB	1.10 Flash back		X	X	X 60%	X 60%	X	X 40%	X 60%	X	X	X 23%
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2		NA	NA		X	NA	NA			X (**)
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2		NA	NA		X	NA	NA			X (**)
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2		NA	NA		X	NA	NA			X (**)
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	X	NA	NA	X	X 20%	NA	NA			X (**)
DI	4.1 Delayed ignition test.	CH4+30%H2										
S	4.2 Soundness											
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2				NA	NA					X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2										
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
W	4.6 Influence of wind											
LT	4.7 Long time (limited time)	depends on manufacturer									X	
AUX	4.8 Fluctuation of the aux.							X				
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X	X	X	X	X	X	X
O	Other /Operational		X					X (40%)				X (60%)

(*) system doesn't start at 60%

(**) adjusted with O2

Table 8: Safety results for segment 100a - Part 2.

	Appliance ID		GW10	GW11	GW17	EB01	EN01	GA11	EN21	GW13	GW23	GW21
	Segment		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Qmin (kW)		2.5	2.9	5.1	4.8	2.1	6.1	3.3	3.2	4.5	4.4
	Qmax (kW)		32	28	32	30	10.5	17.0	38.3	25	15.2	28.4
	Combustion control feature (Y/N)		Y	0	N	Y	N	n	Y	Y	Y	Y
	Appliance category		I2N3P	2N3P	I2H3P	I2E(S)	I2Esi3P	I2E(S)	I2H3P	I2N3P	I2H	I2N3P
At what level of H2 the problem may occur : reference gas + %H2 used	**%H2 in test gas**	**0**	X	X	X	X	X	X	X	X	X	X
		0-**10**	X	X	X	X	X	X		X	X	X
		10-**20**				X	X	X				
		20-**23**	X	X	X	X	X		X	X	X	X
		23-**30**	X	X	X	X	X	X		X	X	X
		30-**40**	X	X	X	X	X	X	X	X	X	X
		40-**50**	X	X	X	X				X	X	X
		50-**60**	X	X	X	X				X	X	X
EE	1.1 Efficiency and emission CH4	CH4 + H2	X	X 50%	X 50%	X	X	X	X	X	X	X 60%
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2				X		X				
EE	1.3 Efficiency and emission G23	G23 + H2	X	X	X			X		X		
CS	1.4 Cold start	CH4+40%H2	X	X	X	X	X	X	X	X		
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X	X	X	X	X	X	X	X		
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2										
FGP	1.7 Flue gas pipe length	CH4+30%H2				X						
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X	X	X	X	X		
FD	1.9 Impact H2 flame detection.		X	X	X	X	X	X	NA			
FB	1.10 Flash back		X	X 50%	X 50%	X	X	X	X	X	X	X 60%
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2						X	NA	NA		
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2						X	NA	NA		
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2				X		X	NA	NA		
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2				X 20%	X	X (20%)	X	NA		
DI	4.1 Delayed ignition test.	CH4+30%H2										
S	4.2 Soundness							X				
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2					X	X				
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2										
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
W	4.6 Influence of wind							X				
LT	4.7 Long time (limited time)	depends on manufacturer				X						
AUX	4.8 Fluctuation of the aux.											
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X	X	X	X	X		
O	Other /Operational											

(*) system doesn't start at 60%　　(**) adjusted with O2

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

2.5.2.1 Overall observations and discussion on safety results:

Most appliances are tested up to 60% H2, many can cope with 60% without problem, unless they are adjusted with a gas containing hydrogen.

Some boilers **were able to cope with up to 60% H2** without any problem, but in this case adjustment tests were not performed or not relevant (appliances with combustion controls). EN02, GW07, GW10, GW23, D4 (but without taking into account the adjustment).

Some boilers **were able to cope with up to 40% H2** (no test above performed in some cases) without any problem, but in this case adjustment tests were not performed or not relevant (appliances with combustion controls). GW01, GW06, D6 (but without taking into account the adjustment).

For boiler GW08, **flash back was observed with 23% H2**. This should not happen with an appliance that is new and certified. Furthermore, this appliance is certified for 30% H2 according to the laboratory. As this test is a standard test for H gas certification the fact that it doesn’t pass the test with 23% Hydrogen raises the question on the validity of the results. We will therefore not include this result in the general conclusion for this segment group.

2.5.2.2 Adjustments

As explained, the following adjustments were included in the test programme of premix appliances

- Adjustment A: appliances are adjusted with EU high and tested with EU low, and EU low + H2
- Adjustment B: appliances are adjusted with EU low and tested with EU high, and EU high+ H2
- Adjustment G: appliances are adjusted with EU low + 20% H2 and tested with EU high, and EU high+H2
- Adjustment H: appliances are adjusted with EU high + 20% H2 and tested with EU low, and EU low + H2

The experimental work carried out on the first appliances has rapidly shown that the most critical adjustment is the “G” due the strong impact on the air excess bringing the combustion close to stoichiometry. The other adjustments have shown no issues neither for CO, nor for flashback, nor for any other safety or operation parameter. As a result, the test program was modified to focus adjustment G on other aspects of testing. This explains why the other adjustments (A, B, H) were not made extensively.

Results of adjustment test G

Out of 6 tests, 3 are showing CO values that are above 1000 ppm when appliances are adjusted at EU LOW + 20% H2 and used with EU HIGH after.

For D4 and EB01, the situation of adjustment is worsened by the fact that the adjustments were made – based on the manufacturer's instruction material – with CO_2 instead of O_2.

As a result, the air excess (lambda) that should normally be the same during any initial adjustment is much lower (here by 5% for D6, and 9% for EB01), bringing the appliance closer to stoichiometry from the start, because of the initial adjustment. And of course, once EU HIGH is used, those appliances will now come very close to stoichiometry leading to high CO.

For EB01,

- The test with CH_4 gives (CO2- O2) = (8,4% – 5,4%)
- Adjustment G gives (8,4% - 3,8%)

So, the CO_2 is quite close to what it should have been, but the resulting O_2 value and lambda are quite far from the theoretical target.

To illustrate the benefit of adjusting with O2: **for GW08, the initial test was done with CO_2 adjustment. The CO value obtained was 1335 ppm (DAF). When adjustment was performed with O_2, the CO value was only 544 ppm[5].**

Discussion of the adjustment test results

The main problem with premix boilers, identified through the tests, is not flashback, but rather the **increase of CO when appliances are adjusted in a situation where, in the grid, we have a gas of low Wobbe index with H2**. This situation could become rather common in many places if hydrogen is injected in the grid. In such situations – if appliances are adjusted while there is H2 in the grid, when gas is switching to a gas with higher Wobbe Index and without H2 (for example in case of interruption of H2 injection) - the appliance's air/gas ratio will come closer to stoichiometry and high CO emissions will occur.

The threshold we have used for the CO evaluation is 1000 ppm (dry, air-free) which is the limit under normal operation and conditions in the existing product standards used for assessing conformity to the essential requirement of GAR. The adjustment that has proven to be the most problematic is the adjustment "G".

With adjustment" G", but not any other adjustments (A, B, H), the issue observed was high CO, we have not been confronted with flashback during the experimental testing phase of adjustments.

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[5] More information about adjustment with CO2 or O2 are given in THyGA report D5.2 « Test report of the identified mitigation solution on problematic appliances »

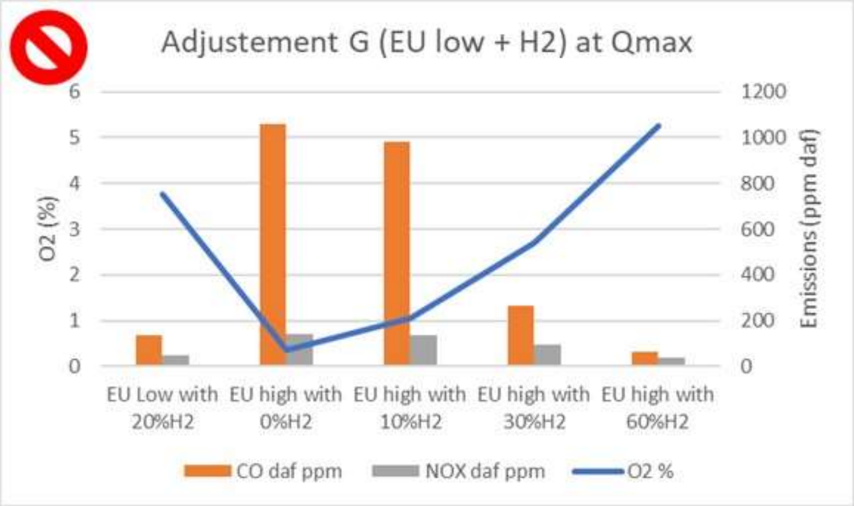

Figure 16: Example of results for adjustment boiler D4.

Figure 16 shows the results obtained with the boiler D4: Adjustment G is leading to a very high increase in CO (> 1000 ppm DAF) at the maximum power of the boiler. At minimum power, this is not the case at all, and the appliance is safe for all points measured.

The adjustment B shows the same situation but starting from a gas without hydrogen. As expected, there is still an increase of CO, but much lower (we have here about 300 ppm DAF).

The reason for the CO increase is that, because of the adjustment, the combustion comes very close to stoichiometry after changing gas.

As demonstrated in the project GASQUAL /7/, those scenarios are not H2 specific and may happen without injection of H2, but H2 increases the potential amplitude of Wobbe index variation, which we know may bring issues to some appliances when adjusted. For more details see also the Section 8 of D2.2 /2/.

This is especially true when an appliance is adjusted with a lean gas with H2 (low Wobbe index) and then used with a rich gas (high Wobbe index). In this case, the main issue observed is CO due to the decrease of air excess, similarly to GASQUAL observations.

- Therefore, the main concern with the adjustments including gases with H2 is not the flashback, but CO emissions due to changes in air excess.
- In general, CO emissions from premixed burners as well as other burners follow a U-shaped curve, the bottom of the curve being the air excess range for which the burners offer the best compromise between efficiency and emissions (e.g., λ =1.3).
    - for this point CO emissions are typically low (around 10 ppm to 50 pm DAF).
    - Coming closer to stoichiometry (air excess = 1), CO emission increases strongly up to several 1000 of ppm.
- The same happens also for the other side of the U with very high air excess (e.g., λ =1.8) also resulting in high CO values.

The Figure 9 (from GASQUAL) illustrates the above explained concept, but the air excess is here replaced by O2%. For more details see also the Section 8 of D2.2 /2/.

Consequences of the findings

The **principal reason for issues with the premix appliances is the adjustment.** If we consider this can be solved (blocking the hardware on appliances so that adjustments by third party are impossible, or new instructions to the installers, etc.), most appliances will have no problem anymore and can burn up gas with at least 40% H2.

Indeed, there may be potential consequences in the field:

- The installers would need to be able to know about the gas characteristics (the percentage of H2 and other components **or the Wobbe**) in the grid as well as ambient conditions during installation and maintenance to determine the correct settings (how will they get the information? Which frequency?).
- According to the theory and practice (see results presented above), the adjustment should preferably be done with O_2% rather than CO_2%, as this adjustment method is less susceptible to uncertainties due to unknown gas compositions, but this alone will not guarantee the safety of appliances, if adjusted when H2 was present in the grid (see also more test data in D5.2 WP5 report).

In general, this raises new question about the policy for adjustment of such appliances with the possible presence of H2 and what would be the best way to proceed in practice. Installers of appliances need to know the gas quality during the settings and therefore have H2 meters **or Wobbe meters** for installing gas boilers (or other new sensors); or local adjustment shall be strictly prohibited in areas where H2 can be injected. More thoughts and test results are given in D5.2[6].

Additional test results and verbatim

Some complementary tests of adjustment have been done on appliances with combustion control, this should normally not be done, but instruction manuals from manufacturers may not always be clear about this.

- **Such test was done with D5 (combustion control based on ionization)**, and the following observations were made (from the test report):
    - *The appliance was tested for short-term test with up to 40-60% H2 depending on test purpose. Within the test program executed there have been safety issues when the appliance is adjusted with EU low including 20% H2 and is operated with EU high. Safety issues were apparent as detonation/flashback and high CO concentrations larger than 6000 ppm during auto adjustment performed by the boiler electronics.*
    - *Note that this test was done to show how systems with combustion controls are behaving when adjusting them (despite this should in principle not been done). The boiler may be adjusted with CO2 as reference, but this is not part of the standard commissioning procedure.*
      According to the manual, adjustment is only required when converting to another fuel gas or when extraordinary maintenance is performed involving the replacement of a component, such as the P.C.B. (Printed circuit board) or components in the air, gas and flame control circuits. In that case the boiler will need to be calibrated. No safety issues at Qmax when the appliances were adjusted with CH4. CO peaks larger than 300 ppm during auto adjust at Qmin. Efficiency and emissions are impacted by H2.

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[6] THyGA report D5.2 « Test report of the identified mitigation solution on problematic appliances »

- The **same test was also done with D6 (combustion control based on ionization),** and the following observations were made (from the test report):
  - *"The boiler should be calibrated and controlled for correct CO_2 content as part of the standard commissioning procedure. According to the installers manual this adjustment is also required when converting to another fuel gas or when extraordinary maintenance is performed involving the replacement of a component, such as the P.C.B. or components in the air, gas and flame control circuits. In that case the boiler will need to be calibrated. It was not possible to calibrate the boiler to the desired 8,8 % CO_2 when operated on EU low or EUlow+20% H2."*

- and **with EN21 that is equipped with a CO combustion control system**
  - For a part of the test, autocalibration was forced at each gas composition to see how the boiler performed after auto-adjustment.
  - For the second part, no autocalibration was performed except on the adjustment gas.
  - We do not have any information on when the appliance performs spontaneously its autocalibration. So, we can consider that, when gas composition changes, this boiler performs like a standard boiler until it performs its autocalibration.

The adjustment G2 shows remarkably good results (low CO) both here with calibration.

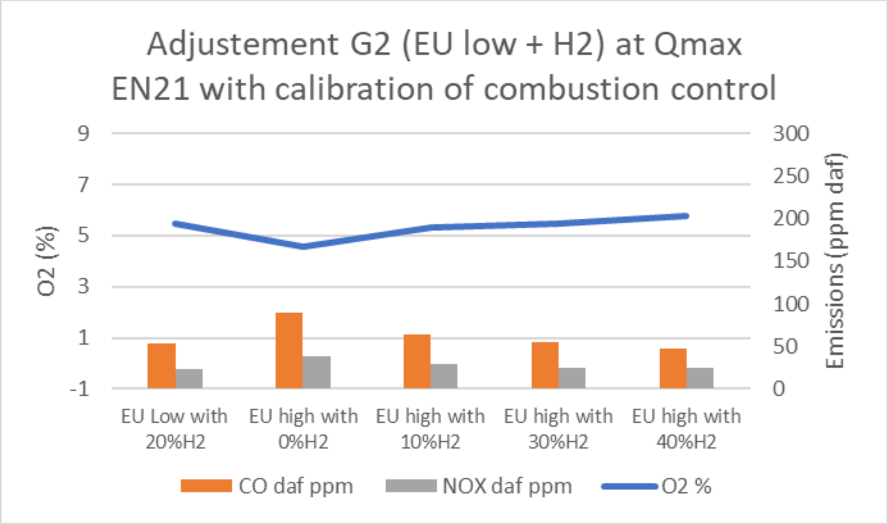

Figure 17: O2% according to gas quality for G2 adjustment for EN21 – Autocalibration forced (adjustment with CO2).

The other remarkable result is the ability of the sensor to maintain the air excess. The O2 curve is much flatter once the CO sensor is calibrated.

For the tests without calibration the results are less good (see more detailed discussion in WP5).

However, it seems that (for this boiler) adjustment based on O2 will not be as good as the adjustment with CO2: (larger variations of O2 and higher CO emissions with adjustment based on O2).

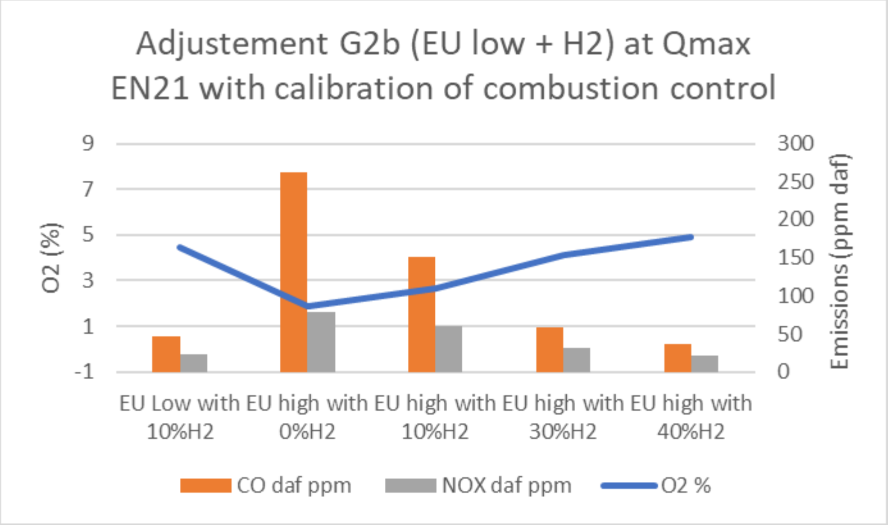

Figure 18: O2% according to gas quality for G2 adjustment for EN21 – no Autocalibration (adjustment with O2).

2.5.2.3 Flame stability - flashback

The flashback occurrence may sometimes be difficult to identify for appliances where the burner is not visible (typically for fully premix appliances), consequently there may have been some flashback that we are not aware of.

Flash back at 60% was observed for GW03, GW21, AP02, D5, GW05

- "*When flashback happened, some parts on the boiler fell apart, e.g. air collector, once mounted again the boiler works again. No major damage was observed*" (AP02).
- "*Flashback makes the system turn off by Qmin at 60% - flashback. Violent bang. Air intake unit broke in half. The system can be restarted after reinstalling the tube.*" (GW05)
- "*The appliance had flashback at Qmin with 60% H2. There was no visible physical damage to the boiler. The boiler was louder than before.*" (GW21)

Flashback at 50% was observed for GW11 (Qmin), GW17 (Qmin)

- "*There was no significant damage, the system gets very loud and after the flashback the system is still functional.*" (GW11)
- "*The system gets louder, there was an error, and the system went off. No physical damages.*" (GW17)

Flashback at 40% was observed for D6.

Flashback at 23% was observed for GW08. **For GW08,** flash back happened in the following cases:

- Qmin G 20 + 60 Vol.-% H2
- Qmax G 23 + 30 Vol.-% H2 (G 23= 92,5 Vol.-% CH4 + 7,5 Vol.-% N2)
- Qmax G 23 + 23 Vol.-% H2 (G 23= 92,5 Vol.-% CH4 + 7,5 Vol.-% N2) (see discussion explanation under the table at the beginning of this section)
- Qmin EU high + 60 Vol.-% H2 (EU high= 93,4 Vol.-% CH4 + 6,6 Vol.-% C3H8)

- Qmin EU low + 60 Vol.-% H2 (EU low= 95,6 Vol.-% CH4 + 4,4 Vol.-% N2)
- No specific explosion or loud noise, the system just goes into an error "Flameout"
- **Note that paradoxically GW08 is designed to cope with 30% H2.**

Discussion of the flashback observations

Flashback result with G23 should be interpreted carefully. G23 is a limit gas out of the specification for gas distributed in the EU. Moreover, G23 should normally not increase the risk of flashback compared to CH4. The results may be explained by the appliance adjustment (or not) for this test. See also further in this report the discussion of the tests with G23 in Annex 4.

Forced adjustment of boiler equipped with combustion controls may lead to Flashback (D5), as well as short periods with very high CO, but those peaks are linked to the autocalibration and not to H2.

2.5.2.4 Flame detection

Most of the tested appliances have flame supervision systems based on flame ionisation currents. For most of them, the ionisation signal remains quite high and above the threshold (below which the safety system closes the gas inlet). Most of the results below are obtained thanks to manufacturers providing data from appliances' software.

The ionisation works surprisingly well with the level of H2 tested (up to 60% in many cases) for flame detection, while we expected problems since the hydrogen flame is supposed to generate a lower ionisation current. This is a positive result. It should be pointed out, however, that if the flame ionisation signal is also used for combustion control purposes, this approach is insufficient and unable to maintain a constant air excess ratio. The reason for this failure is that due to the presence of hydrogen, the position of the flame relative to the sensor shifts significantly, and the control logic is confronted with conflicting signals.

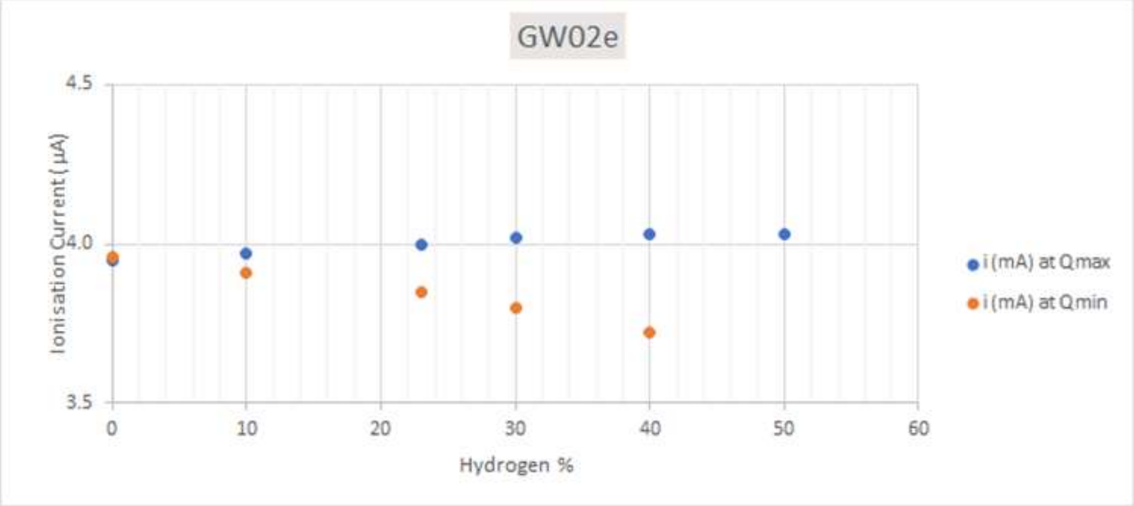

Figure 19: Example of ionization signal evolution with %H2 for GW02.

In order to compare the signal measured on different appliances, we have gathered all measurement done on the appliances under the section Flame detection - Ionisation current.

The conclusion is that ionisation works very well for the flame detection for the %of H2 investigated.

2.5.2.5 CO Emissions (dry air free)

CO emissions with CH4

At Qmax, the CO emissions decrease with increasing levels of H2 in the vast majority of the cases, but increases in a few cases. The noticeable increase in the boiler GW17, that ends at 120ppm for 60% H2. CO emissions are very much dependent on the air excess, but we are not able to explain GW17 results with the air excess evolution.

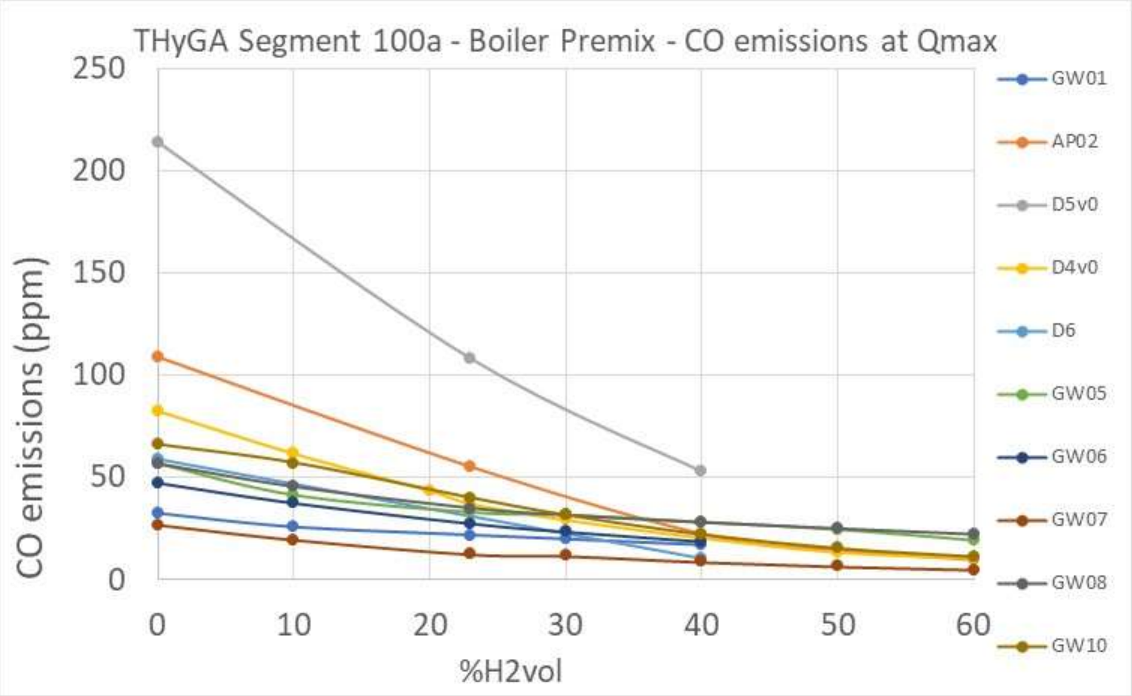

Figure 20: Segment 100a - CO emissions at Qmax - Part 1.

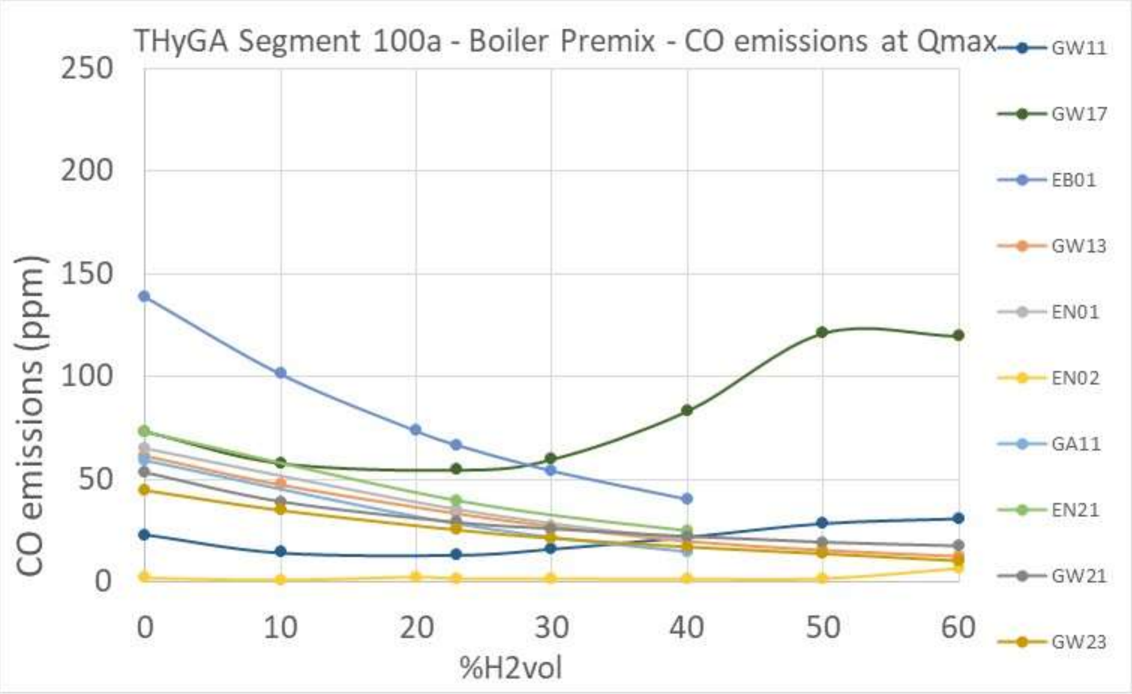

Figure 21: Segment 100a - CO emissions at Qmax - Part 2.

At Qmin, the CO emissions curve is always flat. Emissions are lower compared to Qmax and H2 injection has no impact on the CO levels.

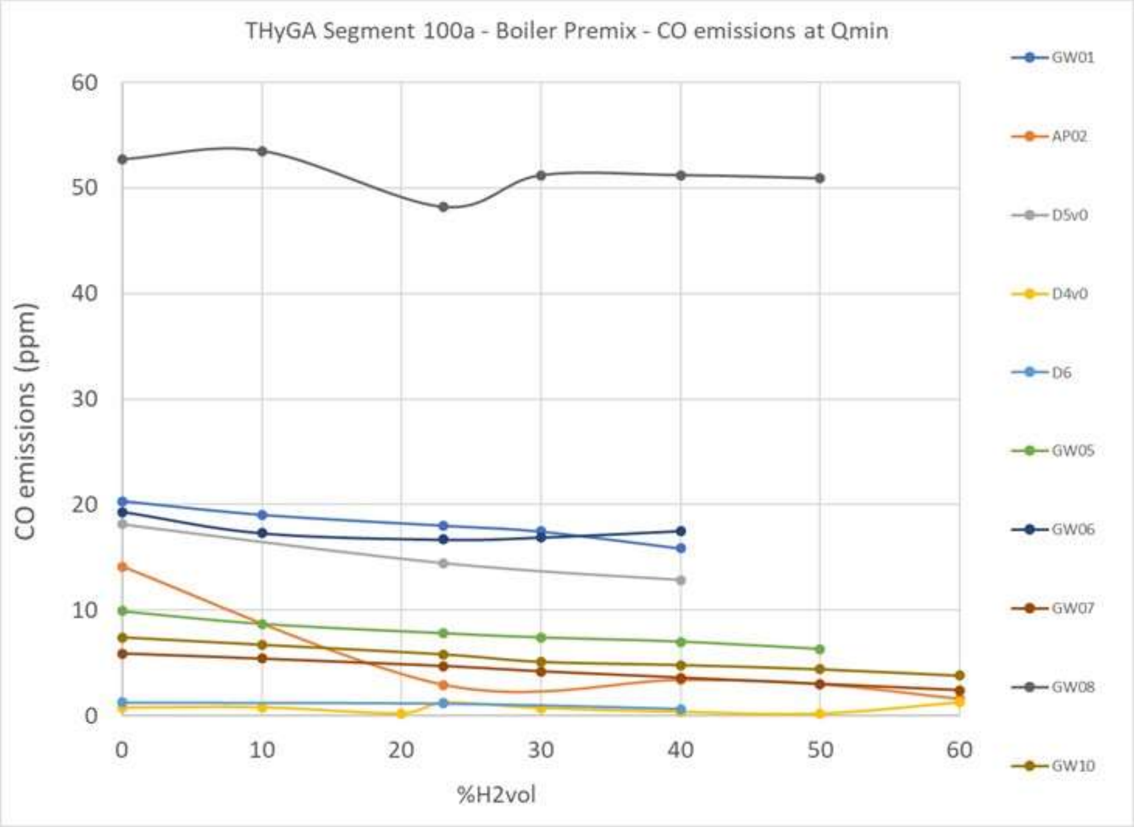

Figure 22: Segment 100a - CO emissions at Qmin - Part 1.

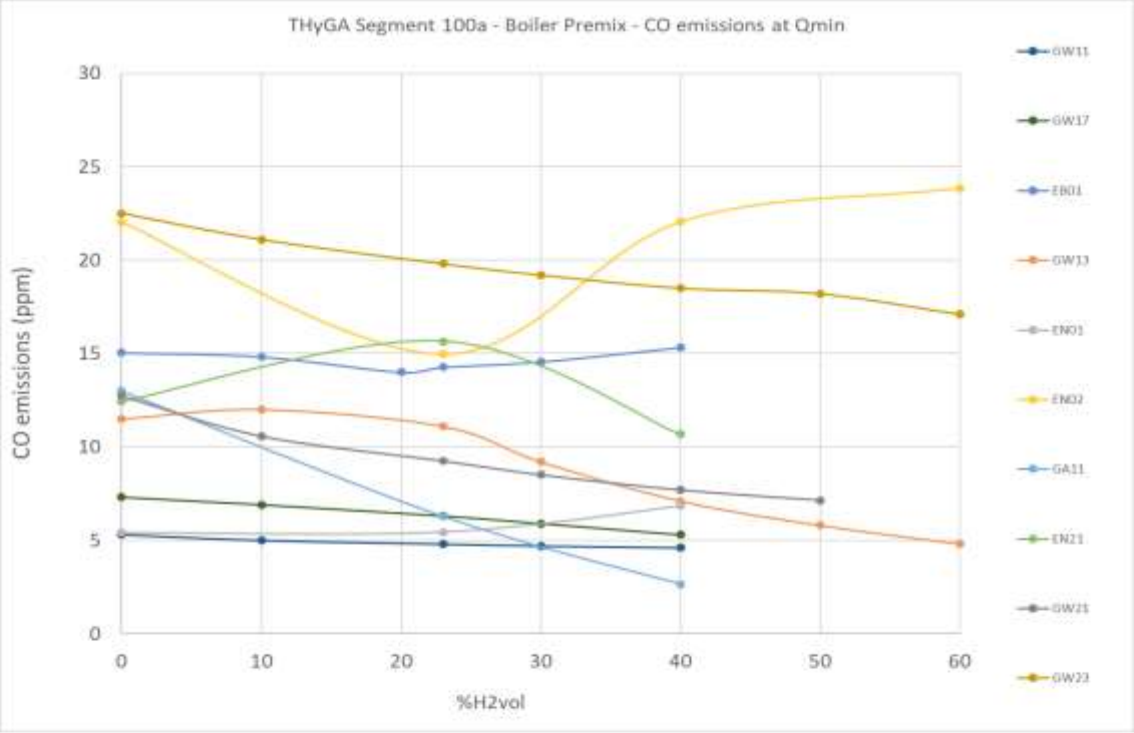

Figure 23: Segment 100a - CO emissions at Qmin - Part 2.

In conclusion, the addition of H2 generally resulting in lower or stable CO emissions and there is only one case where we see an increase but not at all at a level that the appliance can be considered as unsafe.

Comparative CO emissions at Qmax with G23 and CH4

G23 is a limit gas, for which the characteristics are out of the range of the gases distributed in the EU (see Figure 3 showing Wobbe Index and density for G23 compared to G20, EU LOW, EU HIGH etc.).

G23 is a gas that would increase flame lift and so probably more CO.

Using G23 instead of CH_4 would not impact the flame speed very much as, in general, the impact can be considered as marginal with the gas composition of natural gases L distributed in Europe (see Figure 24). Therefore, making the test with CH_4 or with another gas in the range EU low – EU high will not make a significant difference for the flame speed.

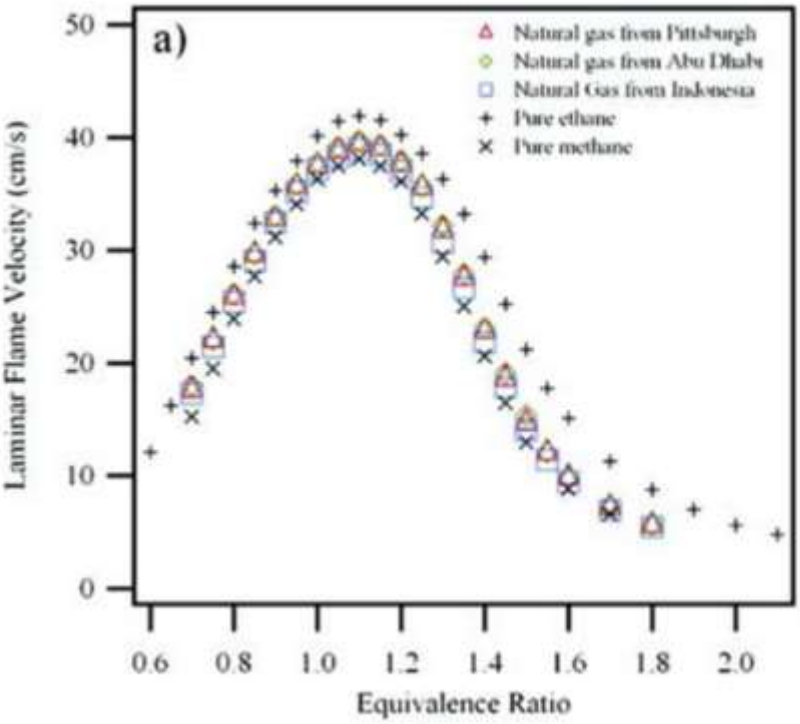

Figure 24: Flame speed for different natural gas qualities[7].

The following tests have been done with boilers adjusted on G20.

With G23, the CO level is generally higher (as expected), but the trend of adding hydrogen is the same, the emissions globally diminish or stay the same as observed with CH4.

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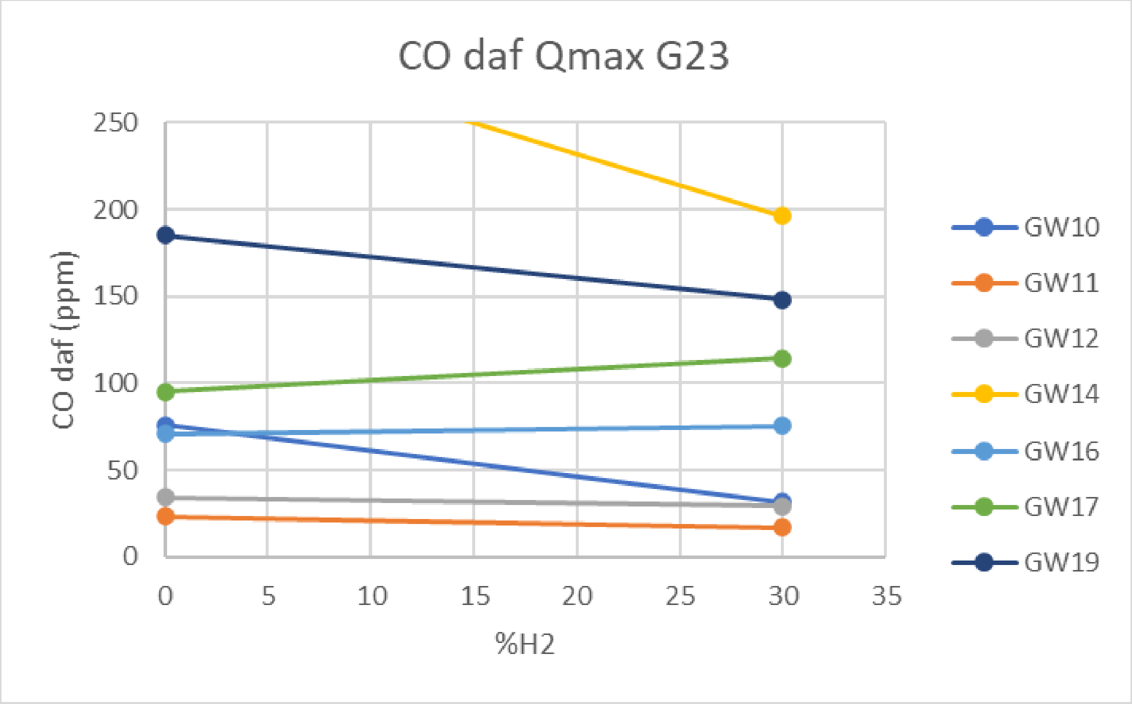
[7] Ref: Measurements of Laminar Flame Velocity for Components of Natural Gas. Patricia Dirrenberger, Hervé Le Gall, Roda Bounaceur, Olivier Herbinet, Pierre-Alexandre Glaude, et al. Measurements of Laminar Flame Velocity for Components of Natural Gas. Energy and Fuels, American Chemical Society, 2011, 25 (9), pp.3875-3884. ff10.1021/ef200707hff. ffhal-00776646f



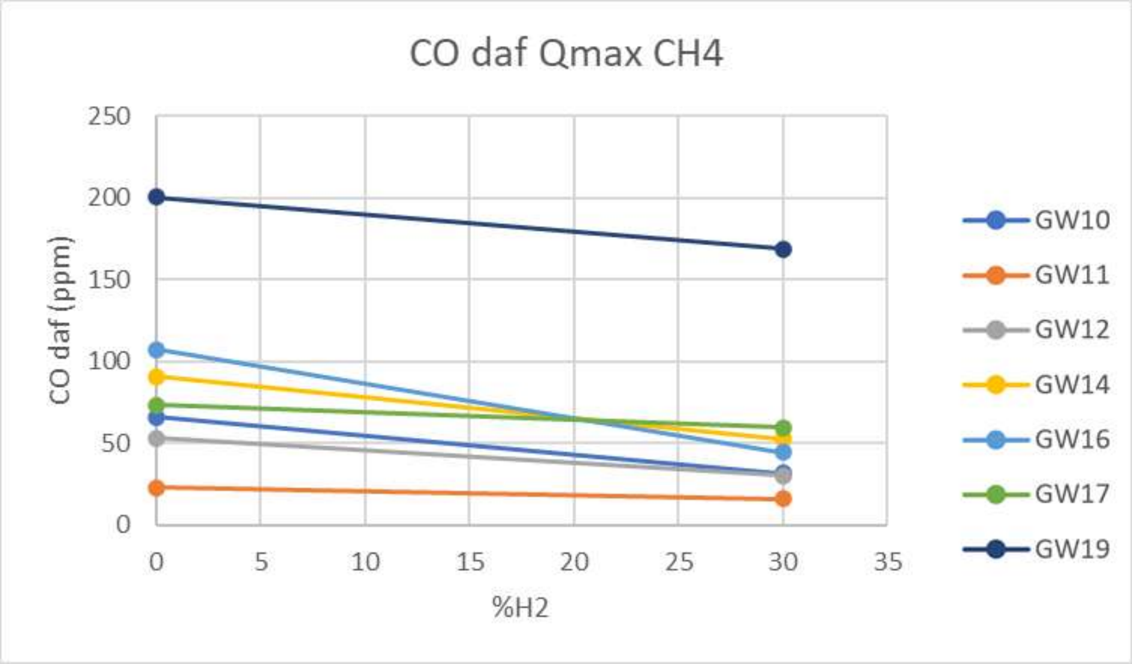


Figure 25: Segment 100a - CO emissions, comparison between G20+H2 and G23+H2.

More data (other boilers and also for Qmin) are given in Annex 4.

2.5.2.6 Other safety aspects - not being an issue

The following test were performed and have not given any issues:

- **Flue pipe length (tested with 4m and 8m long pipe) and external air temperature (down to 0 °C)** seems to have no impact on safety for the test carried out, nor no changes in the heat output (GW01).
- **Quick variation between Qmin and Qmax**, does not seem to be a problem.
- **ROC (PLUG FLOW test is performed by changing brutally gas composition coming to the tested appliance)** was executed without showing any issue (generally variation from 0 to 40% H2 and the other way round).
- **Pressure variation** does not seem to be a problem; note that appliances are probably all equipped with pressure regulators.
- Both impacts of "**low air temperature (-10 °C)**" and "**Flue gas pipe length**" have been tested on 1 and 2 appliances (boilers), respectively, and the results from the test done show no impact of hydrogen.
- **Fluctuation of the auxiliary energy** shows no impact on safety.
- The **influence of wind** on exhaust ducts was tested (no impact was seen).
- **Short "long term"** (limited time)[8] **test was performed** and did not show any issues. For **for example**
  - The long-term limited time test showed that there is no problem when switching from G20 (1 hour long) to G20+30%H2, no flashback, no problems with emissions (GW07).
  - After 1hour run with G20 and then fast change with G20+40%H2 no change and no flashback occurred (GW10).
  - No problem occurred with the limited long-term tests (GW11).

2.5.3 Emissions

2.5.3.1 NOx Emissions (dry air free)

NOx emissions with CH4

In principle, H2 injection on uncontrolled premix boilers will result in higher air excess and lower flame temperature resulting in lower NO_x (in principle, one could run a premixed burner with H2 with constant air excess ratio as long as one has a working control system, but appliances on the market are not presently equipped with such system).

For CO, things are slightly more complicated as CO is following a "U curve" and slight changes on air excess will not impact CO emissions until a certain point, where CO can increase dramatically as seen in the analysis for the adjustment discussion.

As expected, the tests show a decrease of NO_x emissions in the vast majority of cases. The actual decrease is different by technology and from appliance to appliance.

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[8] Note that long-term tests are done and reported in deliverable D3.9

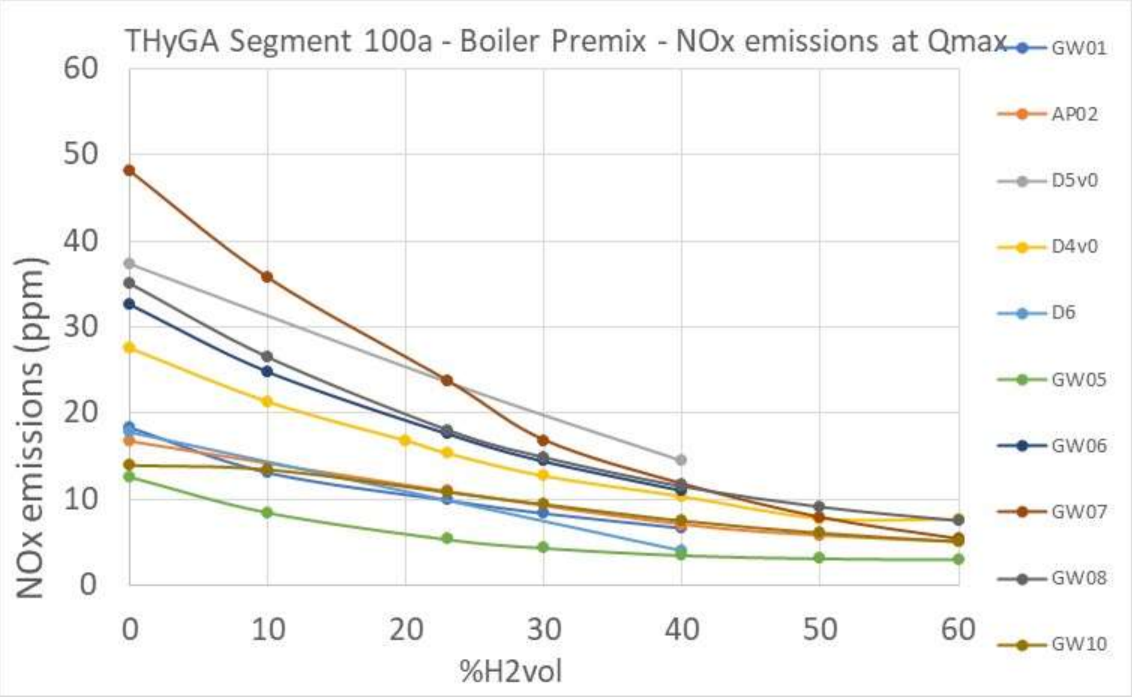

Figure 26: Segment 100a - NOx emissions at Qmax - Part 1.

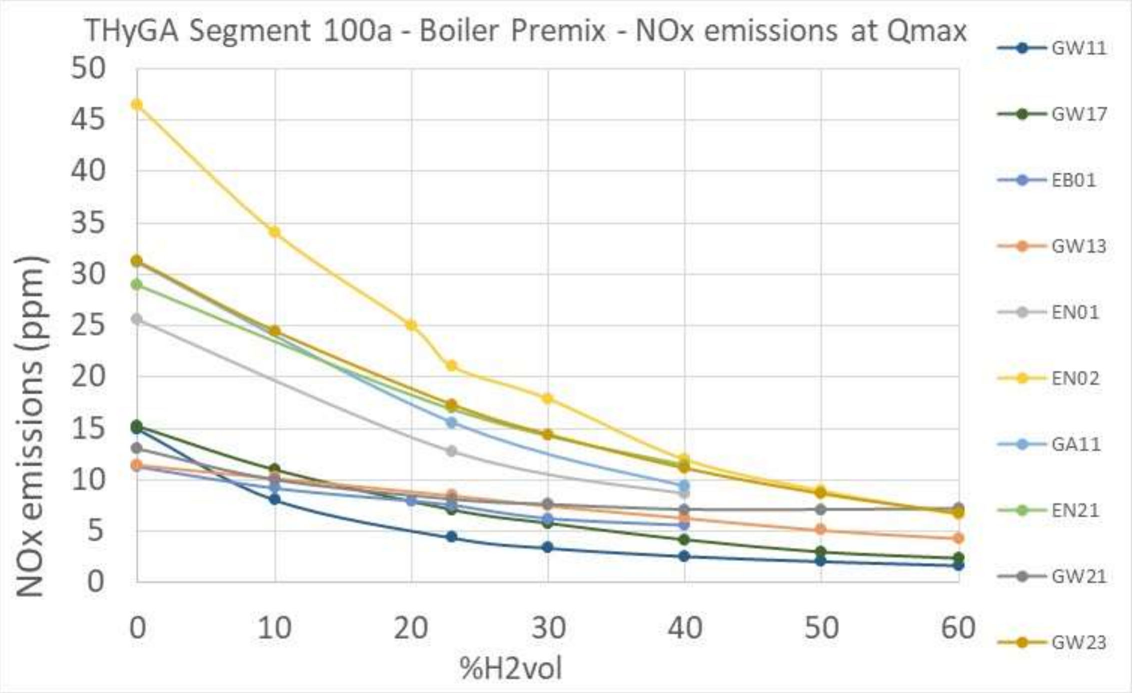

Figure 27: Segment 100a - NOx emissions at Qmax - Part 2.

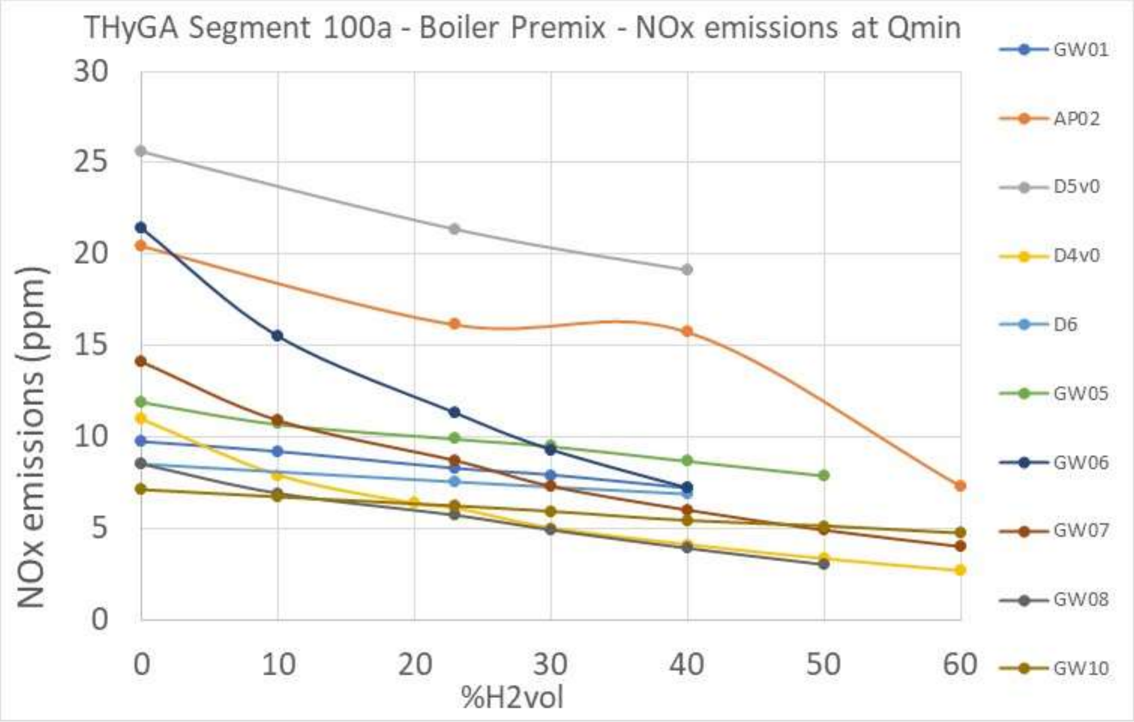

Figure 28: Segment 100a - NOx emissions at Qmin - Part 1.

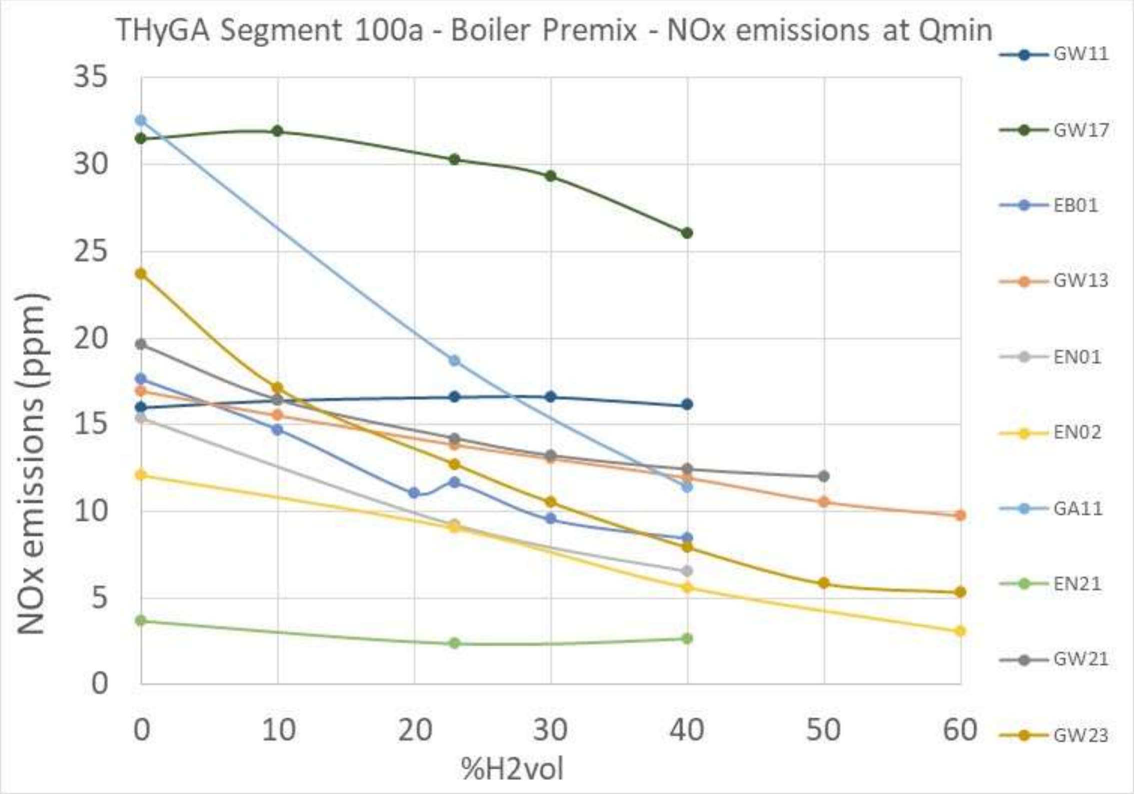

Figure 29: Segment 100a - NOx emissions at Qmin - Part 2.

Comparative NO_x emissions at Qmax with G23 and CH_4

The following tests have been done with boilers adjusted on G20.

The addition of H2 to CH_4 or G23 will generally result in a decrease of emissions (with one exception, GW09, here).

The level of NO_x is, however, different (generally higher for G23).

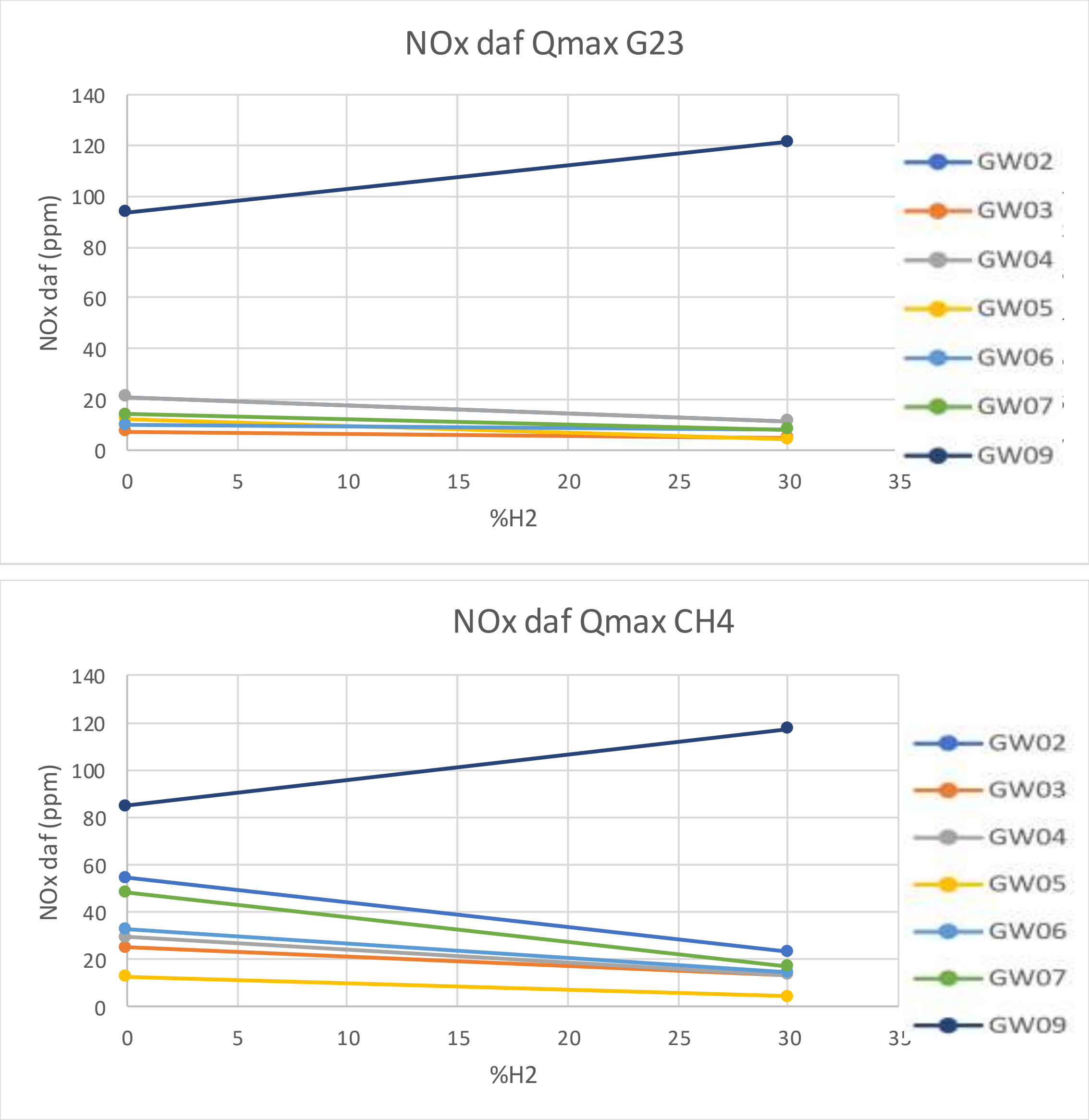

Figure 30: Segment 100a - NOx emissions, comparison between G20+H2 and G23+H2.

2.5.3.2 UHC

UHC are discussed in section 3.5. For the boiler tested, the addition of H2 results in a reduction of CH_4 emissions, this reduction is generally higher than the proportion of the CH_4 replaced by H2 which means a stronger relative impact on unburnt emissions.

2.5.4 Efficiency

In this section, we discuss the impact on efficiency when adding hydrogen to natural gas. This analysis has been done in synergy with the GERG project WP8 /8/ . See also D2.3 for more discussions on this topic /2/.

The potential changes in efficiency for a boiler are due to the following factors and could counteract each other:

1. The ratio Hs/Hi is higher for blends of hydrogen with methane, compared to methane alone.
    a. When expressed on Hi the efficiency for condensing appliances will increase due to a higher volume of water in the flue gas and, so, more potential for latent heat recovery (in case the boiler is condensing).
    b. With the addition of H2, the dew point temperature increases, and there will be condensation and consequently a gain in efficiency. Note that the gain will very much depend on the return temperature of the boiler.
    c. This will not be the case at low water temperature, at a level where condensation is already complete or near complete with natural gas; this effect is therefore marginal (effect only due to the “additional” water condensate).
2. The impact will also be different comparing a non-condensing boiler to a condensing one.
3. The injection of hydrogen, in case the air excess is not controlled, will result in higher air excess and as a result higher flue gas loss and, so, a decrease in efficiency.
4. Assuming a constant air excess ratio, the combustion efficiency of a combustion application will improve (slightly) with higher levels of hydrogen.
5. If not changing any operation parameters when injecting hydrogen, the flow temperature of heating appliances will decrease (because of the lower heat input), and this will result in an increase of the efficiency.

These elements explain why there are different conclusions on the topics in literature about the impact of hydrogen on efficiency: condensing boilers tested at low water temperature will have an increase of efficiency due to the condensate impact as explained above, this resulting in a situation where some references say there is an increase of efficiency, and some say there is a decrease[9].

In addition, **the effects are generally small and thus difficult to measure. It is generally not larger than 1%,** which is below the uncertainty of measurement of laboratories. The tests shall be done under repeatable conditions, as the repeatability of labs should be better than the uncertainty, and repeatability of 0.5 % is not unusual when the tests with and without H2 are performed immediately after each other, if possible, the same day.

The project will consider here that differences below 0.5% (net efficiency) are not significant when tests are carried out the same day. If carried out on different days, the differences below 1% are not significant either. **This means in such situations when the differences are inferior to the proposed thresholds, we will not be able to conclude about the hydrogen having an impact on efficiency**.

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[9] More details in THyGA deliverable D2.3

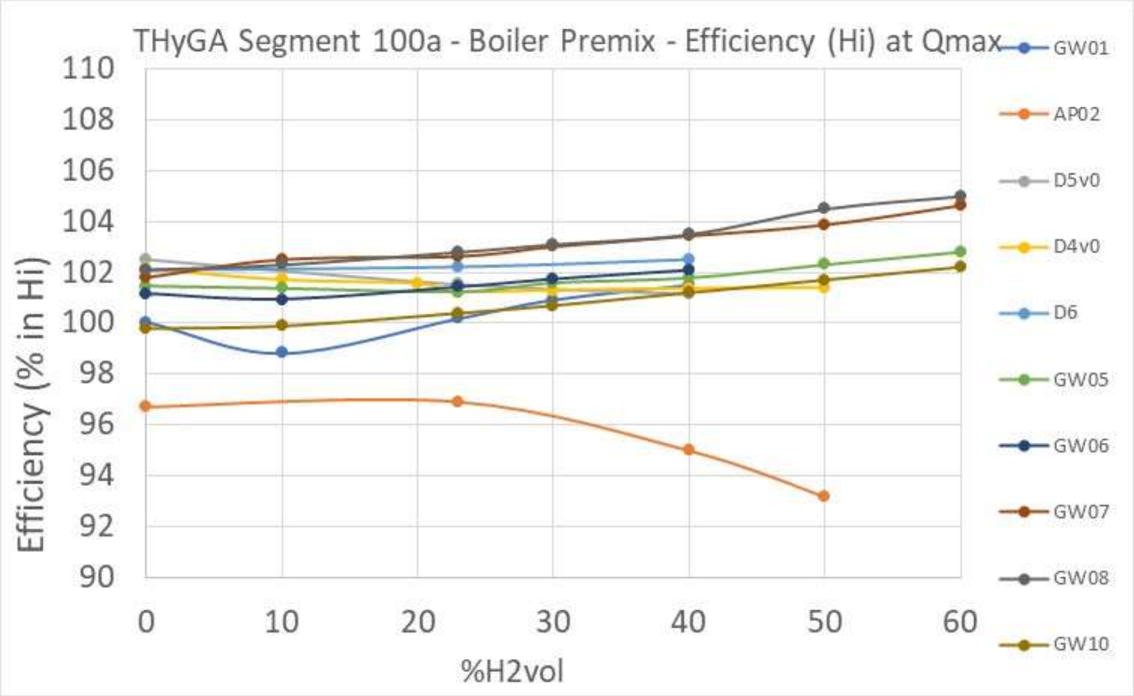


Figure 31: Segment 100a – Efficiency at Qmax - Part 1.

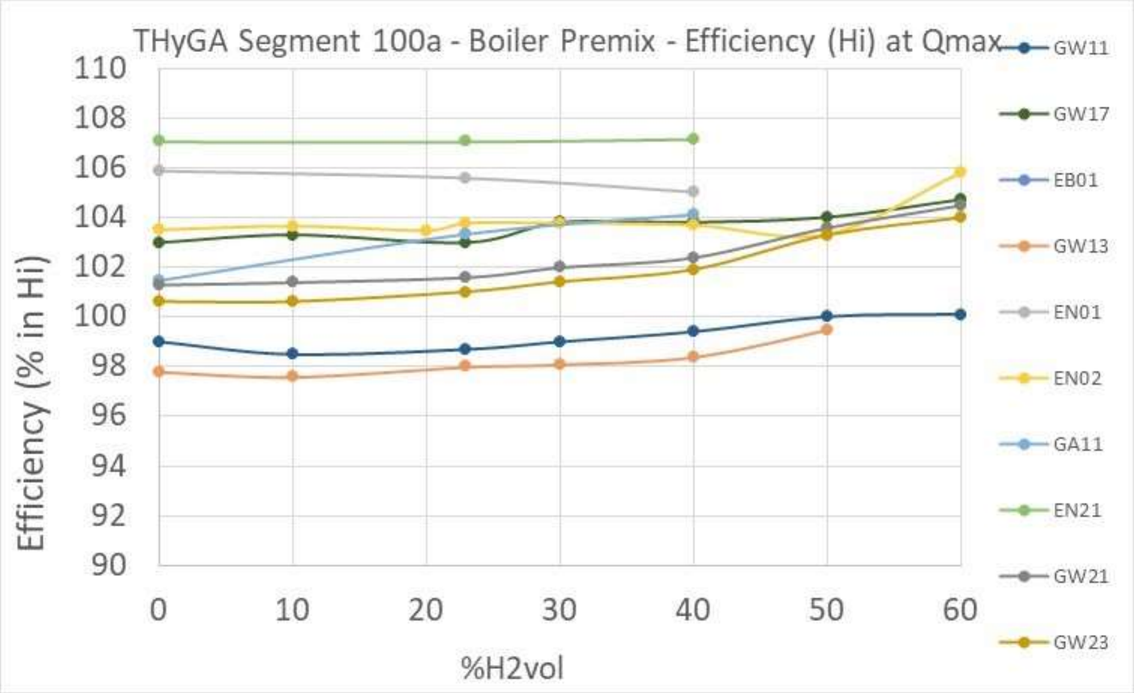


Figure 32: Segment 100a – Efficiency at Qmax - Part 2.

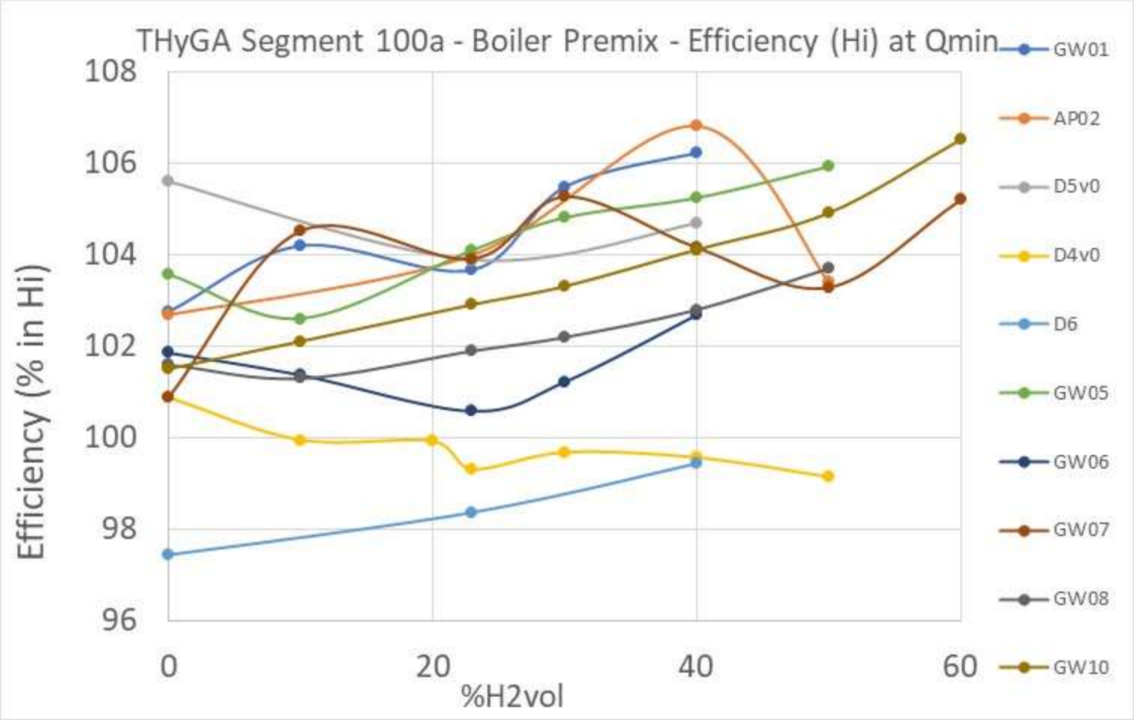


Figure 33: Segment 100a – Efficiency at Qmin - Part 1.

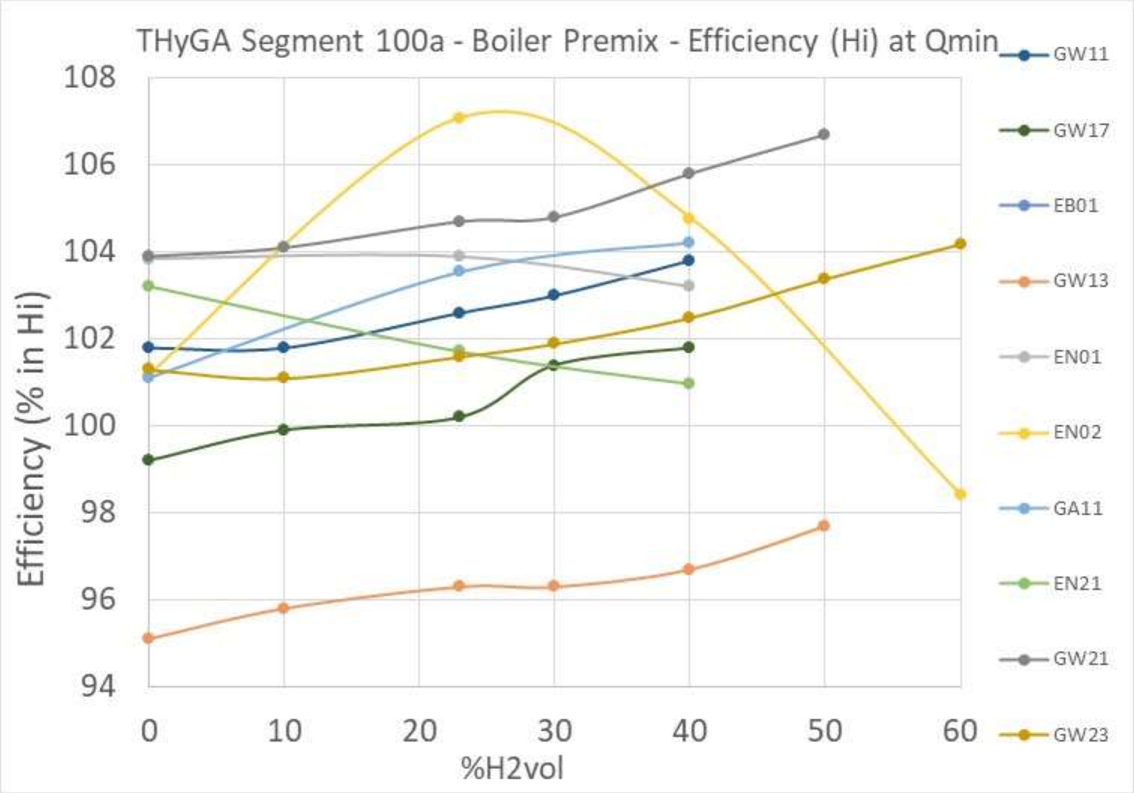


Figure 34: Segment 100a – Efficiency at Qmin - Part 2.

Conclusions

The efficiency expressed on lower calorific value (Hi) measured under the condition of the testing (Return temperature at 40 °C) **slightly increases** with the addition of H2 to CH_4.

For some boilers, the efficiency is decreasing or is more or less constant.

2.5.5 Operational

Operational issues are observed from H2 > 40%, several different effects were identified by the project.

Noise

Several appliances have more noise with the increase of H2, already with 40% H2. Combustion is louder after 40% H2 (GW03) or 50% H2 (GW17).

Cold start (« CS »)

Some appliances experienced cold start issues **from 40 % H2. Some were also having cold start issues without H2 at EU LOW.**

- Cold start issues with 40% H2 (D6) (note that cold start was also observed for EU LOW, EU LOW+20% H2 and CH4+40% H2,
- Cold start is observed with BA01, but it has only occurred at 60% H2.
- Hot start was also an issue for GW03. It has occurred at 60% H2 for both. GW03 has passed at 40% (50% not tested).
- Flame needs some seconds-minutes to stabilize for cold/hot start. No other safety issues observed. (EB01)

Note that other boilers were able to cope with cold start at 40% H2 (as GW08).

Other

Boiler switches off at the 60 vol% (GW08): *"The system switches off at the 60 vol% hydrogen by Qmin admixture with a "flameout" message. After a short time, the device switches on again. The system switches off at O2 adjustment tests 60 vol% hydrogen by Qmin admixture with a ""flameout"" message. After a short time, the device switches on again. After several repetitions, the unit goes into fault mode, i.e. the unit no longer switches on. There was no noise and no explosion.* After several repetitions, the unit goes into fault mode, i.e. the unit no longer switches on."

Operational aspects for appliances with combustion controls

We encountered the case of a boiler with a combustion control (D5) where the boiler may be adjusted with CO_2 as reference, but this is not part of the standard commissioning procedure. According to the manual, adjustment is only required when converting to another fuel gas or when extraordinary maintenance is performed involving the replacement of a component, such as the P.C.B. or components in the air, gas and flame control circuits. In that case, the boiler needs to be calibrated (means "adjusted" here).

When performing this test with 20% H2 in EU LOW, we could observe some instability in the “auto adjust” function of the boiler, with frequent auto adjust attempts accompanied by CO peaks.

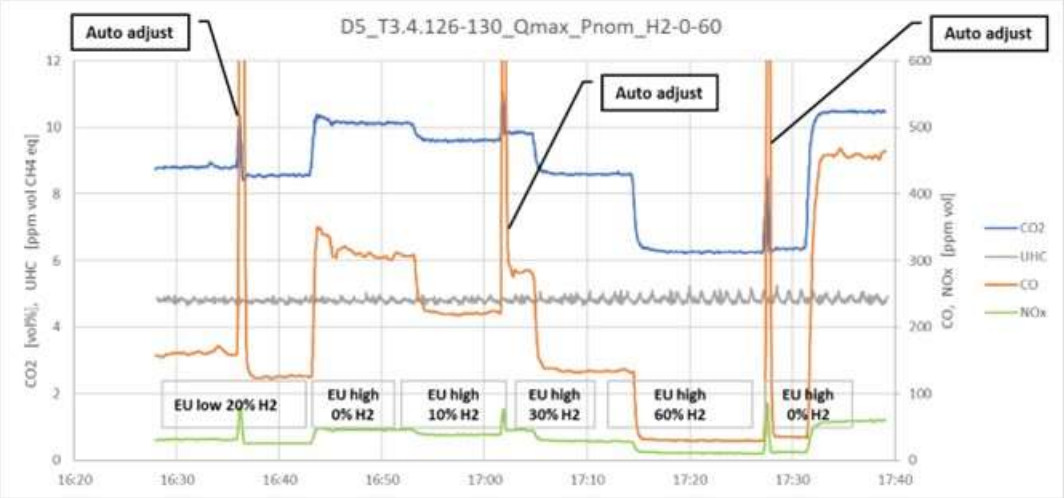


Figure 35: Boiler D5 ADJUSTMENT G2 (Qmax - GAS set to EU low + 20% H2 and used with EU high with increasing H2%).

2.5.6 Conclusion for segment 100a

Table 9: Conclusions for segment 100a (impact card).

		H2 % Tested							
		0	0-10	10-20	20-23	23-30	30-40	40-50	50-60
100a Boilers fully premix	Safety	🟩	🟩	simple mitigation (3)	mitigation to be defined		5	8	11
	Safety with mitigation	🟩	🟩	Dedicated adjustment methodology			2	5	8
	Operational	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧

Note that the above table doesn’t take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 100a, a total of 20 appliances were tested. The number of appliances having issues are indicated in the red cells of the “impact card” above. Note that not all appliances may have issues for the same tests, and not all tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

The premix boilers would be able to cope with 30% H2 or more if adequate measures are taken to avoid the situation where appliances are adjusted wrongly in a situation when there is a presence of H2 in natural gas during this adjustment. Such an issue can even occur with 20% hydrogen in the grid, but a simple solution to mitigate the problem is to base the adjustment on O2 instead of CO2.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

2.6 Not fully premix boiler (Segm. 100b) and Forced draught burner (Segm. 100c)

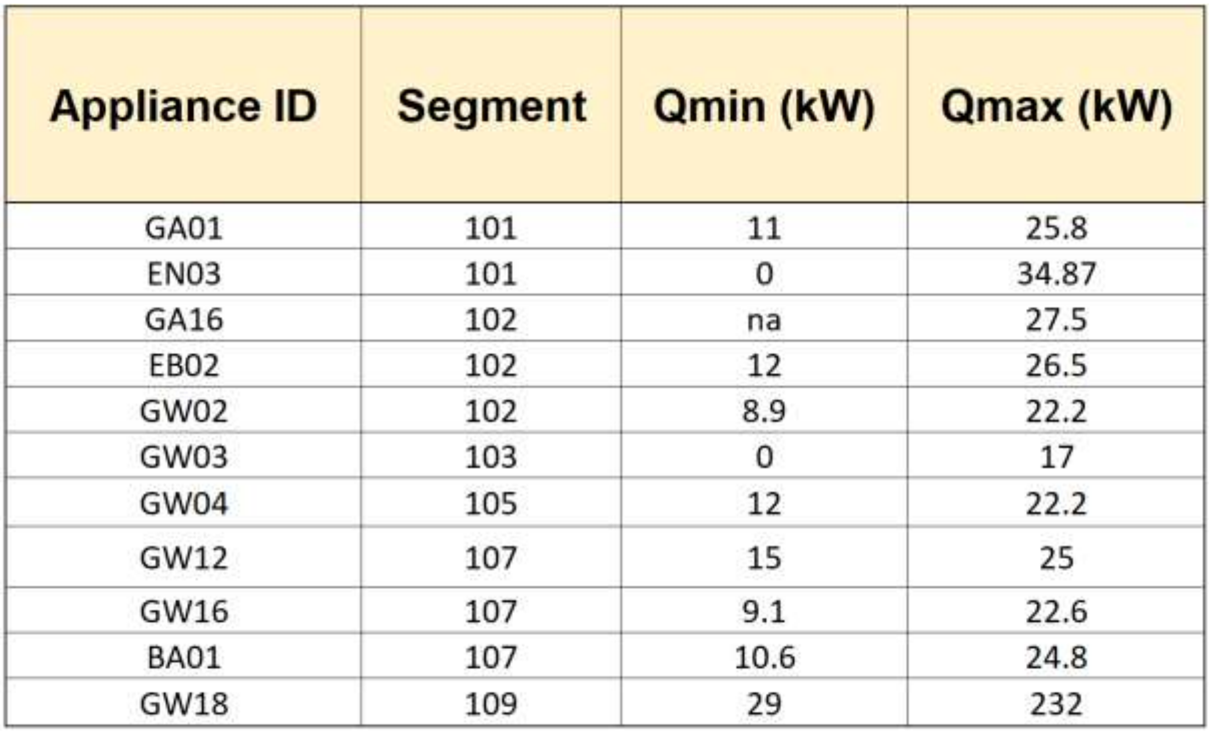
2.6.1 Appliances tested

Not fully premix boiler (Segm. 100b) mean literally boilers which are partially premixed boilers, meaning the **THyGA segments 101, 102, 104, 105, 107.**

In view of the results of delayed ignition this segment group was reworked. See the discussion of delayed ignition in section 3.3.

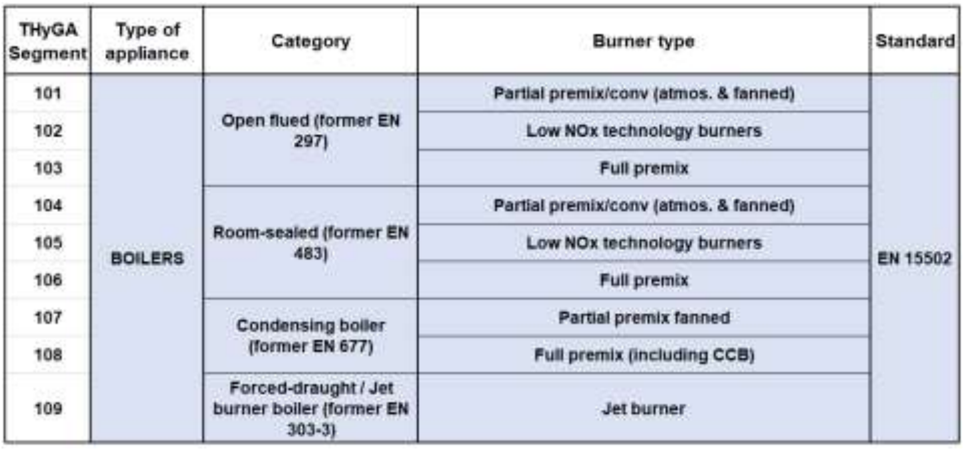
Forced draught burner (Segm. 100c) is the **THyGA segment 109.** See Annex 2 for more details.

Table 10: Characteristics of the 11 boilers from segment 100b tested.



Appliance ID	Segment	Qmin (kW)	Qmax (kW)
GA01	101	11	25.8
EN03	101	0	34.87
GA16	102	na	27.5
EB02	102	12	26.5
GW02	102	8.9	22.2
GW03	103	0	17
GW04	105	12	22.2
GW12	107	15	25
GW16	107	9.1	22.6
BA01	107	10.6	24.8
GW18	109	29	232

Table 11: Segmentation of the boiler category



THyGA Segment	Type of appliance	Category	Burner type	Standard
101	BOILERS	Open flued (former EN 297)	Partial premix/conv (atmos. & fanned)	EN 15502
102			Low NOx technology burners	
103			Full premix	
104		Room-sealed (former EN 483)	Partial premix/conv (atmos. & fanned)	
105			Low NOx technology burners	
106			Full premix	
107		Condensing boiler (former EN 677)	Partial premix fanned	
108			Full premix (including CCB)	
109		Forced-draught / Jet burner boiler (former EN 303-3)	Jet burner	

2.6.2 Safety

Table 12: Safety results for segment 100b.

	Appliance ID		GA01	EN03	GA16	EB02	GW02	GW03	GW04	GW12	GW16	BA01	GW18	X
	Segment		101	101	102	102	102	103	105	107	107	107	109	102
	Qmin (kW)		11	0	na	12	8.9	0	12	15	9.1	10.6	29	
	Qmax (kW)		25.8	34.87	27.5	26.5	22.2	17	22.2	25	22.6	24.8	232	
	Combustion control feature (Y/N)		N	N	N	Y	N	N	N	N	N	Y	Y	results sent late
At what level of H2 the problem may occur : reference gas + %H2 used	%H2 in test gas	0	X	X	X	X	X	X	X	X	X	X	X	
		0-10				X	X			X		X		
		10-20				X	X					X		
		20-23	X	X	X	X	X	X	X	X	X	X	X	
		23-30	X		X	X	X		X	X		X		
		30-40	X	X	X	X	X	X	X	X	X	X	X	
		40-50	X				X	X	X	X	X	X		
		50-60						X	X	X	X	X	X	
EE	1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X	X (30%)	X (60%)	X	X	X (60%)	X (60%)	X	
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2	X		X			X				X		
EE	1.3 Efficiency and emission G23	G23 + H2	(*)				X		X	X	X			
CS	1.4 Cold start	CH4+40%H2	X	X	X	X	X	X	X	X	X	X (40%)		
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)		X	X (40%)	X	X	X	X	X	X	X		
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2			X		X							
FGP	1.7 Flue gas pipe length	CH4+30%H2										X		
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X	X	X	X	X	X	X		
FD	1.9 Impact H2 flame detection.		X	X	X	X	X	X				X		
FB	1.10 Flash back		X	X	X (40%)	X	X	X (60%)	X	X	X (60%)	X (60%)	X	
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2		NA				X						
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2		NA				X						
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2		NA										
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2		NA				X						
DI	4.1 Delayed ignition test.	CH4+30%H2										X		X (20%)
S	4.2 Soundness													
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X		X									
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2			X (30%)									
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA		NA	NA	NA	NA	NA	NA	NA	
W	4.6 Influence of wind													
LT	4.7 Long time (limited time)	depends on manufacturer			X	X								
AUX	4.8 Fluctuation of the aux.				X							X		
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X		X	X	X	X	X		
O	Other /Operational			X	X			X (40%)						

(*) performed without H2

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

Hot start of GA16 is marked red as flashback was observed.

2.6.2.1 Overall observations and discussion on safety results:

Out of 11 boilers, 7 have performed without any issues. Most of them (6) were tested up to 50 or 60% H2, one up to 40%.

The issues registered are:

- Cold start (1) at 60 % H2 (BA01)
- Hot start (1) at 40% H2 (GA16)
- Flashback (4) (GW16, GW03, BA01, GA16). Flashback has occurred from 40 % H2.
  - For GA16, the appliance suffered sudden bursts of flashback, from 40%H2. This flashback not only causes poor combustion, but also burner damage.
  - For GW03, the system works well up to 40% H2. After 40%, it gets louder, flashback happens at 60% H2 and the system doesn't start again after that.

Figure 36: Illustration of flashback effect on GA16, with 40%H2.

Finally, we have received at the very end of the project data from boiler manufacturers showing issues with delayed ignition on appliances from the segments 101 and 102. This is discussed further in the section 3.3 of this report.

Many tests were carried out and have shown no issue:

- Delayed ignition test (BA01)
- Quick variation Qmin-Qmax Shut-off
- Long time (limited time)
- Fluctuation of the aux. energy
- Fluctuation of pressure
- Overheat for 30 % H2 (GA16). However, for this test there is a discoloration of the burner and therefore we have marked the results as "orange" in Table 12.
- ROC

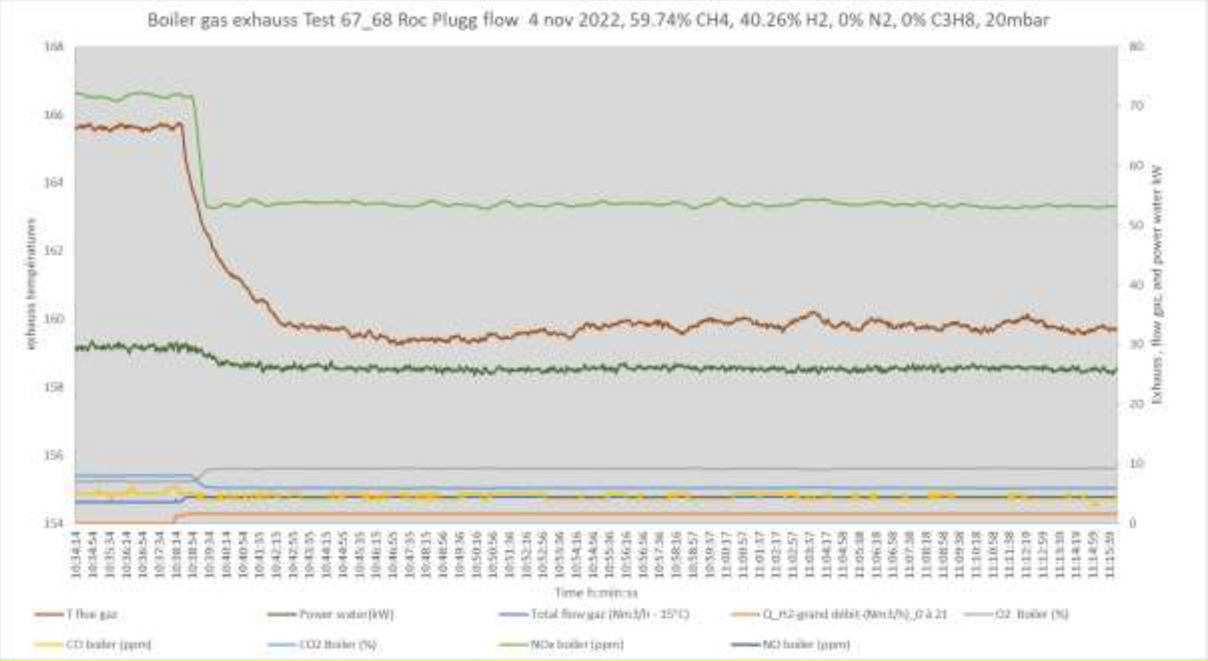


Figure 37: Example of measured data during a ROC test on EN03.

Other comments from labs (BA01)

- *"The boiler works correctly up to 40% of H2 in the blend. Using G20, EU LOW or EU HIGH in the mixture does not compromise the correct operation of the boiler. The differences between the three types of gas can be seen in slightly different emissions and heat inputs due to the different compositions and Wobbe indexes.*
- *Adding H2 to the blend makes the flame come closer to the burner surface, improving the flame ionization detection at max heat input and getting a little worse at minimum heat input; anyway, the ionization current is always far from the lower limit (1,7 µA).*
- *Quick variation of the blend does not compromise the correct operation for the tested blends. The addition of H2 in the mixture significantly decreases CO and NO_x emissions at the expense of power output.*
- *Efficiency does not seem to be affected by H2 blending.*
- *Burner temperature does not change significantly; maybe, the increasing of temperatures due to a closer flame to the burner surface, is rewarded by an increasing of lambda which cools it down."*

2.6.2.2 CO emissions (dry air free)

CO emissions are generally decreasing with H2% at Qmax and are stable at Qmin.

In conclusion, the addition of H2 generally results in lower or stable CO emissions, and there is only one case where we see an increase (GW12 that ends at 117 ppm at 60% H2), but not at all at a level where the appliance can be considered unsafe.

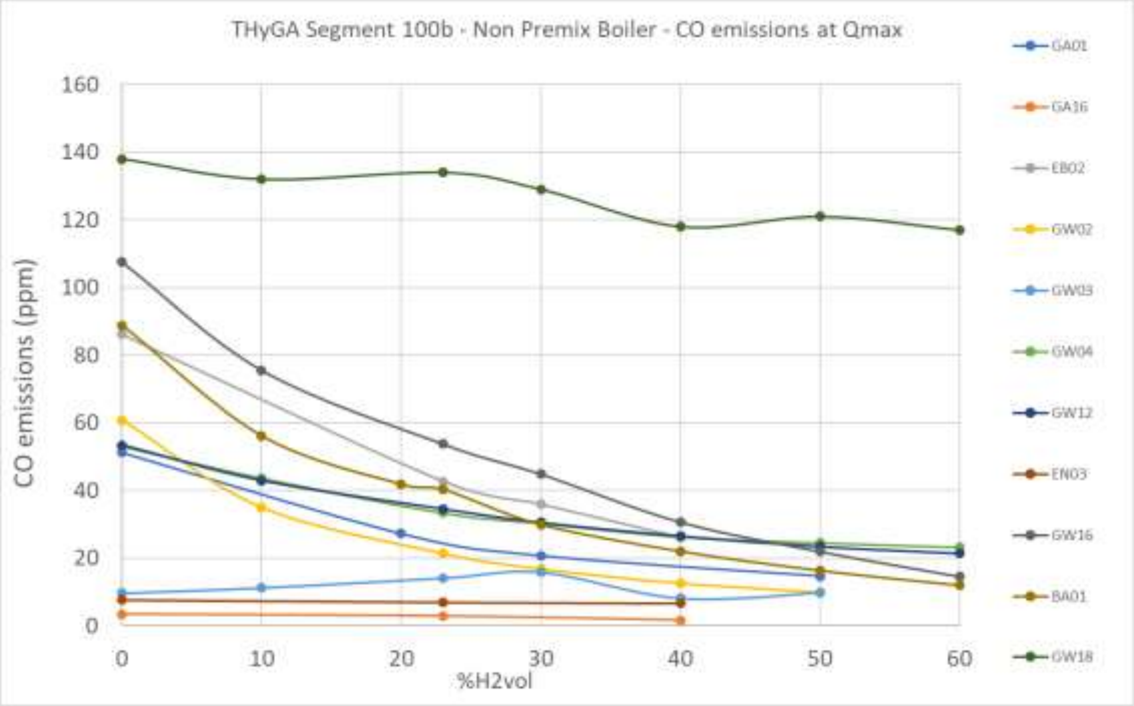


Figure 38: Segment 100b - CO emissions at Qmax.

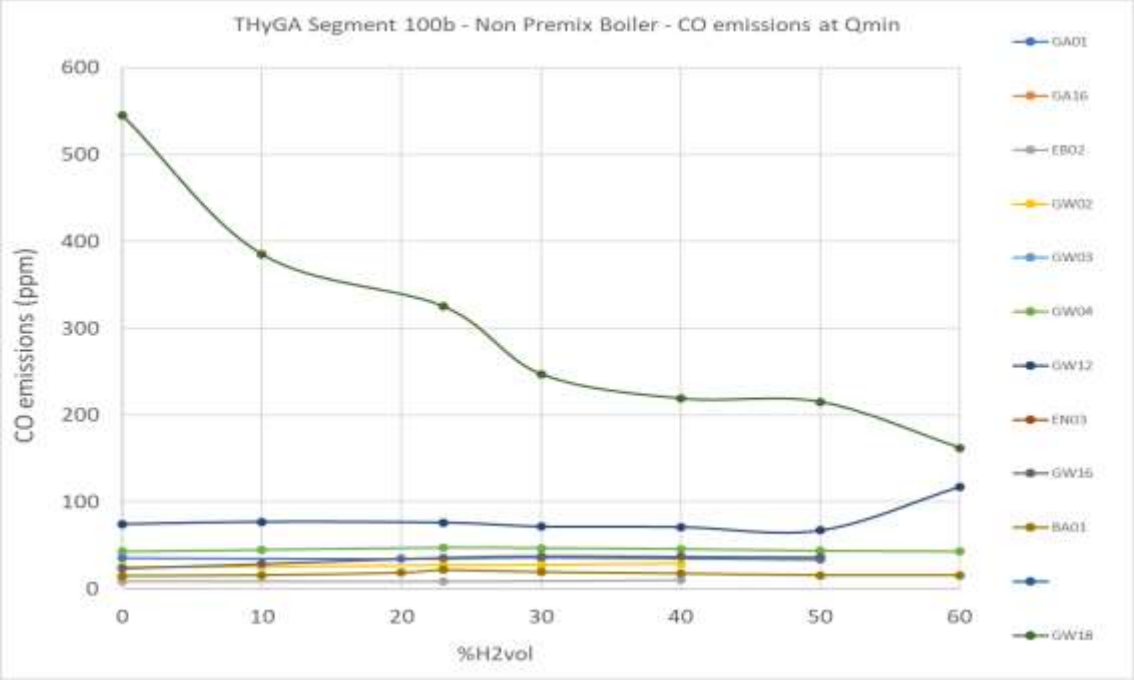


Figure 39: Segment 100b - CO emissions at Qmin.

2.6.2.3 Delayed ignition

Delayed ignition is discussed extensively in section 3.3.

2.6.3 Emissions

2.6.3.1 NOx (dry air free)

NO_x emissions are generally decreasing with H2% at Qmax and slightly decreasing or stable at Qmin.

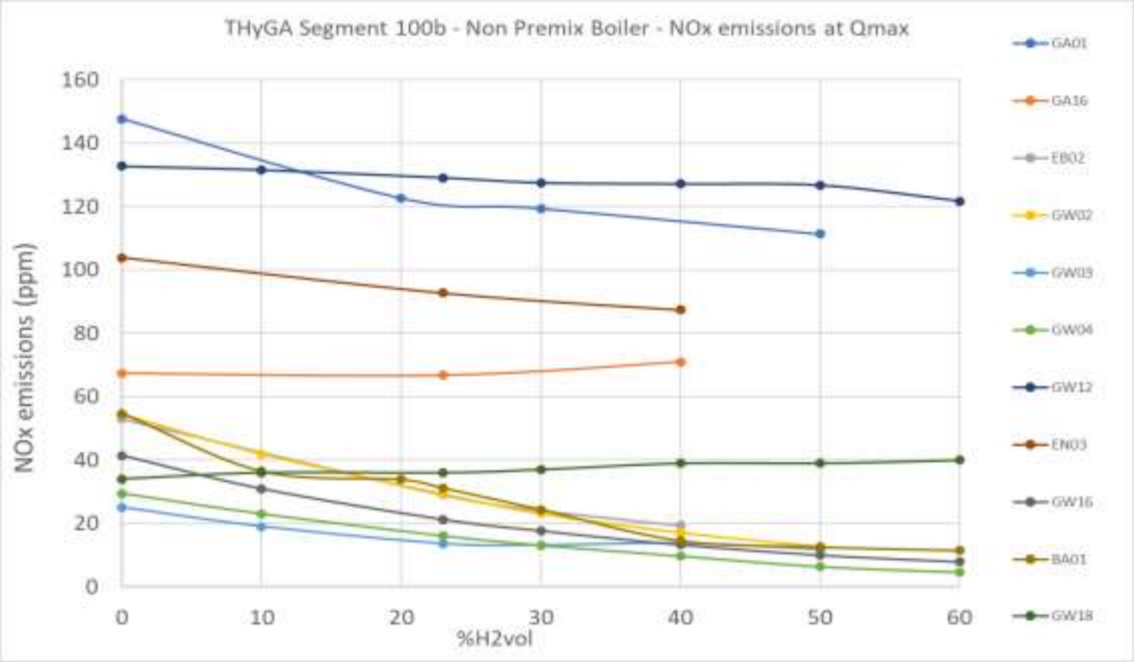


Figure 40: Segment 100b - NOx emissions at Qmax.

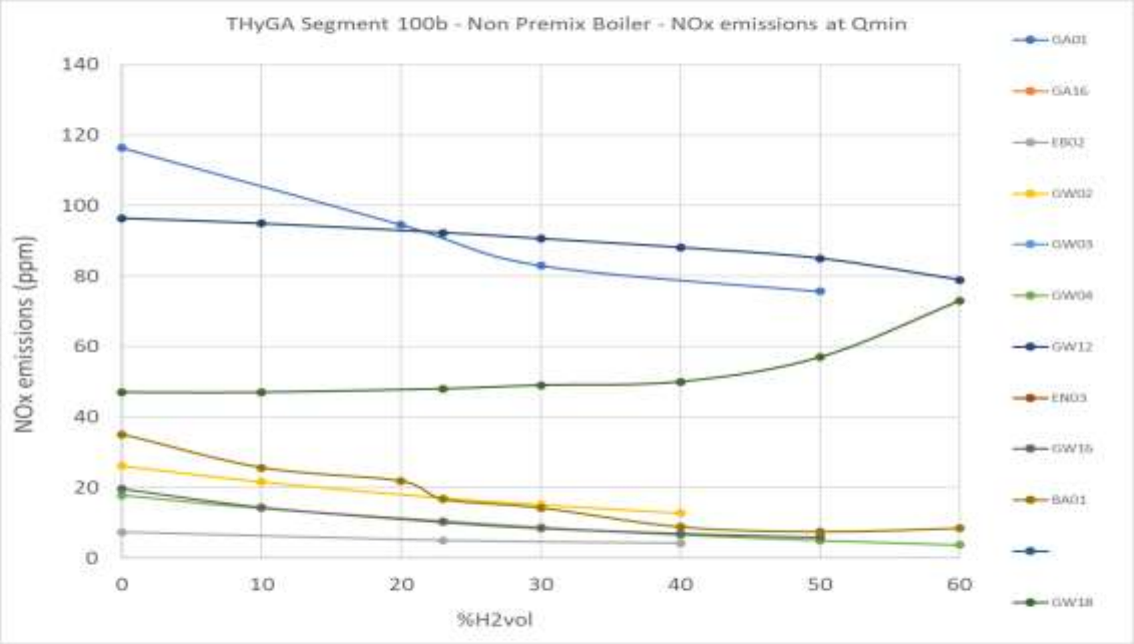


Figure 41: Segment 100b - NOx emissions at Qmin.

2.6.3.2 UHC

UHC are discussed in section 3.5.

2.6.4 Efficiency

In this section, we discuss the impact on efficiency when adding hydrogen to natural gas, more general thoughts on the factors influencing efficiency are given in previous section on fully premix boilers in this report.

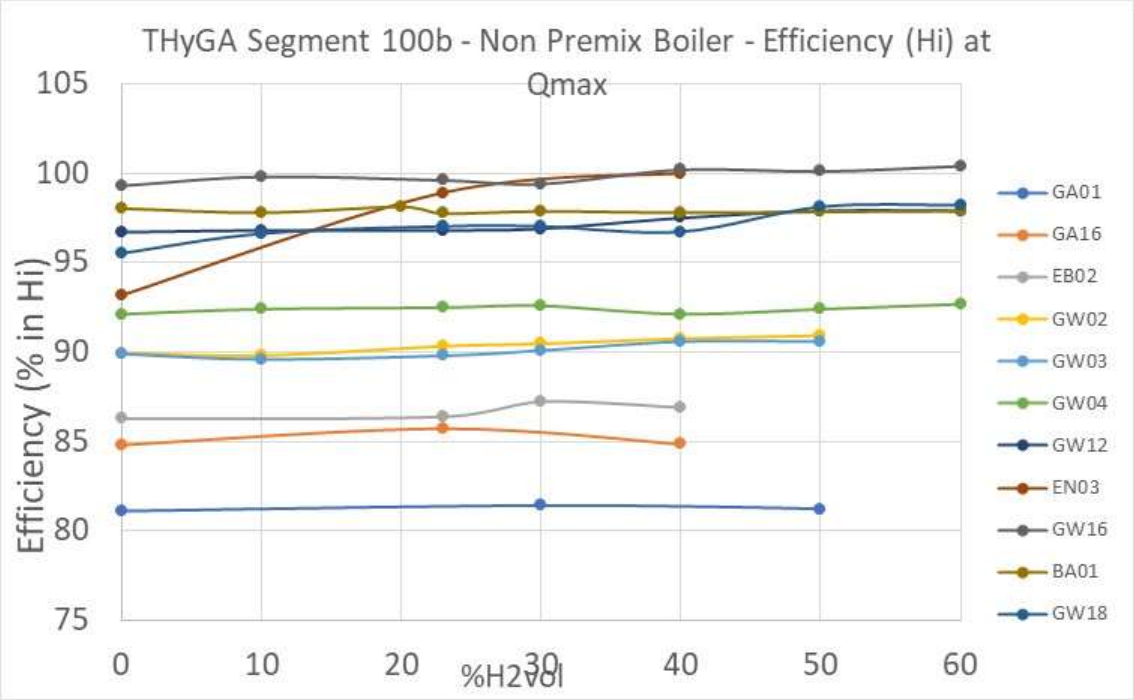


Figure 42: Segment 100b – Efficiency at Qmax.

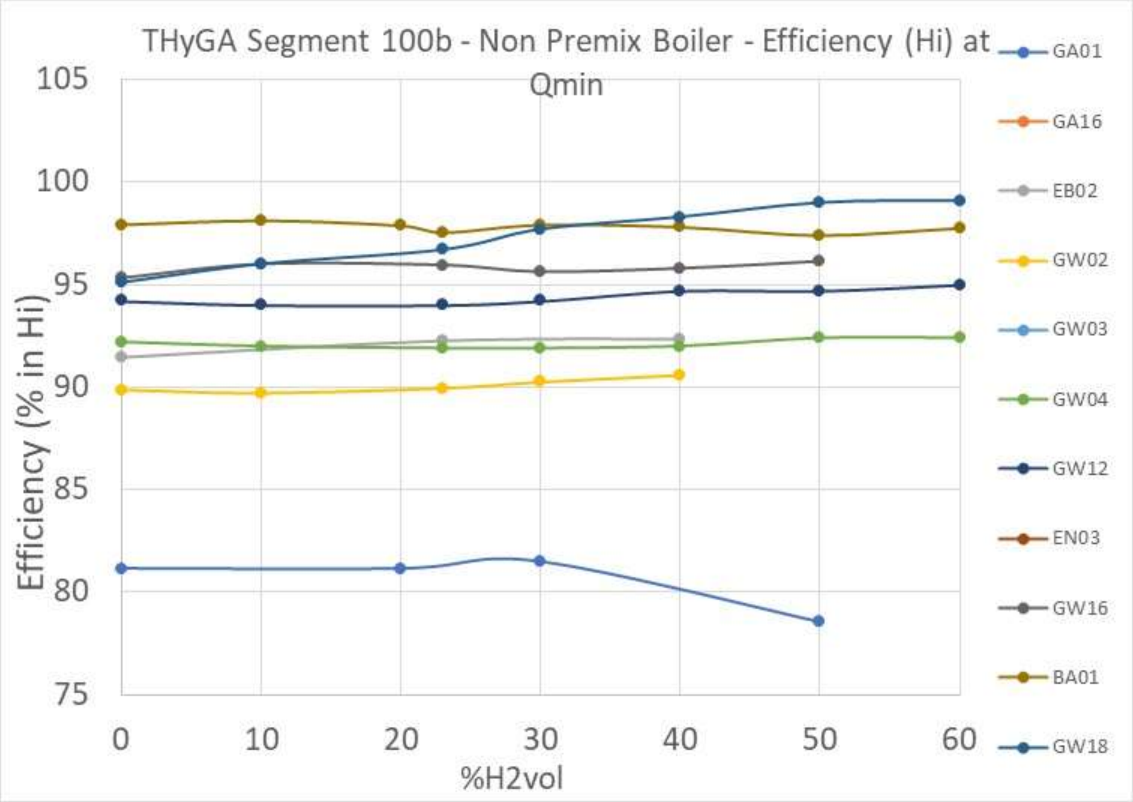


Figure 43: Segment 100b – Efficiency at Qmin.

The efficiency is rather constant.

The air ratio without H2 starts at 1.5, so it is close to what we see for fully premix boilers. This could explain a trend that is similar to what we see for the premix boilers.

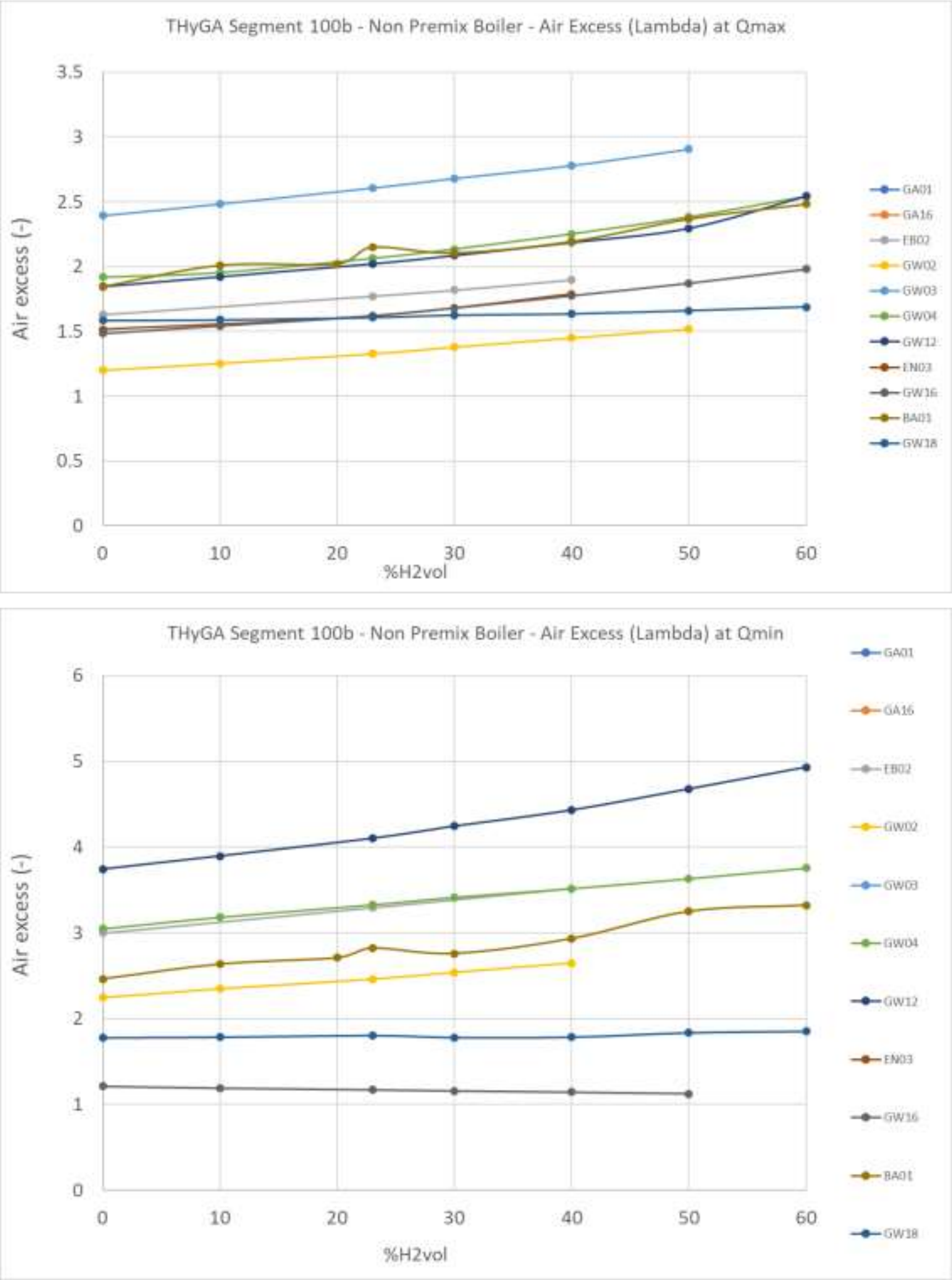


Figure 44: Segment 100b – Air excess at Qmax and Qmin.

2.6.5 Operational

Cold start (« CS ») is an issue for one appliance, GW02 appliance, that is not working for H2 above 40% at minimum load (the appliance simply does not start).

As already mentioned, for GW03, the system works well up till 40% H2, but after 40% it gets louder.

2.6.6 Conclusion for segment 100b

Table 13: Conclusions for segment 100b.

		H2 % Tested							
		0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
100b Boilers Not premix	*Safety*	🟩	🟩	🟩	🟩	🟩	1	1	4
	Operational	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 100b, a total of 12 appliances were tested. The number of appliances having issues are indicated in the red cells of the "impact card" above. Note that not all appliances may have issues for the same tests, and not all tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

The group of appliances of segments 100b is quite tolerant to H2, the first issues are only happening with 40% H2 where mainly flashback was observed. Overheating tests with 30% H2 are showing a burner discoloration that can be a sign that it may - in the long run - result in burner damage, but this is purely hypothetical. Furthermore, overload test was only carried out on one single appliance in this group.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

Considering delayed ignition, especially appliances without fan from this group have shown issues already at 20% H2

2.7 Water heaters (Segm. 200)

2.7.1 Appliances tested

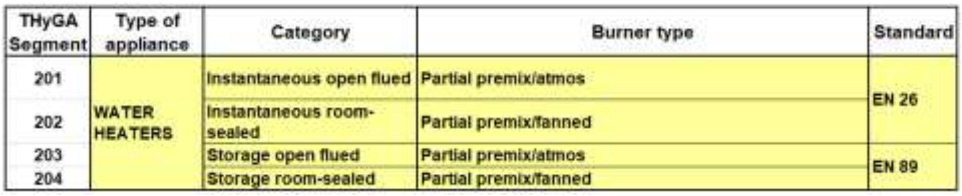
Water heaters (Segm. 200) include **THyGA segments 201** (instantaneous open flued), **202** (instantaneous room sealed), **203** (storage open flued) and **204** (storage room sealed) (see Annex 2 for more details).

6 water heaters were tested, one has caused issues with the initial test with CH_4, so the results shall be carefully used in this case.

Table 14: Characteristics of the 6 water heaters tested

Appliance ID	Segment	Qmin (kW)	Qmax (kW)
GA05	201	5.3	10.5
GA10	202	9	26.2
GW14	202	9.3	22.6
GW19	202	9.5	30
GA09	203	NA	7.7
EN04	204	13.5	57

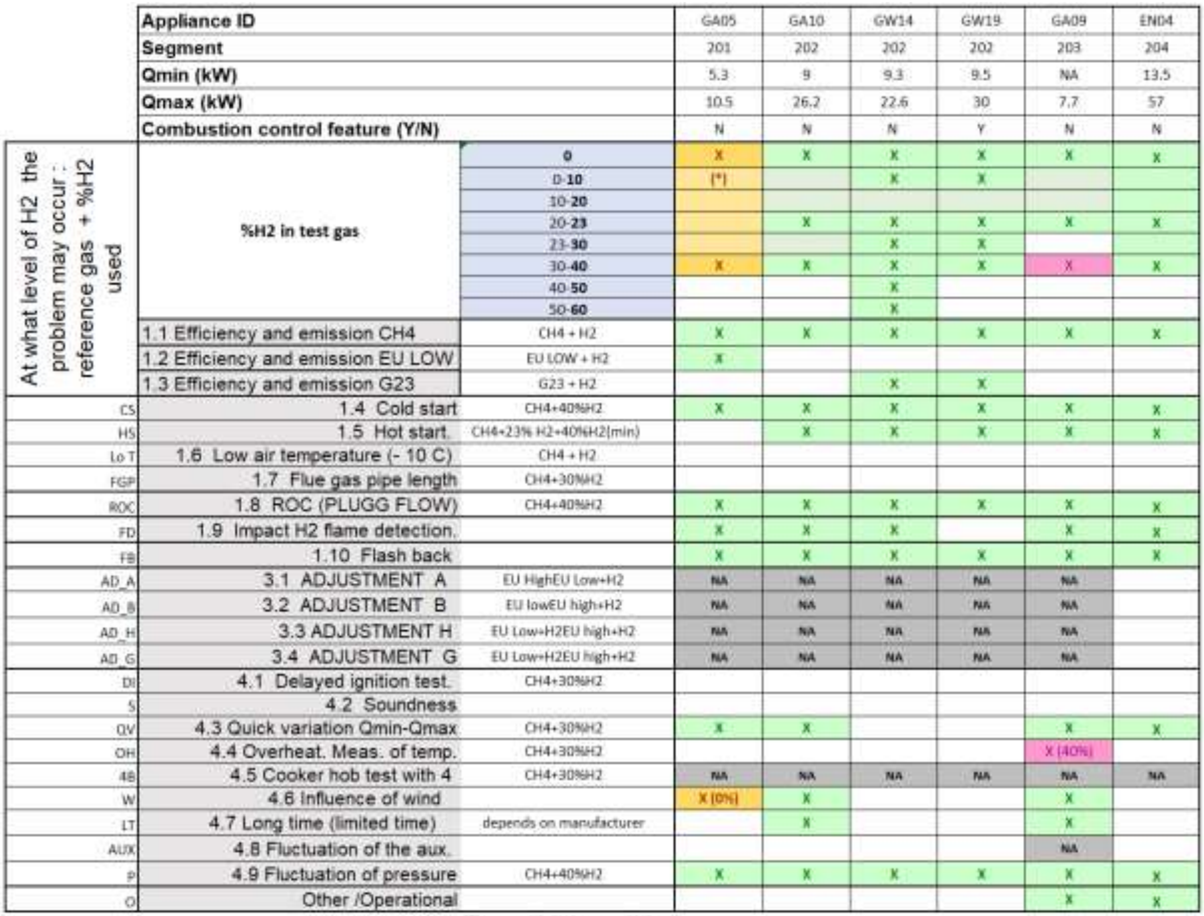
Table 15: Segmentation of the water heater category



THyGA Segment	Type of appliance	Category	Burner type	Standard
201	WATER HEATERS	Instantaneous open flued	Partial premix/atmos	EN 26
202		Instantaneous room-sealed	Partial premix/fanned	
203		Storage open flued	Partial premix/atmos	EN 89
204		Storage room-sealed	Partial premix/fanned	

2.7.2 Safety

Table 16: Safety results for segment 200



	Appliance ID		GA05	GA10	GW14	GW19	GA09	EN04
	Segment		201	202	202	202	203	204
	Qmin (kW)		5.3	9	9.3	9.5	NA	13.5
	Qmax (kW)		10.5	26.2	22.6	30	7.7	57
	Combustion control feature (Y/N)		N	N	N	Y	N	N
At what level of H2 the problem may occur : reference gas + %H2 used	%H2 in test gas	0	X	X	X	X	X	X
		0-10	(*)		X	X		
		10-20						
		20-23		X	X	X	X	X
		23-30			X	X		
		30-40	X	X	X	X	X	X
		40-50			X			
		50-60			X			
	1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X	X	X
	1.2 Efficiency and emission EU LOW	EU LOW + H2	X					
	1.3 Efficiency and emission G23	G23 + H2			X	X		
CS	1.4 Cold start	CH4+40%H2	X	X	X	X	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)		X	X	X	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2						
FGP	1.7 Flue gas pipe length	CH4+30%H2						
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X	X	X
FD	1.9 Impact H2 flame detection.		X	X	X		X	X
FB	1.10 Flash back		X	X	X	X	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA	NA	
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA	NA	
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	
DI	4.1 Delayed ignition test.	CH4+30%H2						
S	4.2 Soundness							
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X	X			X	X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2					X (40%)	
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA	NA	NA
W	4.6 Influence of wind		X (0%)	X			X	
LT	4.7 Long time (limited time)	depends on manufacturer		X			X	
AUX	4.8 Fluctuation of the aux.						NA	
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X	X	X
O	Other /Operational						X	X

(*) Issue with CH4 test and H2 test

X	Test realized and no issues
	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

2.7.2.1 *Overall observations and discussion on safety results:*

The only test really giving an issue is the test where the appliance is exposed to wind (GA05). **Note that the issue occurs already without hydrogen, and therefore H2 is not the cause of the problem here.**

The wind test performed with CH_4 shows that the appliance is not conform to the applicable standards for natural gas appliances (the reason here is that the wind moves flame away from detecting thermocouple). **As the appliance is not conform with CH_4 we will not use the result for this appliance.**

Also for GA09, an overheating test (not part of the testing program according to the standard) was done, which produced some CO issues. (Red for the test conditions in , but not likely to happen in real situations)

Otherwise, no issues were found. Most of the appliances were tested up to 40% H2 and a single one up to 60%.

The following tests were carried out without noticeable issues:

- Cold start.
- Hot start.
- ROC (PLUG FLOW).
- Impact of H2 on flame detection.
- Quick variation Qmin-Qmax Shut-off.
- Fluctuation of pressure.
- There is also an impact of H2 on flame detection on GA09, (higher thermocouple voltage, resulting in an increase of the safety time, but we are still within the CEN requirements.
- Combustion safety device (TTB) was tested on GA09 (Figure 45). At 40% H2 the laboratory observed a sudden doubling of the time, but still far below the current limit in the device standard.

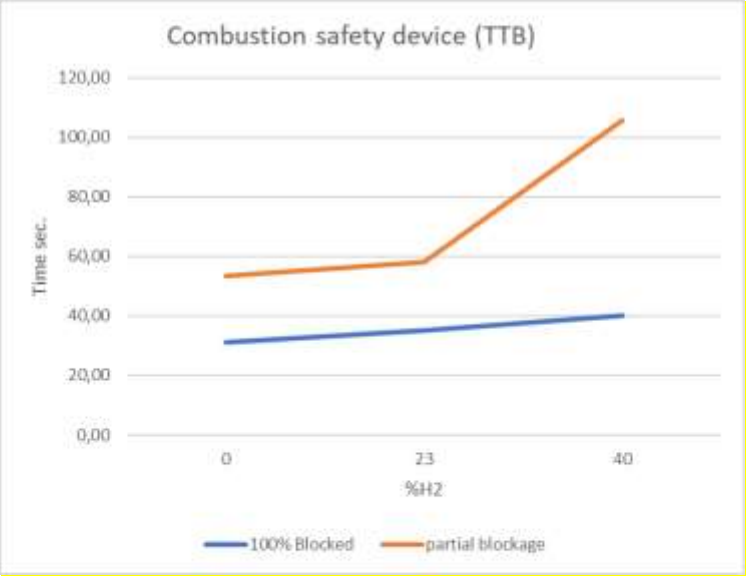


Figure 45: TTB test on GA09.

2.7.2.2 CO emissions (dry air free)

Globally, the CO emissions decrease for the tested water heaters, especially at Qmax.

- At Qmax, the absolute value of the decrease is more important when appliances have high emissions (about 50 ppm decrease from 0 to 40% H2).
- At Qmin the conclusion is not so obvious.

In conclusion, the addition of H2 generally results in lower or stable CO emissions, and there is only one case where we see an increase, but not at all at a level where the appliance can be considered unsafe.

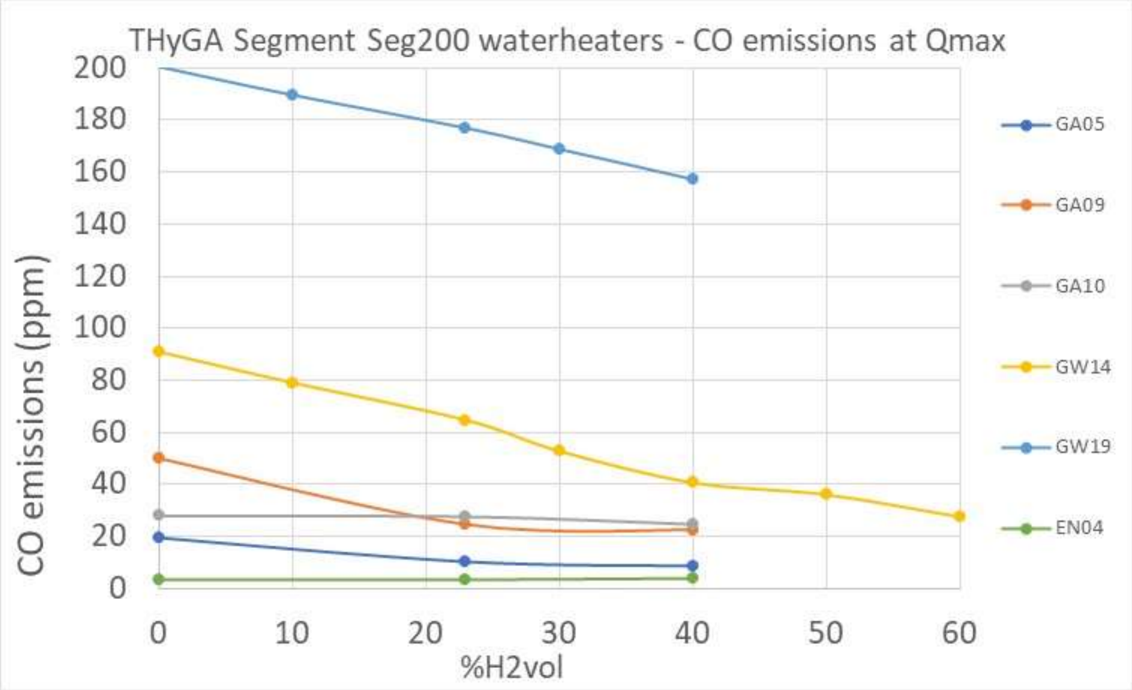


Figure 46: Segment 200 - CO emissions at Qmax.

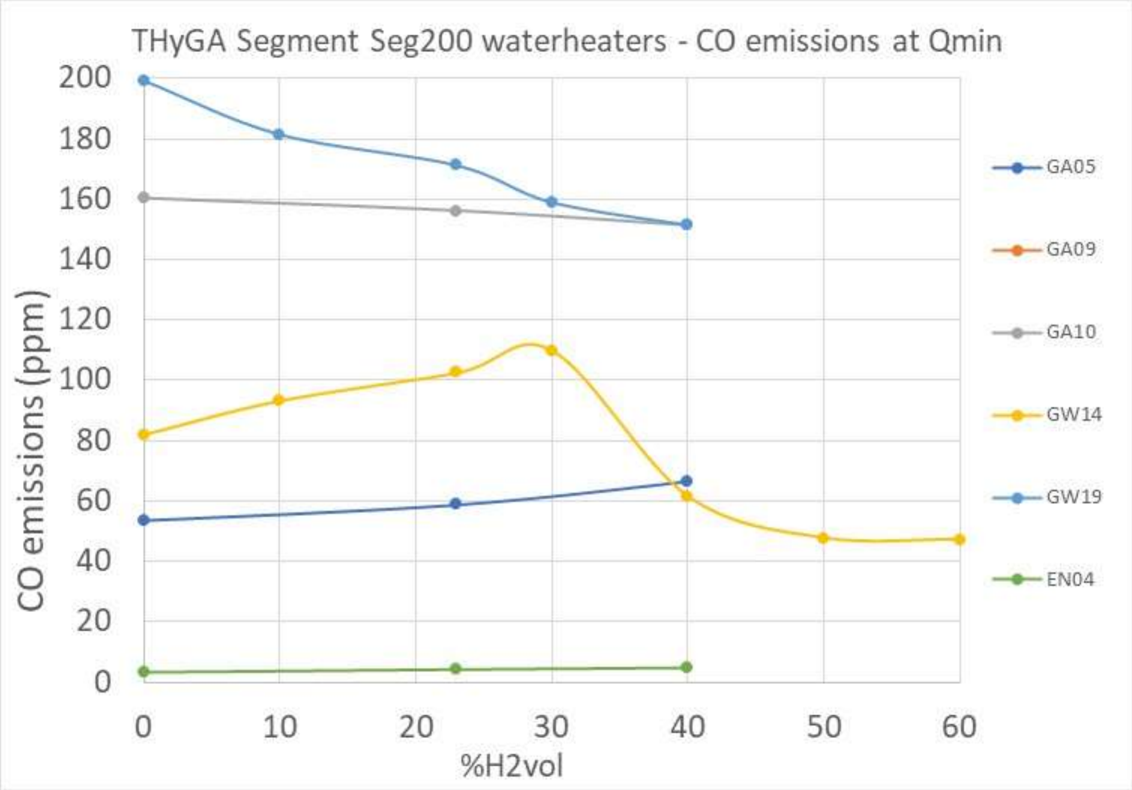


Figure 47: Segment 200 - CO emissions at Qmin.

2.7.3 Emissions

2.7.3.1 NOx (dry air free)

The NO_x emissions are globally constant or not impacted very much by H2 injection, for the tested water heaters.

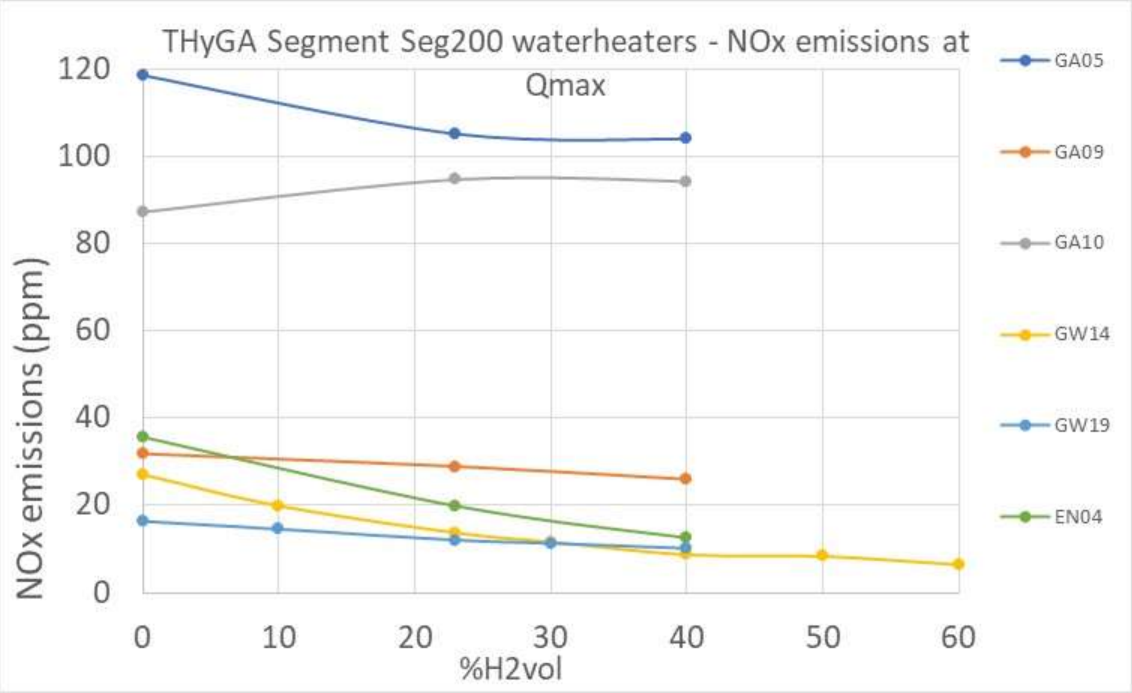


Figure 48: Segment 200 - NOx emissions at Qmax.

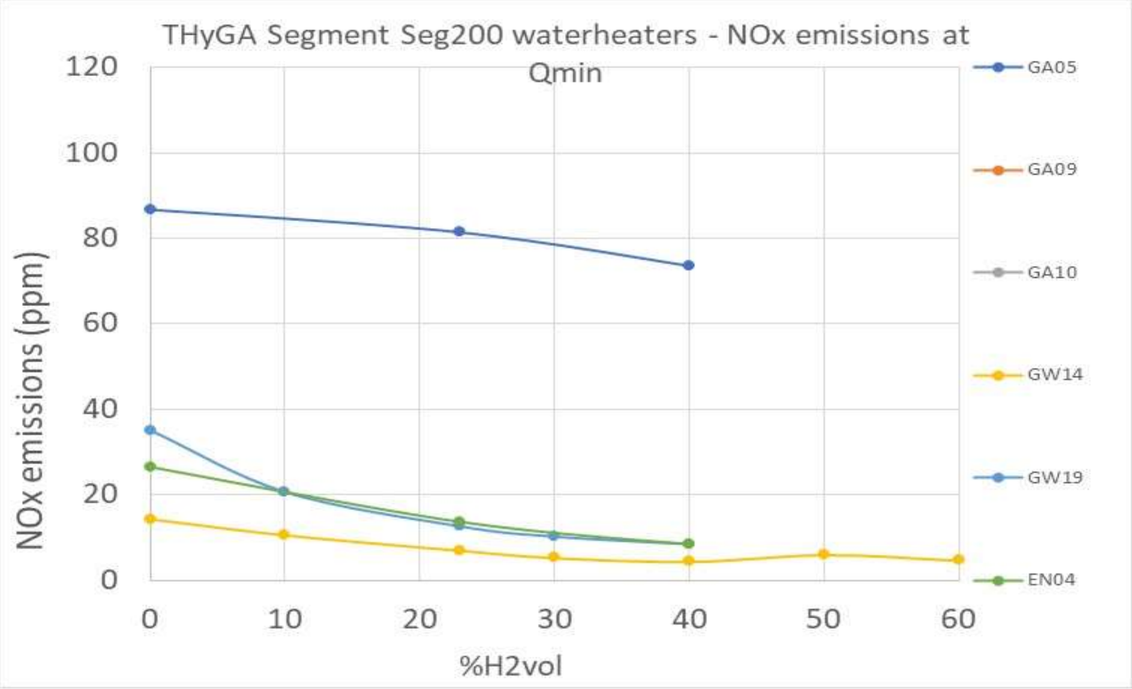


Figure 49: Segment 200 - NOx emissions at Qmin.

2.7.3.2 UHC

UHC is discussed in section 3.5.

2.7.4 Efficiency

In this section, we discuss the impact on efficiency when adding hydrogen to natural gas.

The tests carried out show that hydrogen has very little or no impact, the variations are mostly in the repeatability range of the labs and most of the evolutions are flat.

Compared to boilers, the main difference is that most water heaters are operated at higher temperature compared to boilers. As a result, there is less condensation, and this will not be adding gains to efficiency as for boilers operating at lower temperatures.

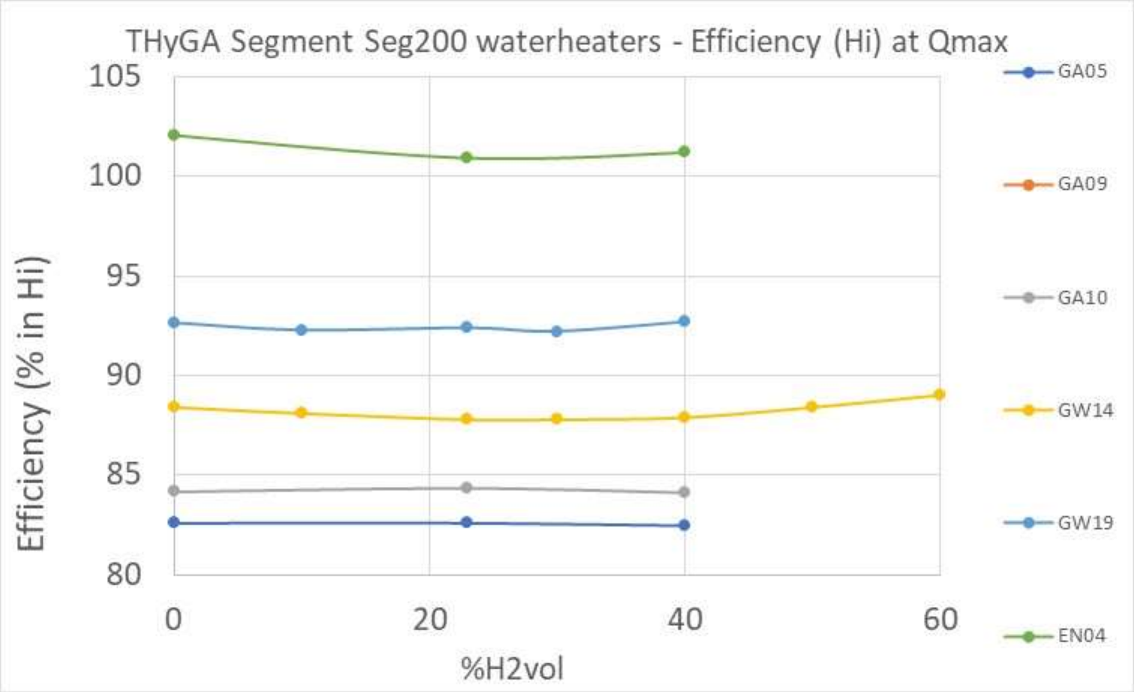


Figure 50: Segment 200 – Efficiency at Qmax.

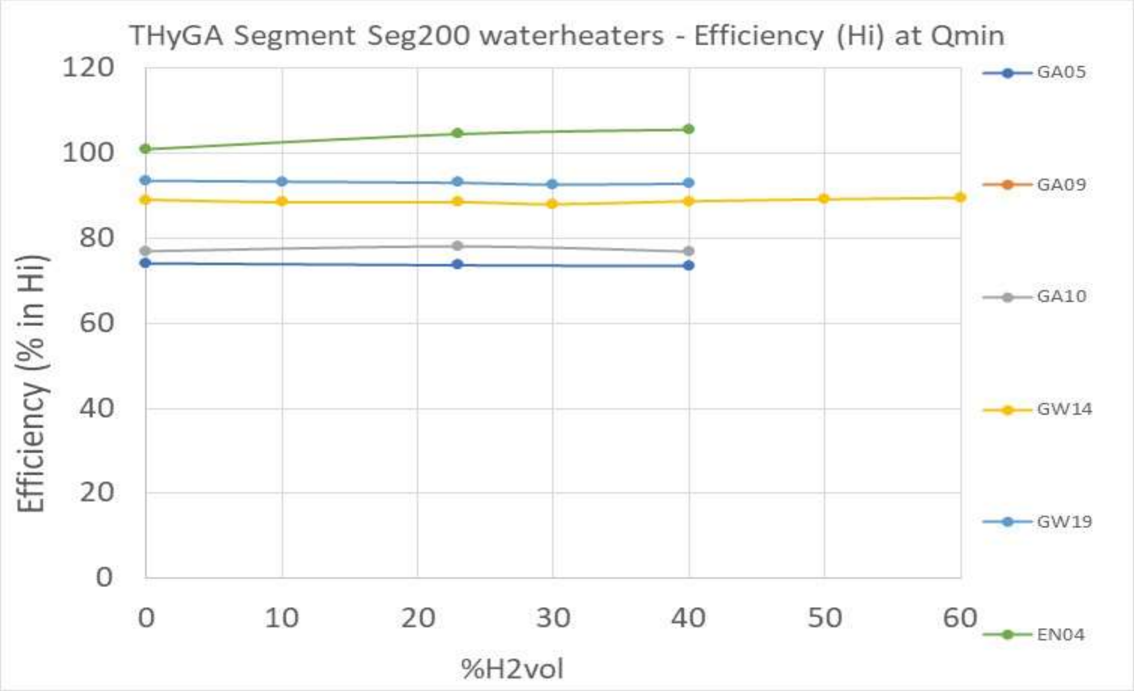


Figure 51: Segment 200 – Efficiency at Qmin.

2.7.5 Operational

No operational issue was identified; however, it should be noted that the heat input and thus the heat output will decrease with H2. This can be an issue for instantaneous appliances that are designed just to cover the customer's need when using natural gas without H2.

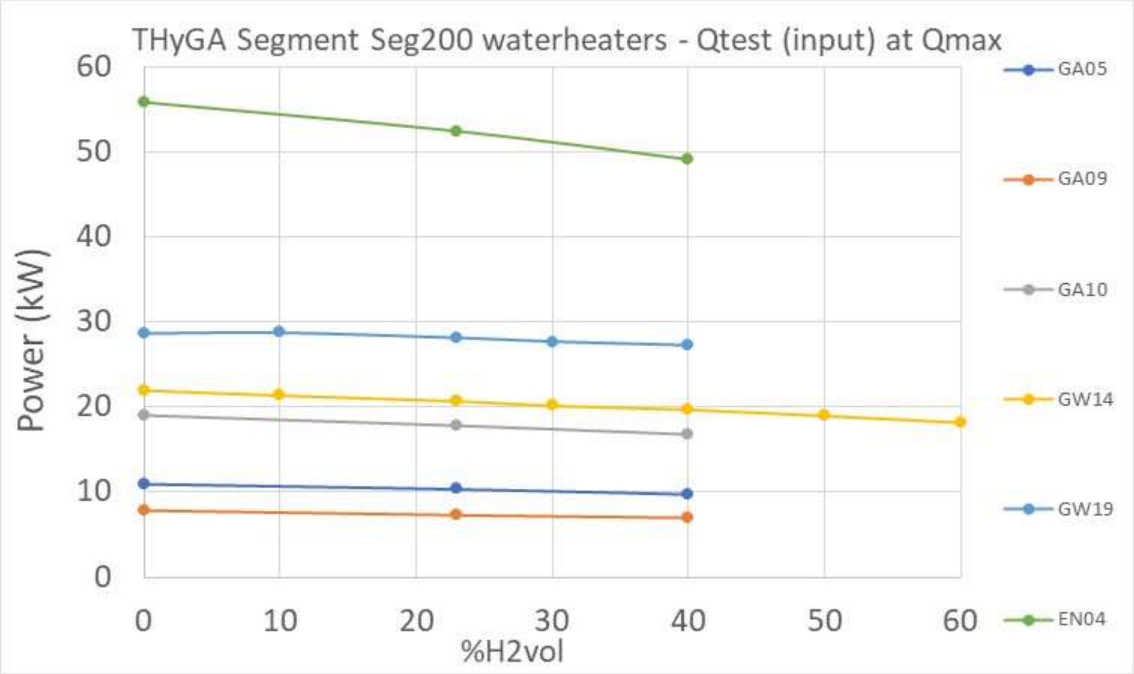


Figure 52: Segment 200 – Heat input at Qmax.

GA5 is an instantaneous water heater, probably for an application with little demand of water. GA9 is a storage water heater, which explains the low nominal heat input.

We can see that for water heaters, the heat input (Qtest) is directly proportional to the Wobbe index, and therefore the reduction of power can be calculated with the change in the Wobbe.

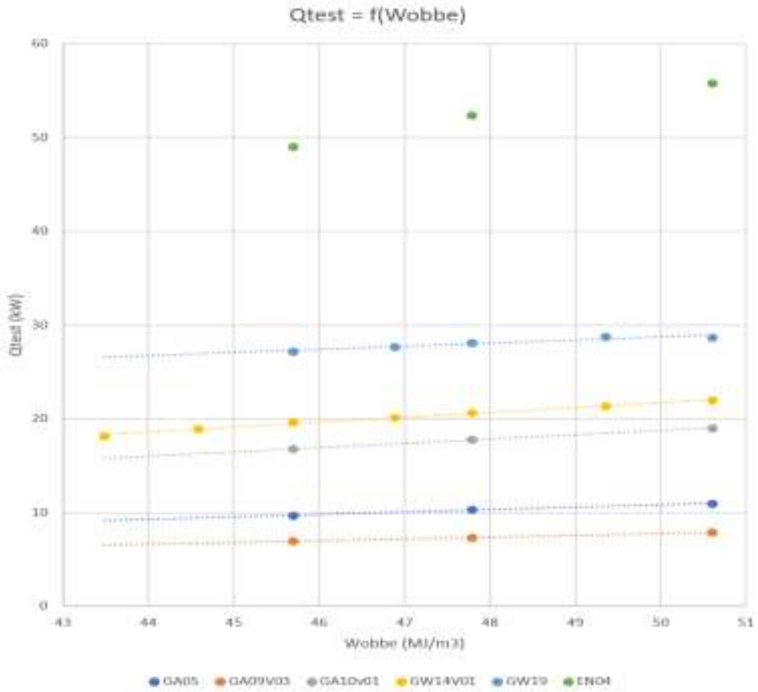


Figure 53: Segment 200 - Heat input (Qtest), function of the Wobbe index.

The relative reduction of heat input (in %) is very close to the relative reduction of the Wobbe (in %) for most appliances.

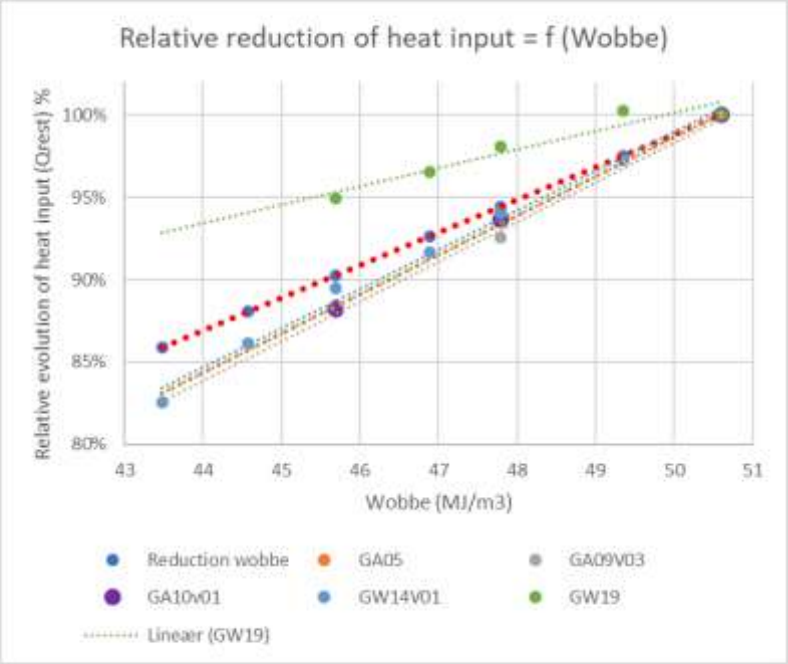


Figure 54: Segment 200 – relative evolution of the Heat input (Qtest), function of the Wobbe index.

2.7.6 Conclusion for segment 200

Table 17: Conclusions for segment 200.

		H2 % Tested							
		0	0-10	10-20	20-23	23-30	30-40	40-50	50-60
200 Water heaters	*Safety*	🟩	🟩	🟩	🟩	🟩	🟥 1	🟥 1	🟥 1
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 200, a total of 6 appliances were tested. The number of appliances having issues are indicated in the red cells of the "impact card" above. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

The group of appliances of segments 200 is quite tolerant to H2, the first issues are only happening with 40% H2 where overheat is resulting in high CO, the use of "red" color in this case may be severe as this test is not part of the standards for such appliance.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

Considering delayed ignition, appliances from this group have shown issues already at 20% H2, especially those without fan.

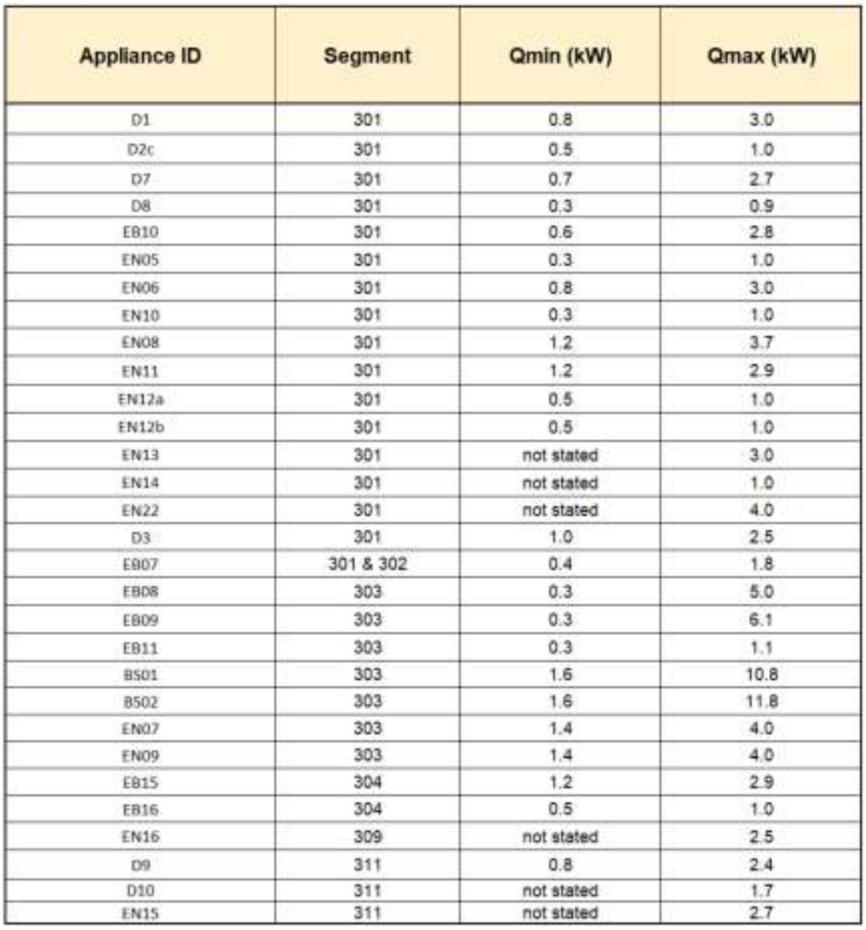
2.8 Domestic Cooker hobs and ovens (Segm. 300)

2.8.1 Appliances tested

Domestic cookers (Segm. 300) include **THyGA segments 301 to 303** (surface burner with atmospheric burner or "Venturi" burner), **segments 304 to 306** (surface burner with partially pre-mix burner), **segments 307 to 309** (cavity burner “tubular), and **segments 310 to 312** (cavity burner “metal sheet”) (see Annex 2 for more details).

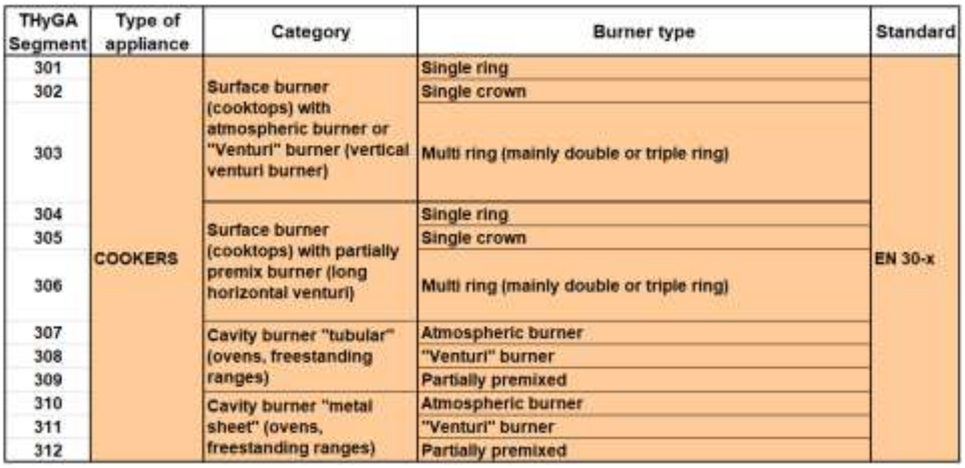
The following appliances have been tested. An important point is that we are abusively talking about tested appliances in this chapter for simplicity of vocabulary, but in reality, these are “tested burners”. Indeed, a same cooking appliance can have several burners which need to be all tested for an overall overview (for example, a piano includes 4 burners and a gas oven).

Table 18: Characteristics of the 30 cooking appliances (burners) tested.



Appliance ID	Segment	Qmin (kW)	Qmax (kW)
D1	301	0.8	3.0
D2c	301	0.5	1.0
D7	301	0.7	2.7
D8	301	0.3	0.9
EB10	301	0.6	2.8
EN05	301	0.3	1.0
EN06	301	0.8	3.0
EN10	301	0.3	1.0
EN08	301	1.2	3.7
EN11	301	1.2	2.9
EN12a	301	0.5	1.0
EN12b	301	0.5	1.0
EN13	301	not stated	3.0
EN14	301	not stated	1.0
EN22	301	not stated	4.0
D3	301	1.0	2.5
EB07	301 & 302	0.4	1.8
EB08	303	0.3	5.0
EB09	303	0.3	6.1
EB11	303	0.3	1.1
BS01	303	1.6	10.8
BS02	303	1.6	11.8
EN07	303	1.4	4.0
EN09	303	1.4	4.0
EB15	304	1.2	2.9
EB16	304	0.5	1.0
EN16	309	not stated	2.5
D9	311	0.8	2.4
D10	311	not stated	1.7
EN15	311	not stated	2.7

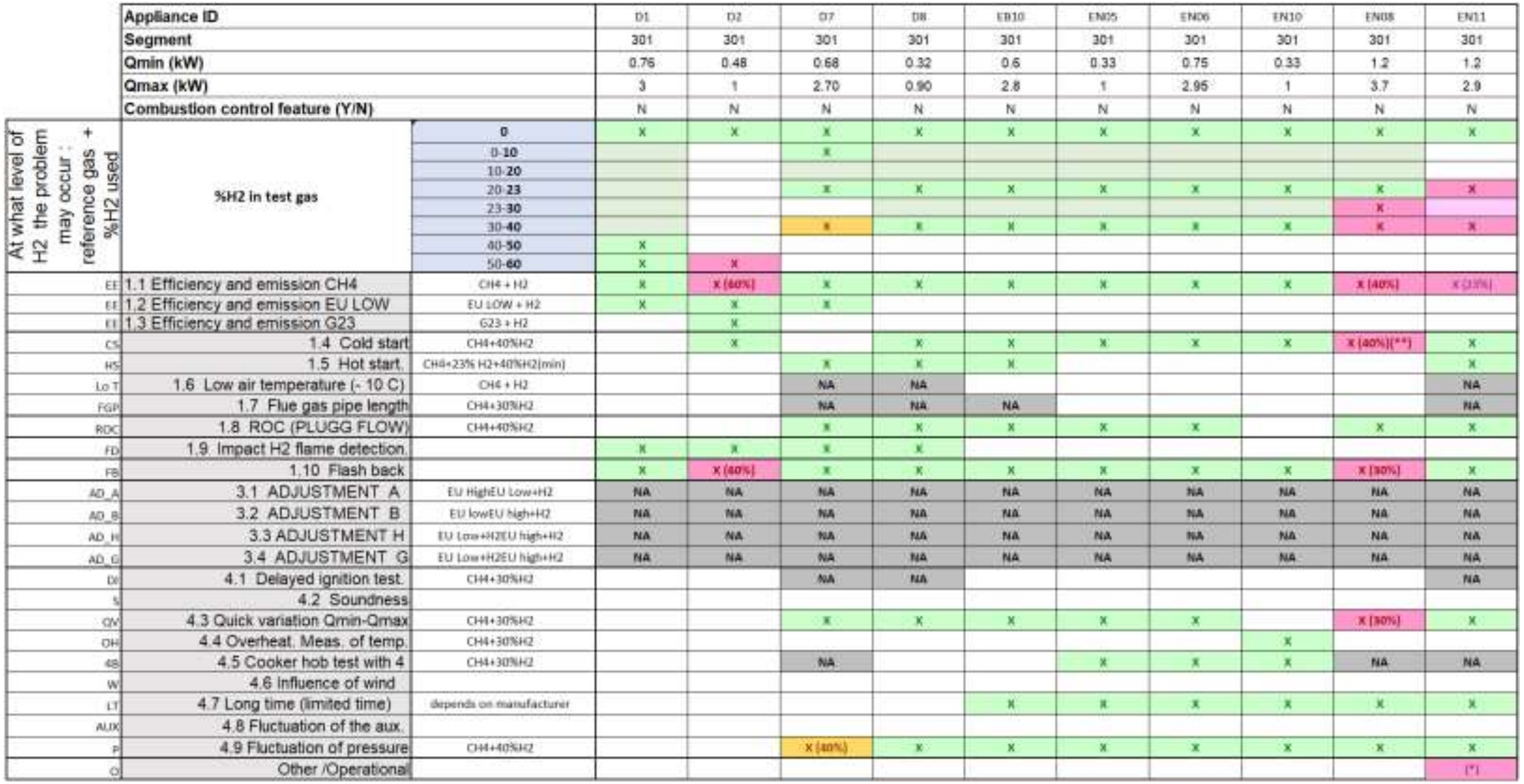
Table 19 : Segmentation of cooker category



THyGA Segment	Type of appliance	Category	Burner type	Standard
301	COOKERS	Surface burner (cooktops) with atmospheric burner or "Venturi" burner (vertical venturi burner)	Single ring	EN 30-x
302			Single crown	
303			Multi ring (mainly double or triple ring)	
304		Surface burner (cooktops) with partially premix burner (long horizontal venturi)	Single ring	
305			Single crown	
306			Multi ring (mainly double or triple ring)	
307		Cavity burner "tubular" (ovens, freestanding ranges)	Atmospheric burner	
308			"Venturi" burner	
309			Partially premixed	
310		Cavity burner "metal sheet" (ovens, freestanding ranges)	Atmospheric burner	
311			"Venturi" burner	
312			Partially premixed	

2.8.2 Safety

Table 20: Safety results for segment 300 - Part 1.



		Appliance ID		D1	D2	D7	D8	EB10	EN05	EN06	EN10	EN08	EN11
		Segment		301	301	301	301	301	301	301	301	301	301
		Qmin (kW)		0.76	0.48	0.68	0.32	0.6	0.33	0.75	0.33	1.2	1.2
		Qmax (kW)		3	1	2.70	0.90	2.8	1	2.95	1	3.7	2.9
		Combustion control feature (Y/N)		N	N	N	N	N	N	N	N	N	N
At what level of H2 the problem may occur : reference gas + %H2 used		%H2 in test gas	0	x	x	x	x	x	x	x	x	x	x
			0-10			x							
			10-20										
			20-23			x	x	x	x	x	x	x	x
			23-30									x	
			30-40			x	x	x	x	x	x	x	x
			40-50	x									
			50-60	x	x								
	EE	1.1 Efficiency and emission CH4	CH4 + H2	x	x (60%)	x	x	x	x	x	x	x (40%)	x (23%)
	EE	1.2 Efficiency and emission EU LOW	EU LOW + H2	x	x	x							
	EE	1.3 Efficiency and emission G23	G23 + H2		x								
	CS	1.4 Cold start	CH4+40%H2		x		x	x	x	x	x	x (40%)(**)	x
	HS	1.5 Hot start.	CH4+23% H2+40%H2(min)			x	x	x					x
	Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2			NA	NA						NA
	FGP	1.7 Flue gas pipe length	CH4+30%H2			NA	NA	NA					NA
	ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2			x	x	x	x	x		x	x
	FD	1.9 Impact H2 flame detection.		x	x	x	x						
	FB	1.10 Flash back		x	x (40%)	x	x	x	x	x	x	x (30%)	x
	AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	DI	4.1 Delayed ignition test.	CH4+30%H2			NA	NA						NA
	S	4.2 Soundness											
	QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2			x	x	x	x	x		x (30%)	x
	OH	4.4 Overheat. Meas. of temp.	CH4+30%H2								x		
	4B	4.5 Cooker hob test with 4	CH4+30%H2			NA			x	x	x	NA	NA
	W	4.6 Influence of wind											
	LT	4.7 Long time (limited time)	depends on manufacturer					x	x	x	x	x	x
	AUX	4.8 Fluctuation of the aux.											
	P	4.9 Fluctuation of pressure	CH4+40%H2			x (40%)	x	x	x	x	x	x	x
	O	Other /Operational											(*)

(*) For EN11, from 23%H2 to above, there is condensation on the bottom of the pan (cold water) that drops on the flame. It causes a partial to full extinction. It is difficult to consider a test with 23%H2 not conform as this this gas is part of the certification with natural gas. For this reason, the appliance can be considered as not conform for use with natural gas and we shall not consider this appliance in the overall picture for this segment group.

(**) For EN08 during the cold start test at 40% H2 Flash back was observed

Table 21: Safety results for segment 300 - Part 2.

	Appliance ID		EN12a	EN12b	EN13	EN14	EN22	D3	EB07	EB08	EB09	EB11
	Segment		301	301	301	301	301	301	301 & 302	303	303	303
	Qmin (kW)		0.5	0.5	not stated	not stated	not stated	1	0.41	0.3	0.3	0.33
	Qmax (kW)		1	1	3	1.0	4	2.5	1.75	5	6.1	1.1
	Combustion control feature (Y/N)		N	N	N	N	N	N	N	N	N	N
At what level of H2 the problem may occur : reference gas + %H2 used	**%H2 in test gas**	0	X	X	X	X	X	X	X	X	X	X
		0-10										
		10-20										
		20-23	X	X	X	X	X		X	X	X	X
		23-30						X				
		30-40		X	X	X	X	X	X	X	X	X
		40-50										
		50-60						X (60%)				
EE	1.1 Efficiency and emission CH4	CH4 + H2	X (23%)	X	X	X	X	X	X	X	X	X
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2						X (60%)	X	X	X	
EE	1.3 Efficiency and emission G23	G23 + H2						X (60%)				
CS	1.4 Cold start	CH4+40%H2	X	X	X	X	X	X (60%)	X	X	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)		X	X	X	X	X (60%)	X	X	X (23%)	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2										
FGP	1.7 Flue gas pipe length	CH4+30%H2							NA	NA	NA	NA
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2		X	X	X	X	X	X	X (40%)	X (40%)	X
FD	1.9 Impact H2 flame detection.											
FB	1.10 Flash back		X (23%)	X	X	X	X	X (60%)	X	X (40%)	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
DI	4.1 Delayed ignition test.	CH4+30%H2										
S	4.2 Soundness											
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X	X (40%)	X	X	X		X	X	X	X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2										
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	X	X				X (40%)		
W	4.6 Influence of wind											
LT	4.7 Long time (limited time)	depends on manufacturer	X	X	X	X	X		X	X (40%)	X (40%)	X
AUX	4.8 Fluctuation of the aux.											
P	4.9 Fluctuation of pressure	CH4+40%H2		X	X (40%)	X (40%)	X	X	X	X	X	X
O	Other /Operational											

Note that for EB09 the test **Hot start** at 23% H2 has shown some difficulties, but as it is not a safety point.

For EN12a because the test could not be reproduced on another appliance (EN12b) after discussions, we have concluded we consider EN12a as outlier.

Table 22: Safety results for segment 300 - Part 3.

	Appliance ID		BS01	BS02	EN07	EN09	EB15	EB16	EN16	D9	D10	EN15
	Segment		303	303	303	303	304	304	309	311	311	311
	Qmin (kW)		1.64	1.64	1.4	1.4	1.2	0.5	not stated	0.81	not stated	not stated
	Qmax (kW)		10.75	11.8	4	4	2.9	1	2.5	2.43	1.71	2.73
	Combustion control feature (Y/N)		N	N	N	N	N	N	N	N	N	N
At what level of H2 the problem may occur : reference gas + %H2 used	%H2 in test gas	**0**	X	X	X	X	X	X	X	X	X	X
		0-**10**										
		10-**20**										
		20-**23**	X	X	X	X	X	X	X	X	X	X
		23-**30**										
		30-**40**	X	X	X	X	X	X	X	X	X	X
		40-**50**	X	X								
		50-**60**										
EE	1.1 Efficiency and emission CH4	CH4 + H2	X (40%)	X (40%)	X	X (40%)	X	X	X	X	X	X
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2					X	X				
EE	1.3 Efficiency and emission G23	G23 + H2										
CS	1.4 Cold start	CH4+40%H2			X	X	X	X	X	X		X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X	X			X (40%)	X	X	X	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2								NA		
FGP	1.7 Flue gas pipe length	CH4+30%H2								NA		
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2			X		X	X	X	X		X
FD	1.9 Impact H2 flame detection.									X		
FB	1.10 Flash back		X (40%)	X (40%)	X	X (40%)	X	X	X	X	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
DI	4.1 Delayed ignition test.	CH4+30%H2								NA		
S	4.2 Soundness											
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X (40%)	X (40%)	X		X	X	X			X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2										
4B	4.5 Cooker hob test with 4	CH4+30%H2			X	X	X			NA		
W	4.6 Influence of wind											
LT	4.7 Long time (limited time)	depends on manufacturer			X	X	X	X	X			X
AUX	4.8 Fluctuation of the aux.						X	X				
P	4.9 Fluctuation of pressure	CH4+40%H2			X	X	X	X	X	X (40%)		X
O	Other /Operational											

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

2.8.2.1 Overall observations on safety results

Most appliances were tested up to 40 % H2 and a few (4) up to 60%.

Out of 20, 10 can manage 40% H2 without issue.

The issues observed are the following (some appliances given as example):

- Flashback (8 out of 30)
- Cold start with 40% H2) (EN08)
- Hot start (EB09, EB15, D3)
- ROC EB08, EB09)
- Quick variation of heat input (BS01, BS02),
- EN08, EN12)
- Issue when 4 burners are on (EB08)
- Limited Long-time testing (EB08, EB09), but no issues with the other test done
- Issue with pressure change (D7 & D9)

2.8.2.2 Main observations from lab report conclusions

Flame instability (from 40% H2)

EB08: In general, the dual wok burner does not have flashback but had flame instability with 40% H2 which might cause flashback. The flame instability extended from the inner ring to the outer ring over hours.

EB09: At 40% H2, with increase in burner running time, it is observed that the inner ring flame is instable.

D9: The flame flickers at 40% H2 and 14mbar.

Yellow flame during long-term test at 40% H2 (EB15V03**) (both Qmin and Qmax)**

“After the 4 hours of long-term test, the burner is tested continuously for 2 more hours with the pressure variation. There we observed the yellow flame on the upper surface (see picture below).”

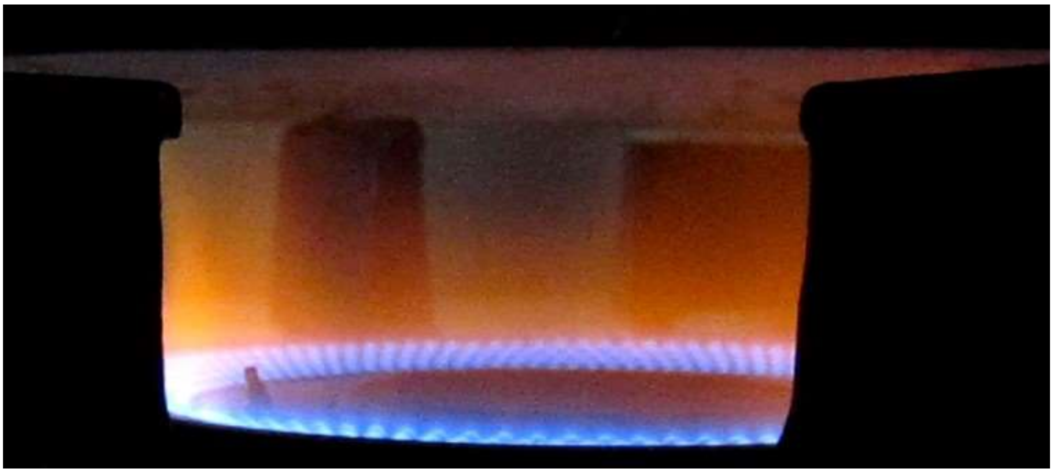


Figure 55: yellow flame on EB15.

Water condensates that create partial extinction

EN11V02: No problems in general. However, with hydrogen and cold water in the pan, condensation appears on the bottom of the pan. When the droplets hit the burner, it causes a partial extinction of the flame. The flame turns orange for a few seconds and becomes blue again when the water has fully evaporated.

EN12a: The burner operated normally during the long-term test (1h at Qmax followed by 30 min at Qmin) with 23% H2 with no pan above. However, during emission measurement with EN30 pot, flashback occurred after 8 min. Further investigations showed that, at 23% H2, condensation occurs on the pot causing water to drop directly on the flame. Examination of the burner showed a crack in the gas pipe of the venturi, so tests were stopped on that burner and started again on the other auxiliary burner (report file EN12b).

Figure 56: EN12 Burner under "normal" operation.

Figure 57:EN12 Burner operation when water is falling on it.

2.8.2.3 Flashback

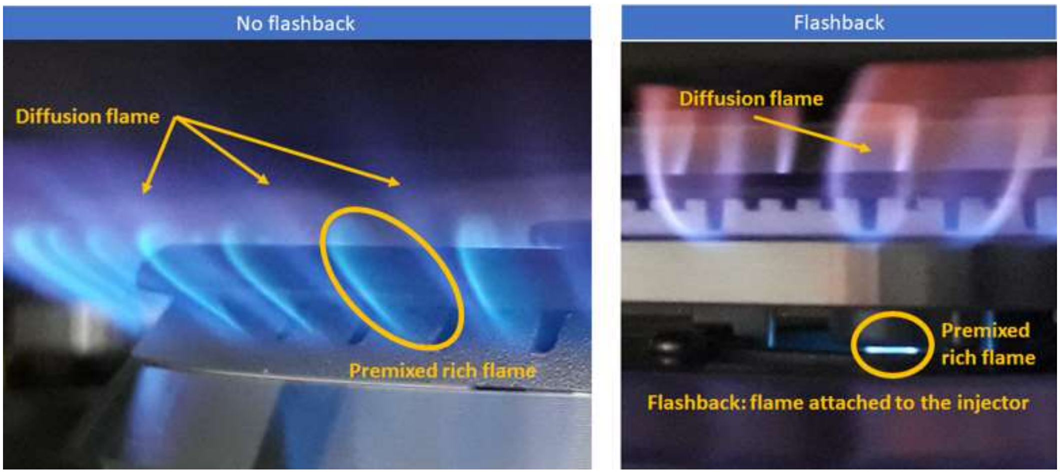


Figure 58: illustration of flashback on a cooking hob (Source: THyGA project)

D2c: during the short-term test up to 60% H2 did not show any issues, flashback was observed during efficiency test with 60% H2 after long running time of the cooker (50 minutes or so). This has resulted in damages making the rest of the test impossible.

EN09v04: Burner EN09 is the same as EN07, however, they had a completely different behavior.

- The burner EN09 operated safely with no flashback up to 40% H2, but flashback occurred during the efficiency test @40%H2.
- Burner EN07 operated with no flashback under the same conditions.

Reasons for this different behavior are not clear. Burner EN07 has higher CO emissions than EN09 with G20. This might be the sign that the primary air/fuel mixture is richer on burner EN07. If this primary mixture is richer, then the burner should be more resilient to flashback. The reason why one flame is richer than the other is unknown (injector sizes were measured: they are the same).

EN08v04: This burner performed well up to 23% H2 but failed to operate properly at 40% H2 due to the appearance of flashback on one of the two burners. The flashback seems to appear at the central junction of the two burners. Flashback occurs only when the pan grid is used, not when the grill is used.

EN12bV02: EN12b is the same burner as EN12a. Its behavior was quite different to EN12a concerning flashback: no flashback was observed during tests performed (0 to 40% H2). However, there was some ignition issues during the quick variation test Qmin/Qmax: An unstable flame appeared near the thermocouple at 40% H2 causing a change in the thermocouple color to dark brown at the end of the tests. This behavior had no impact on safety.

Discussion on Flashback

For several tests, it appears that issues may not appear instantaneously when the burner is used, but later after several minutes or hours. Therefore, the safety should also be evaluated in the light of the long-term tests.

For example, Test D2 showed that the testing time is critical to identify the risk of flashback.

- Tests on cooking hobs with 10 min steps up to 60% H2 showed no flashback. Repeating the test with 60 min steps shows different results: Flashback happens after some time at H2% below 60%.
- The picture from the test D2 (right side of Figure 59) shows the appearance of the burner after FB compared (being darker) to a burner where no FB was observed.

A lesson learned for the future is that the procedure to assess FB needs to be carefully chosen (input to WP4 on standardization/certification).

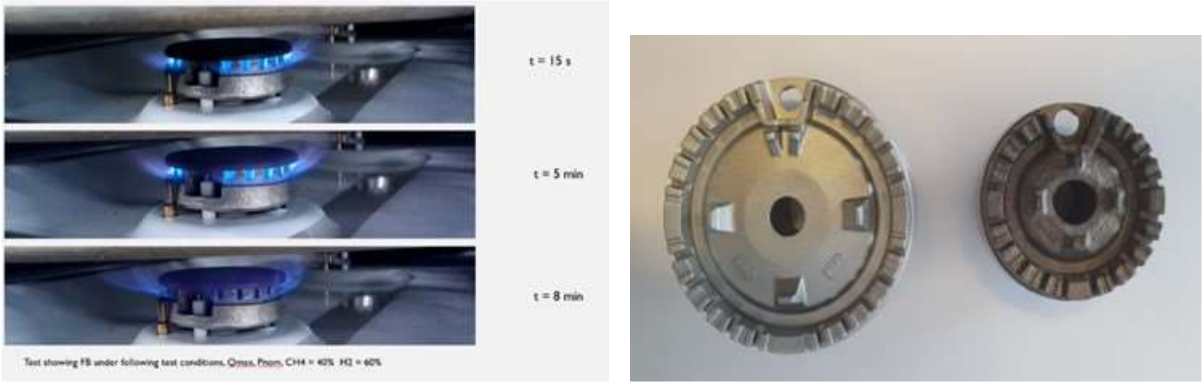


Figure 59: Impact of time on the flame (left picture) and impact of flashback on gas burners (right picture).

2.8.2.4 CO emissions (dry air free)

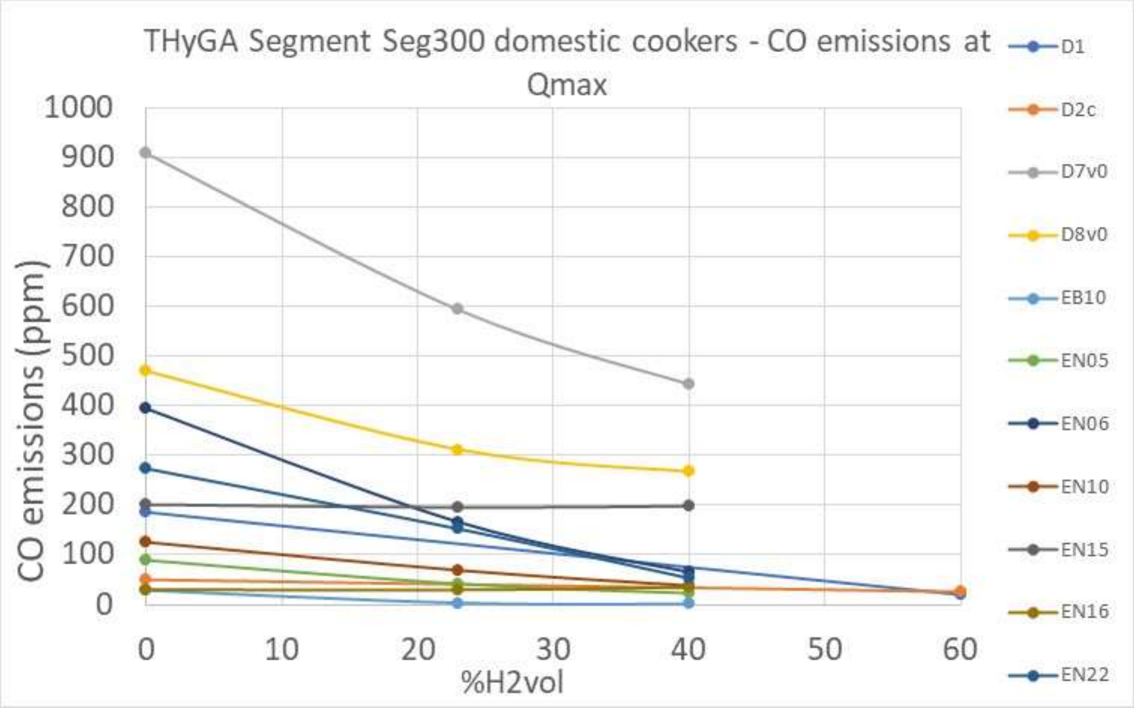


Figure 60: Segment 300 - CO emissions at Qmax - Part 1.

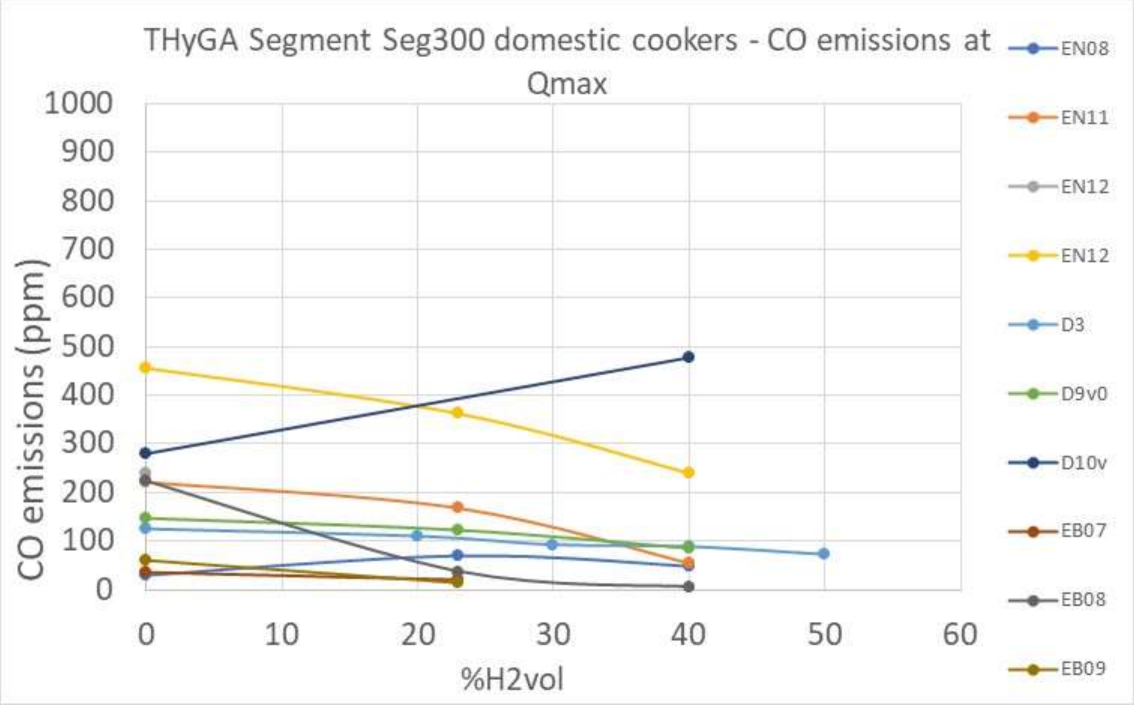


Figure 61: Segment 300 - CO emissions at Qmax - Part 2.

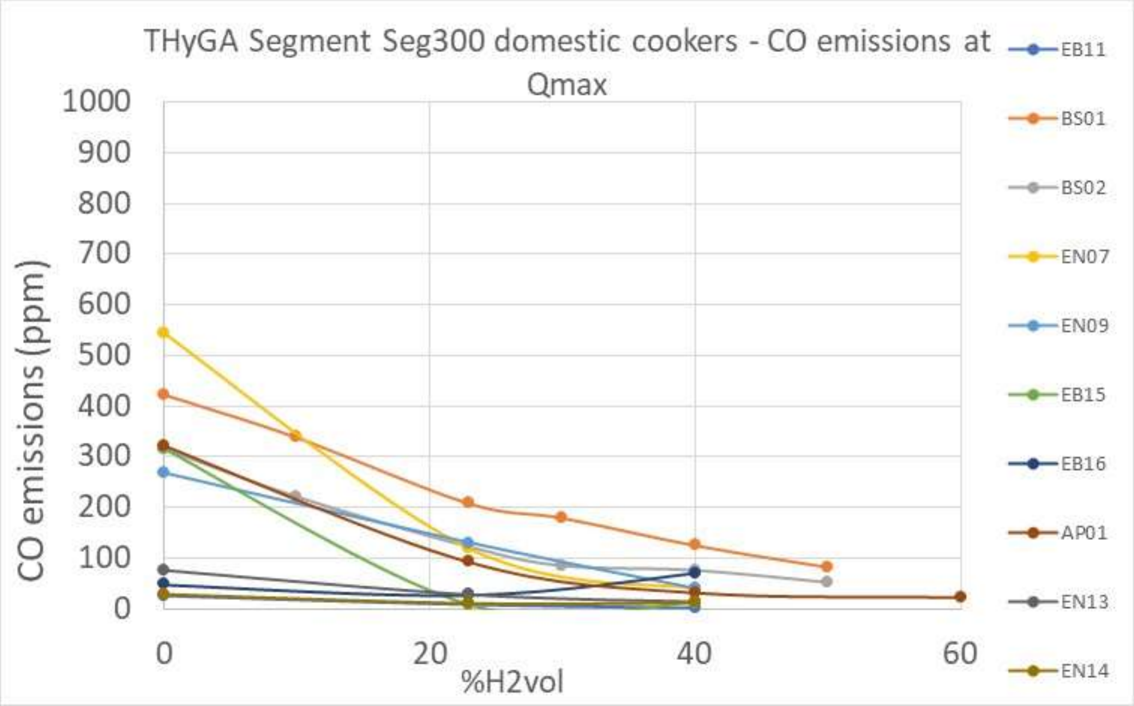


Figure 62: Segment 300 - CO emissions at Qmax - Part 3.

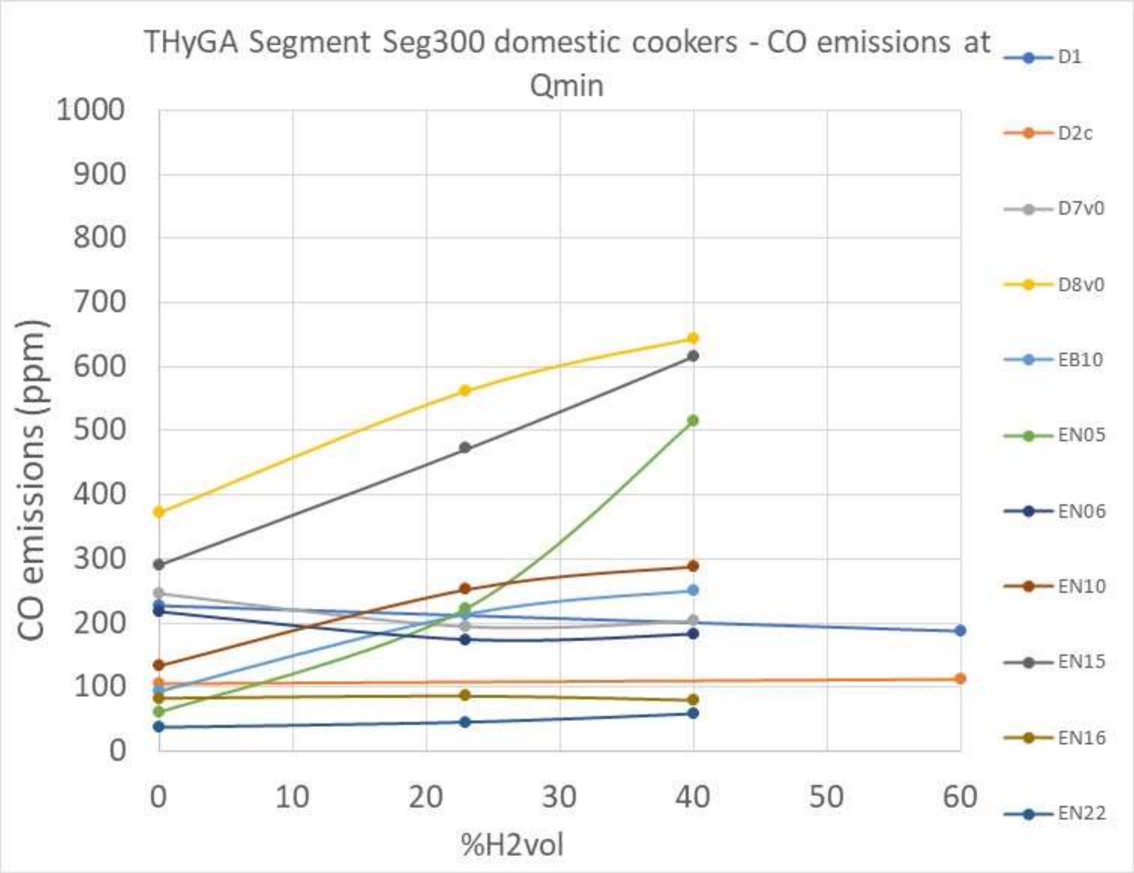


Figure 63: Segment 300 - CO emissions at Qmin - Part 1.

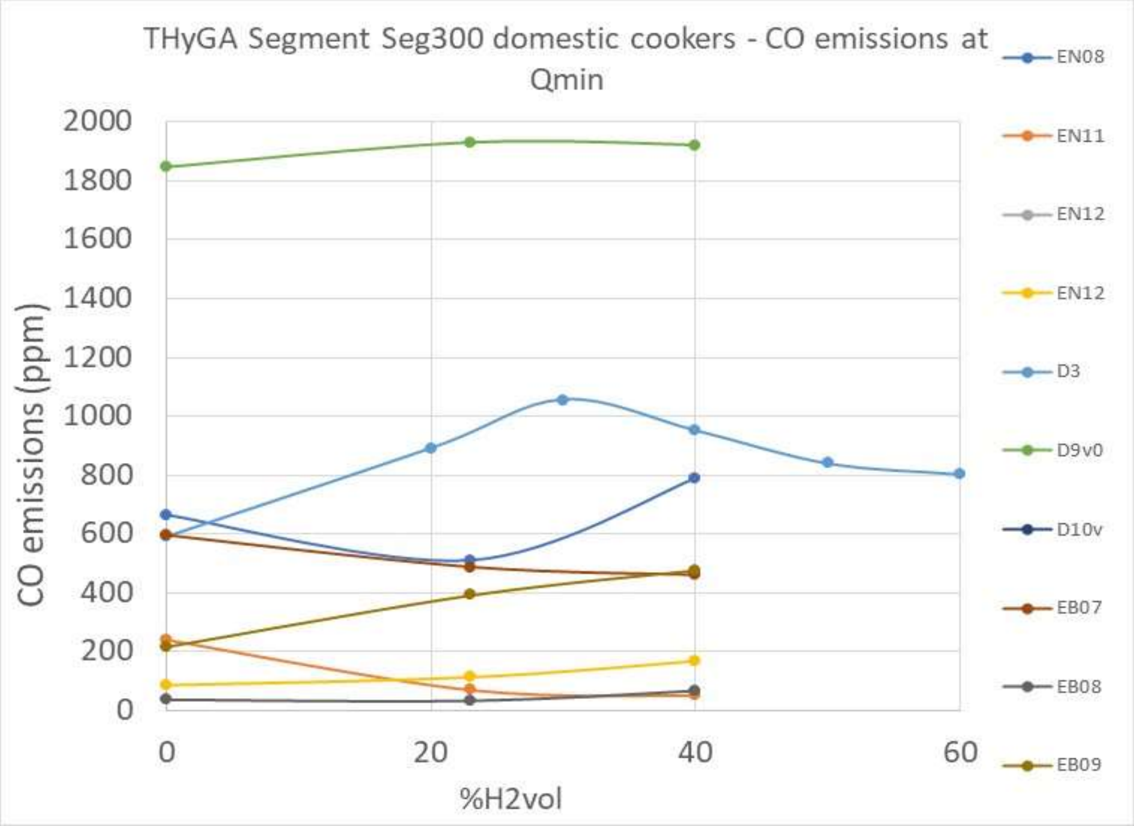


Figure 64: Segment 300 - CO emissions at Qmin - Part 2 (note the different scale compared to the 2 other figures at Qmin).

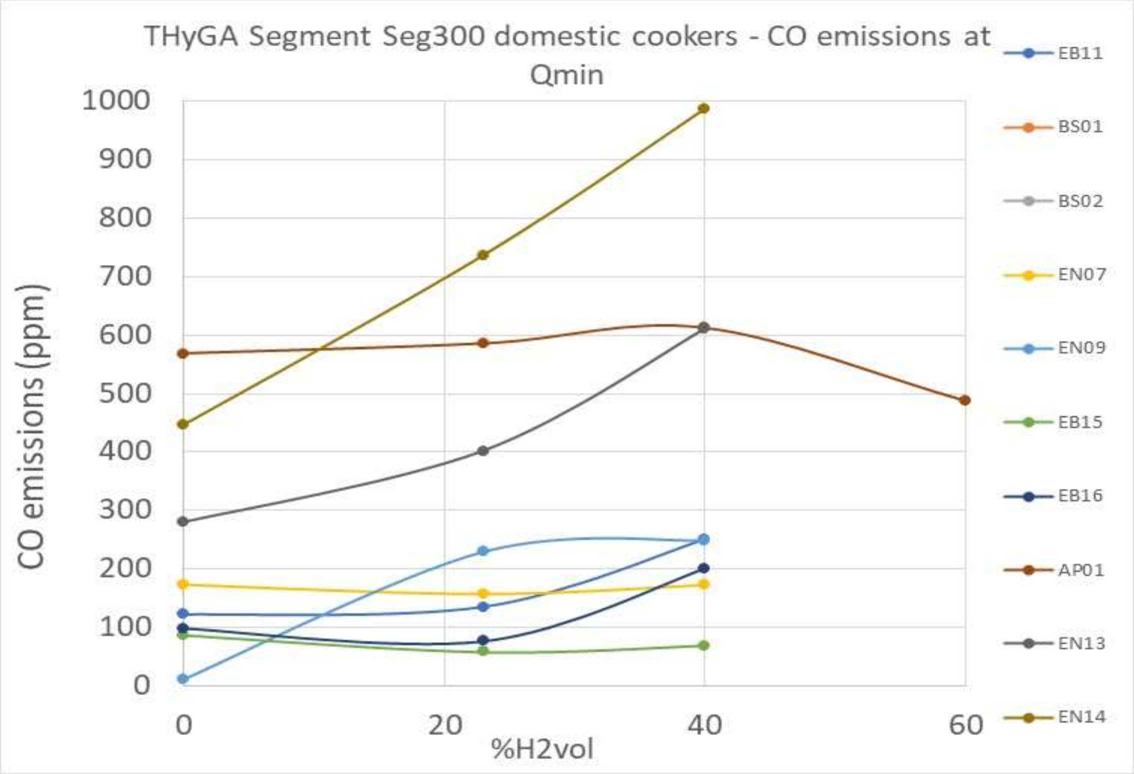


Figure 65: Segment 300 - CO emissions at Qmin - Part 3.

At Qmax, the CO emissions decrease with hydrogen admixture in the vast majority of cases. This is, however, not true anymore at Qmin, where we see more or less stable concentrations together with increase in many cases and decrease in very few.

D7 and D8 have high emissions because the injectors were not well screwed in.

2.8.3 Emissions

2.8.3.1 NOx (dry air free)

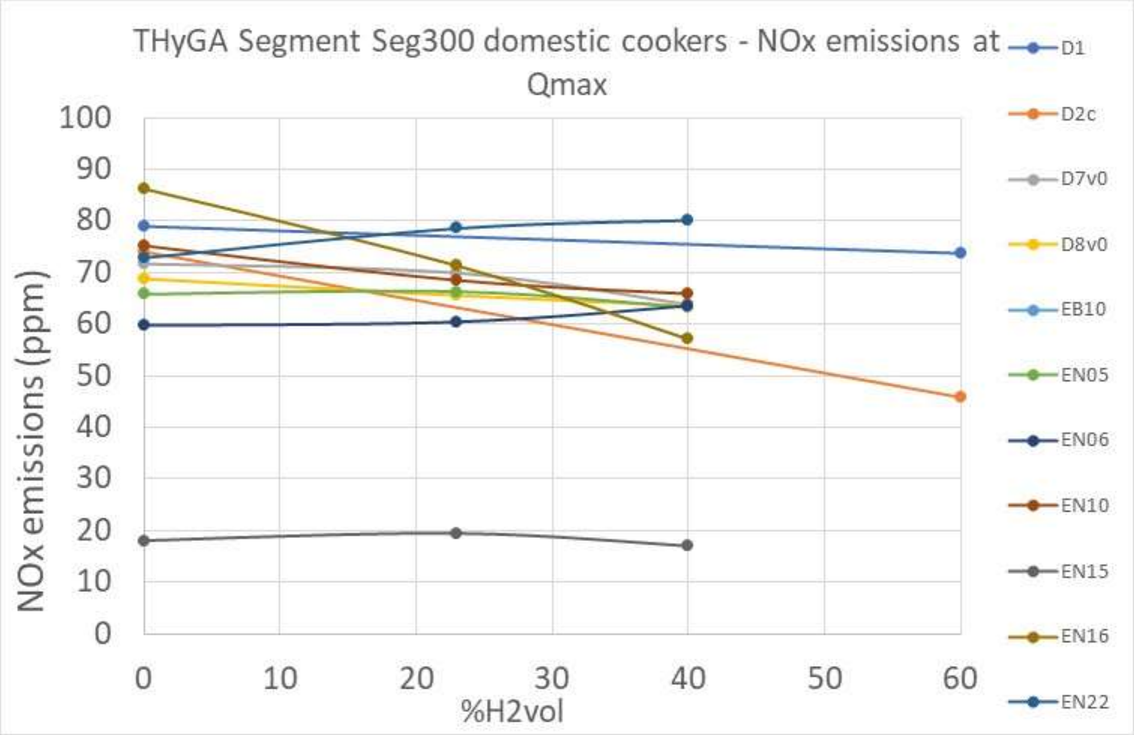


Figure 66: Segment 300 - NOx emissions at Qmax - Part 1.

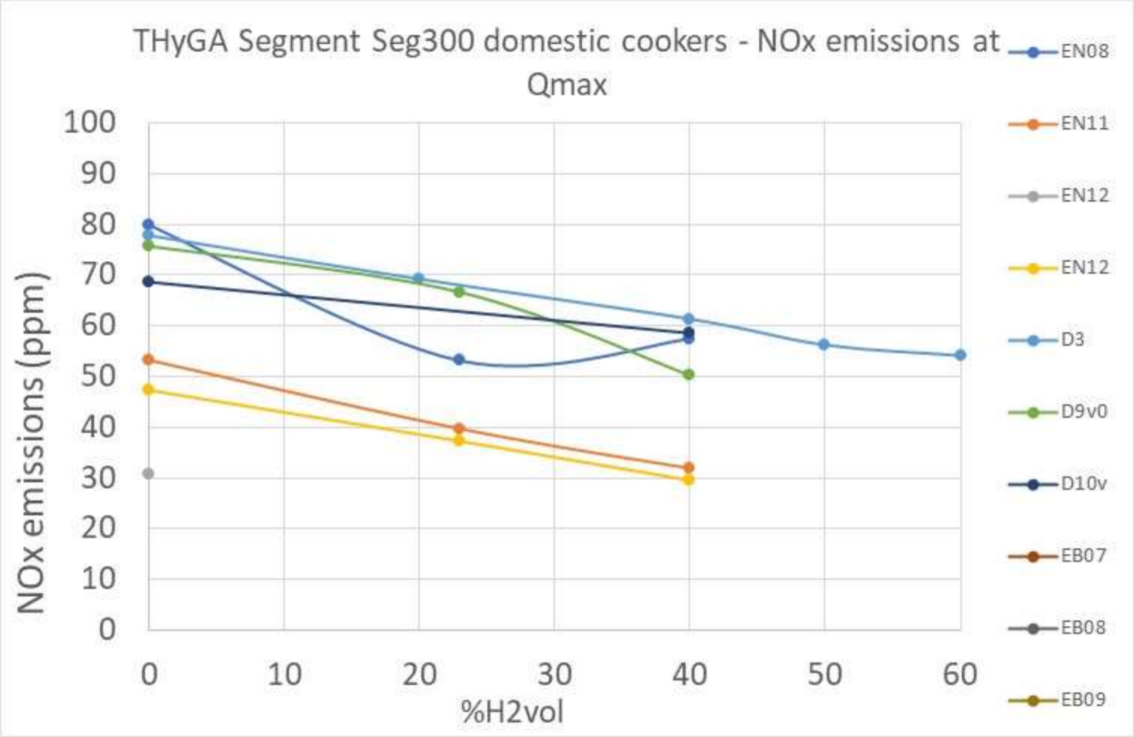


Figure 67: Segment 300 - NOx emissions at Qmax - Part 2.

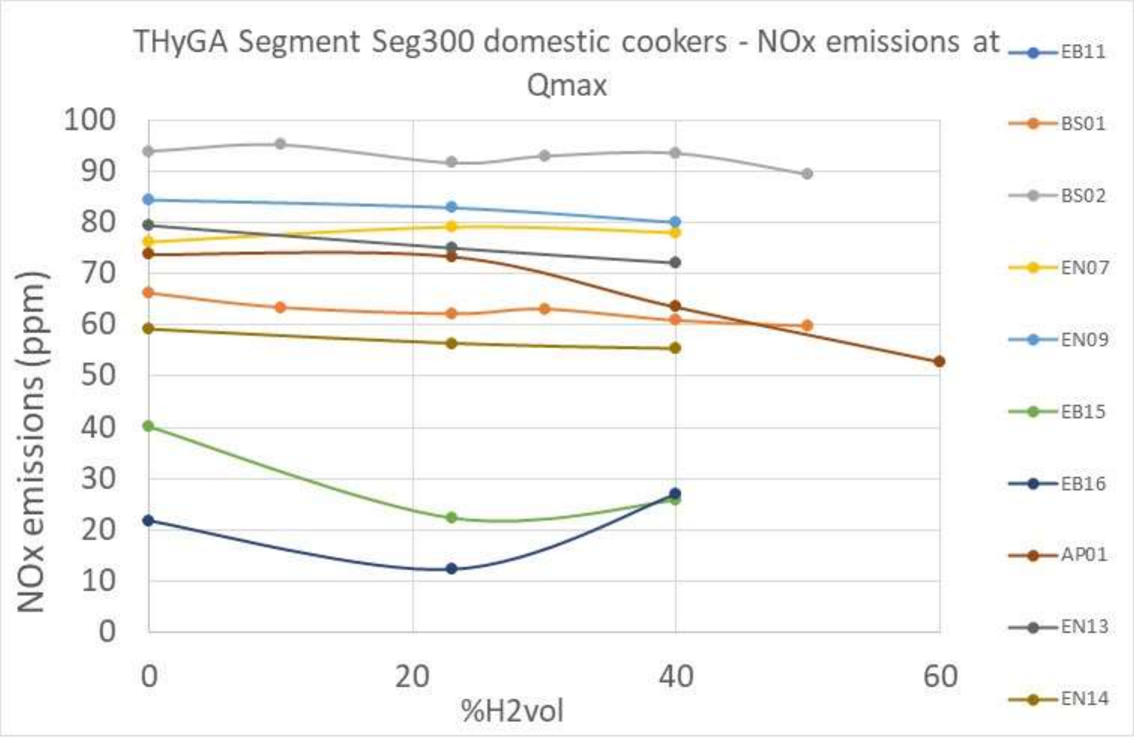


Figure 68: Segment 300 - NOx emissions at Qmax - Part 3.

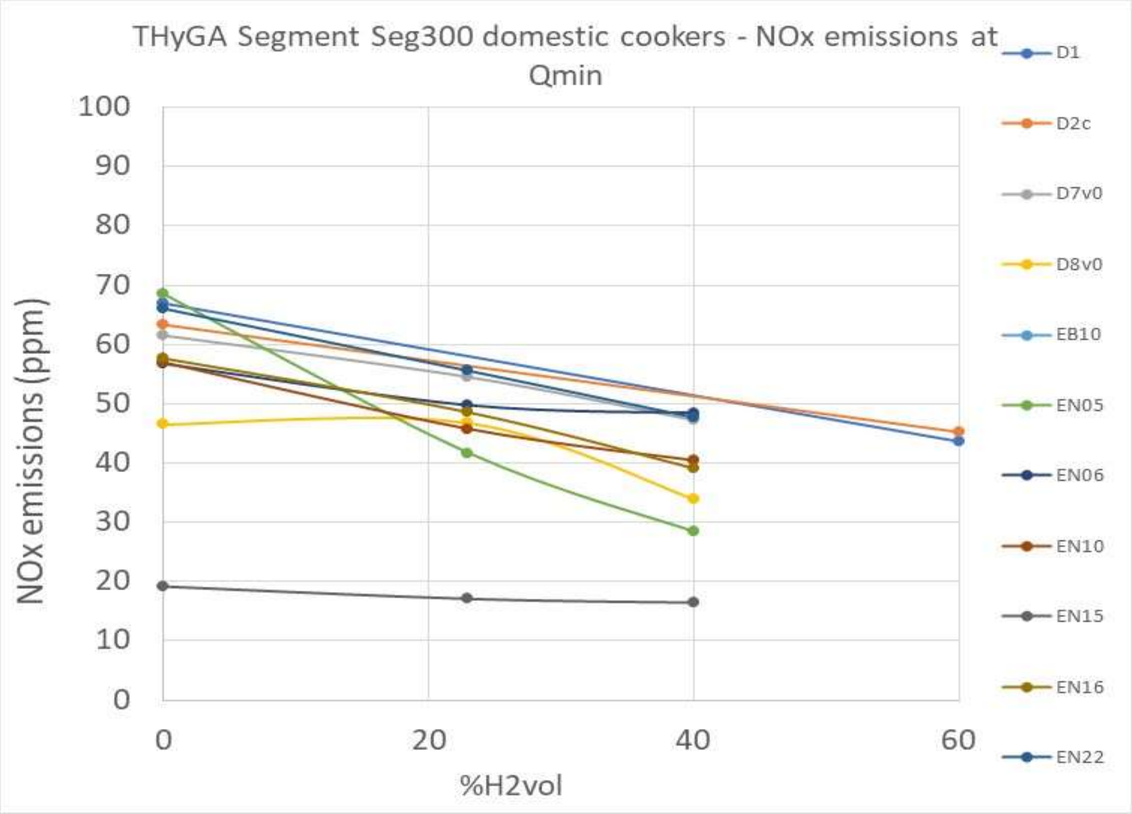


Figure 69: Segment 300 - NOx emissions at Qmin - Part 1.

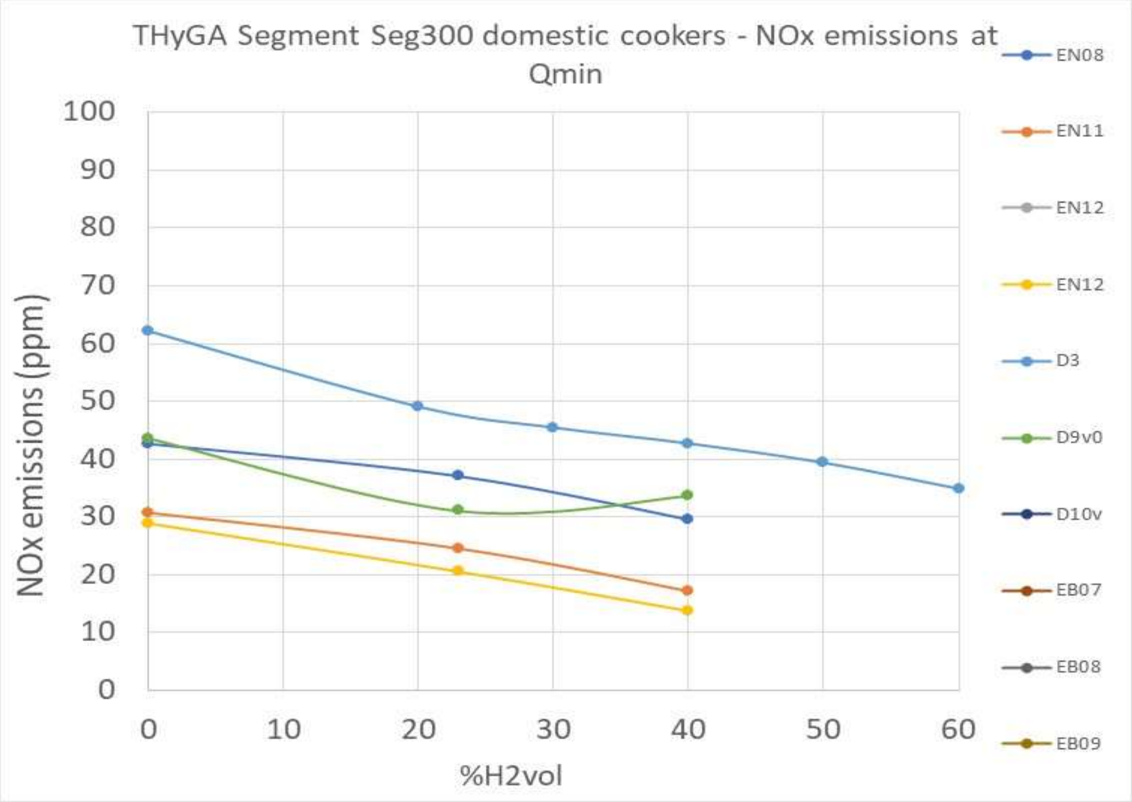


Figure 70: Segment 300 - NOx emissions at Qmin - Part 2.

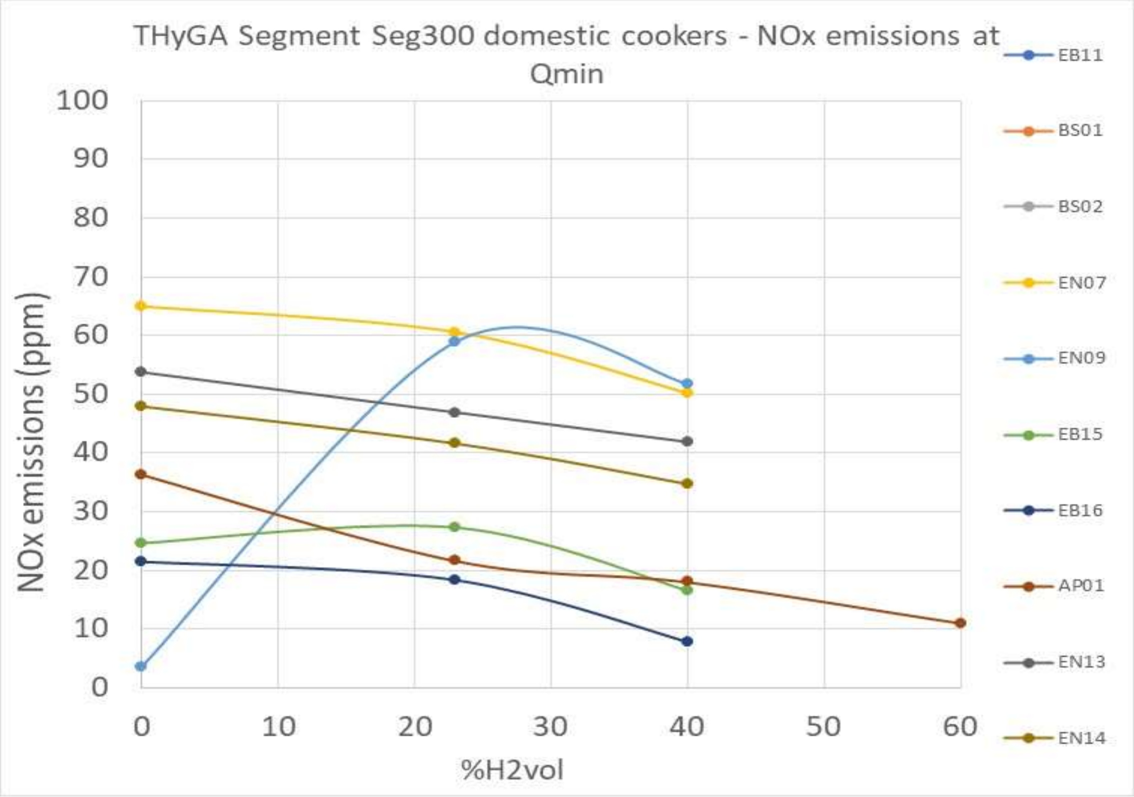


Figure 71: Segment 300 - NOx emissions at Qmin - Part 3.

There are no clear trends for NOx emissions, for domestic cookers. The emissions are more or less stable and not impacted very much by H2, although slight increases and or decreases can be seen depending on the appliance.

2.8.3.2 UHC emissions

UHC are discussed in section 3.5.

2.8.4 Efficiency

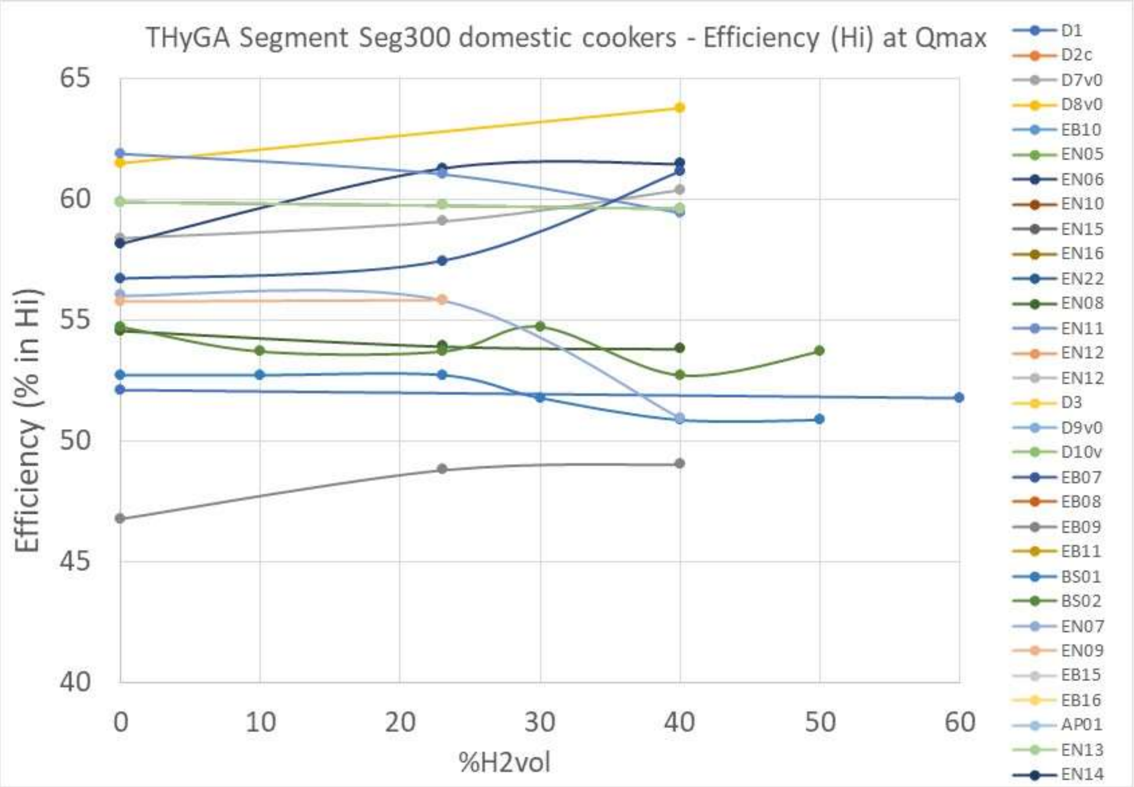


Figure 72: Segment 300 – Efficiency at Qmax (when a curve is missing for an appliance it means it was not measured).

Note that efficiency test was not systematically done, and for this reason for some appliances there are no curves on the figure.

We shall note the following:

Difference in level of efficiency measured

The efficiency depends very much on parameters like quantity of water used for the test, the power of the burner and the size of the pot; this together with the differences in technologies tested (hobs, oven with different burners) can explain the wide range measured.

The repeatability of testing

The repeatability of testing is not as good as for the boilers, we can expect that it is probably > 1% or 2% absolute. Therefore, many of the variations are not significant.

Considering the results, we can conclude that we don't really see trends, as most of the variations are more or less in the measurement repeatability range.

The point at 40% H2 for EN07 shows a significant drop in the efficiency (about 5%), but as the two first points were showing no increase or decrease, this could be an outlier. So, we should not conclude on basis of this single point.

2.8.5 Operational

Issues were observed with cold start and hot start

The reduction of heat with the increase of H2 % will bring longer cooking time.

Also, yellow tipping and **condensate of water at the surface of the pots during testing** were noted. This condensate is possibly interaction with the combustion.

This can be a major issue for the use of H2, but to be more conclusive it would be necessary to test a number of different pot configurations and combine this with various flue gas extraction rates.

2.8.6 Conclusion for segment 300

Table 23: Conclusions for segment 300.

		H2 % Tested							
		0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
300 Cookers domestic	*Safety*	🟩	🟩	🟩	🟩	2	8	8	10
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨

For the interpretation of the table above it is important to note that many of the test were only carried out up to 40% H2

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 300, a total of 30 appliances (mainly cooker hobs burners) were tested. The number of appliances having issues are indicated in the red cells of the "impact card" above. Note that not all appliances may have issues for the same tests, and not all tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

The group of appliances of segments 300 can generally cope with up to 40% H2 where flashback was observed on many appliances. (This means that 30% is OK, but 40% is not). In a single case an appliance was giving issue at 23% H2, but the test repeated on another appliance of the same model doesn't bring any issue.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

2.9 Catering (Segm. 400)

2.9.1 Appliances tested

Catering equipment (Segm.400) include **THyGA segments 401 to 410** (see Annex 2 for more details), some appliances are fully premix (Segm. 400a) and other not fully premix (Segm. 400b).

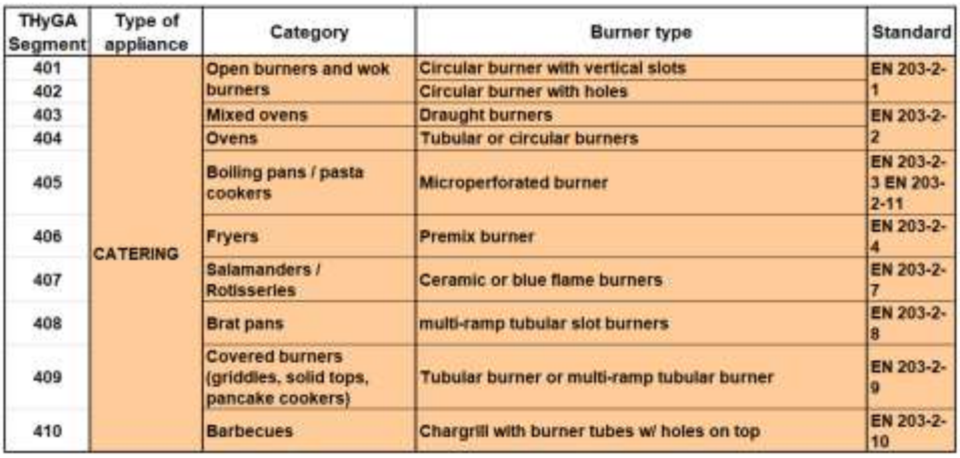
Table 24 : Characteristics of the 11 Catering full premix (Segm. 400a) tested.

Appliance ID	Segment	Qmin (kW)	Qmax (kW)	Combustion control feature (Y/N)
EB22	402	2	7	N
EB23	402	1	3.5	N
EB24	404	-	6	N
EB19	404	5	13	Y
EB20	404	5	13	Y
EB03	404	NA	19	N
EB17	405	3	20	N
GA04	406	16	31	Y
EB18	409	-	10.6	N
EB21	410	12	20	N

Table 25: Characteristics of the 6 Catering not full premix (Segm. 400b) tested.

Appliance ID	Segment	Qmin (kW)	Qmax (kW)
EB14	401	4.15	12
EB04	402	1.55	6
EB05	402	2.5	10
GA17	406	na	15
GA03	407	Not specified	5.9
EB06	408	NA	21

Table 26 : Segmentation of catering category.



THyGA Segment	Type of appliance	Category	Burner type	Standard
401	CATERING	Open burners and wok burners	Circular burner with vertical slots	EN 203-2-1
402			Circular burner with holes	
403		Mixed ovens	Draught burners	EN 203-2-2
404		Ovens	Tubular or circular burners	
405		Boiling pans / pasta cookers	Microperforated burner	EN 203-2-3 EN 203-2-11
406		Fryers	Premix burner	EN 203-2-4
407		Salamanders / Rotisseries	Ceramic or blue flame burners	EN 203-2-7
408		Brat pans	multi-ramp tubular slot burners	EN 203-2-8
409		Covered burners (griddles, solid tops, pancake cookers)	Tubular burner or multi-ramp tubular burner	EN 203-2-9
410		Barbecues	Chargrill with burner tubes w/ holes on top	EN 203-2-10

2.9.2 Pictures

Figure 73: Example of catering oven (Bonnet) on the left, boiling pan (CAPIC) on the right.

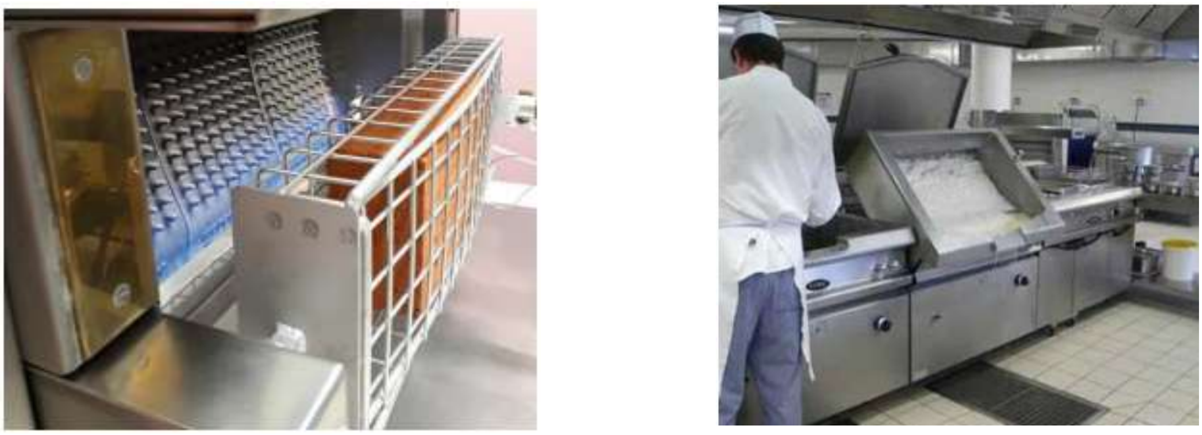


Figure 74: Rotisserie cooker (photo taken during tests at CRIGEN, Engie) on the left, brat pan on the right.

Figure 75: Pancake cooker.

2.9.3 Safety

2.9.3.1 Fully premix catering appliances (Segm. 400a)

Table 27: Segment 400a - safety aspects.

	Appliance ID		EB22	EB23	EB24	EB19	EB20	EB03	EB17	GA04	EB18	EB21
	Segment		402	402	404	404	404	404	405	406	409	410
	Qmin (kW)		2	1	-	5	5	NA	3	16	-	12
	Qmax (kW)		7	3.5	6	13	13	19	20	31	10.6	20
	Combustion control feature (Y/N)		N	N	N	Y	Y	N	N	Y	N	N
At what level of H2 the problem may occur : reference gas + %H2 used	%H2 in test gas	0	X	X	X	X	X	X	X	X	X	X
		0-10				X	X			X		
		10-20				X	X			X		
		20-23	X	X	X	X	X	X	X	X	X	X
		23-30	X	X	X	X	X			X	X	X
		30-40	X	X	X	X	X	X	X	X	X	X
		40-50										
		50-60										
EE	1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X	X	X	X	X	X	X
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2	X	X	X	X	X		X	X	X	X
EE	1.3 Efficiency and emission G23	G23 + H2										
CS	1.4 Cold start	CH4+40%H2	X	X	X	X	X	X	X	X	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X	X	X	X	X	X	X	X	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2										
FGP	1.7 Flue gas pipe length	CH4+30%H2										
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X	X		X	X	X	X
FD	1.9 Impact H2 flame detection.					X	X		X	X		
FB	1.10 Flash back		X	X	X	X	X (40%)	X	X	X	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2						NA		X		
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2						NA		X		
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2						NA				
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2				X (20%)	X (20%)	NA		X (23%)		
DI	4.1 Delayed ignition test.	CH4+30%H2										
S	4.2 Soundness											
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X	X	NA			NA	X	X		X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2										
4B	4.5 Cooker hob test with 4	CH4+30%H2	X	NA	NA	X			NA	NA	NA	
W	4.6 Influence of wind											
LT	4.7 Long time (limited time)	depends on manufacturer	X	X	X	X	X	X	X		X	X
AUX	4.8 Fluctuation of the aux.					X	X		X			X
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X	X	X	X	X	X	X
O	Other /Operational											

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

No safety issues were observed, however:

- because the flame is less visible with H2 it could be a potential problem. This was however, not observed.
- There were actually issues with adjustment G, where we change from a low calorific gas (EU Low + 20% H2) to a highly calorific gas (EU High). Air excess is then too low, which increases CO emissions to a dangerous level.

The main issue with those premix appliances is the same as for the boilers: the possible adjustment that can bring high CO value.

2.9.3.2 *Not fully premix catering appliances (Segm. 400b)*

Table 28: Segment 400b - safety aspects.

			EB14	EB04	EB05	GA17	GA03	EB06
	Appliance ID		EB14	EB04	EB05	GA17	GA03	EB06
	Segment		401	402	402	406	407	408
	Qmin (kW)		4.15	1.55	2.5	na	Not specified	NA
	Qmax (kW)		12	6	10	15	5.9	21
At what level of H2 the problem may occur : reference gas + %H2 used	**%H2 in test gas**	**0**	X	X	X	X	X	X
		0-10	X	X	X			X
		10-20		X	X			X
		20-23	X	X	X	X	X	X
		23-30	X	X	X	X		X
		30-40	X	X	X	X	X	X
		40-50						
		50-60						
EE	1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X (30%)	X	X
EE	1.2 Efficiency and emission EU LOW	EU LOW + H2	X			X	X	X
EE	1.3 Efficiency and emission G23	G23 + H2						
CS	1.4 Cold start	CH4+40%H2	X	X	X	X (30%)	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X	X	X	X (30%)	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2						
FGP	1.7 Flue gas pipe length	CH4+30%H2						
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X (23%)	X	X
FD	1.9 Impact H2 flame detection.					X	X	
FB	1.10 Flash back		X	X	X	X (30%)	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA	NA	NA
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA	NA	NA
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA	NA	NA
DI	4.1 Delayed ignition test.	CH4+30%H2						
S	4.2 Soundness					X		
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X	X	X	X	X	
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2				X		
4B	4.5 Cooker hob test with 4	CH4+30%H2		X	X	NA	NA	NA
W	4.6 Influence of wind						X	
LT	4.7 Long time (limited time)	depends on manufacturer	X	X	X			X
AUX	4.8 Fluctuation of the aux.		X			X		X
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X	X (40%)	X
O	Other /Operational					X		X

Some observations:

GA03: Only the minimum load could be set slightly higher in order to eliminate the occurring noise at 40% H2 (operational test).

GA17: Flashback was observed with 30% H2. For the same appliance correct ignition and cross-lighting was tested with G20 and G20+23%H2.

In general:

- Quick switch from G20 to mix with 23%H2 has no impact on the correct operation of the appliances. The flame aspect changes a little when switching over.
- Variation of the auxiliary energy has no influence on the function of the appliance.
- Appliances without pressure regulators could be impacted by pressure variations with or without H2.

2.9.3.3 CO emissions (dry air free) for fully premix catering appliances (Segm. 400a)

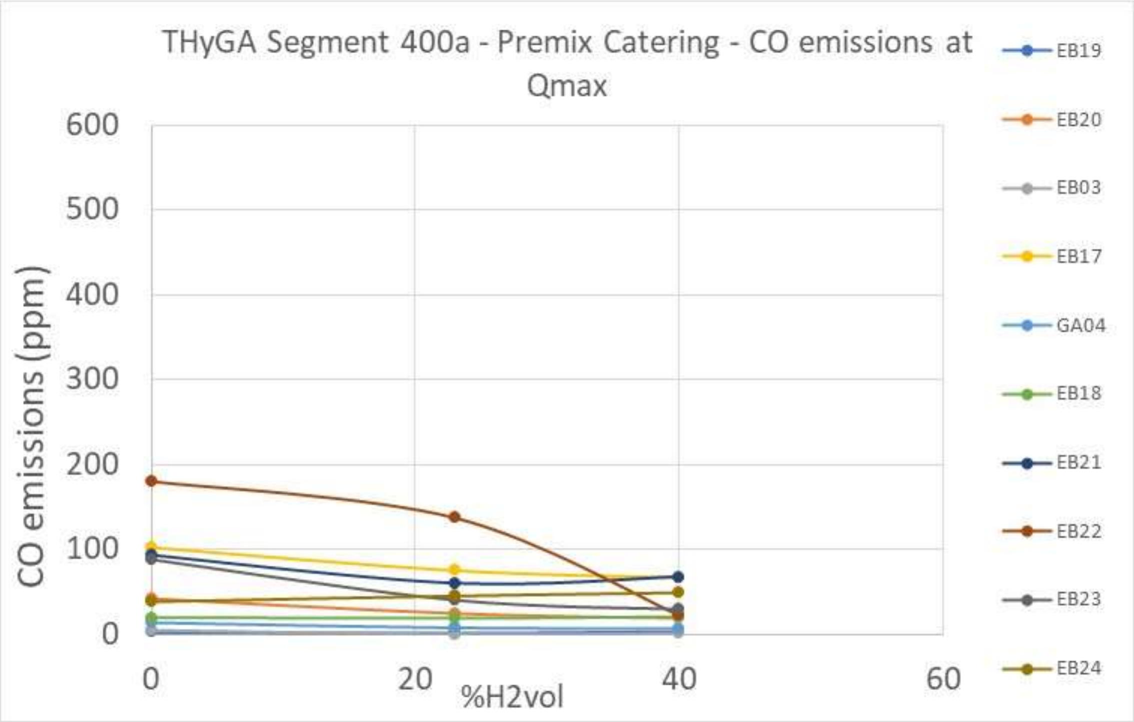


Figure 76: Segment 400a - CO emissions at Qmax.

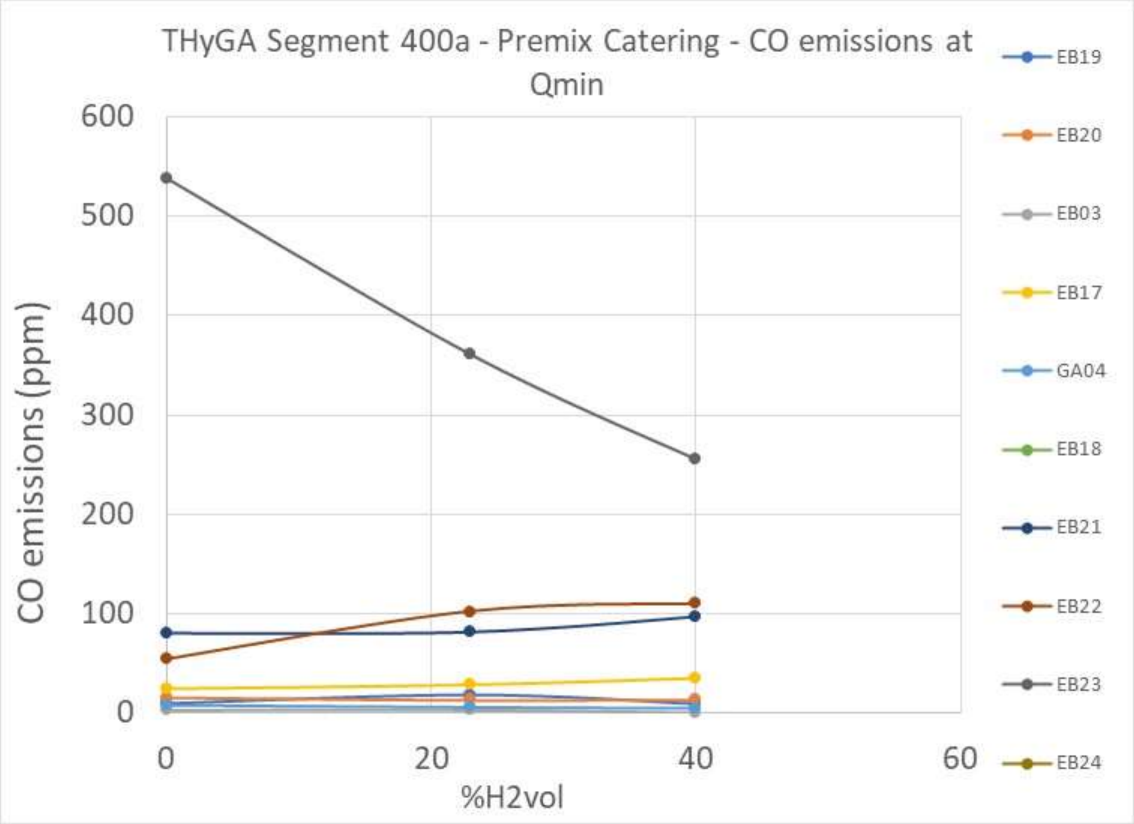


Figure 77: Segment 400a - CO emissions at Qmin.

2.9.3.4 CO emissions (dry air free) for not fully premix catering appliances (Segm. 400b)

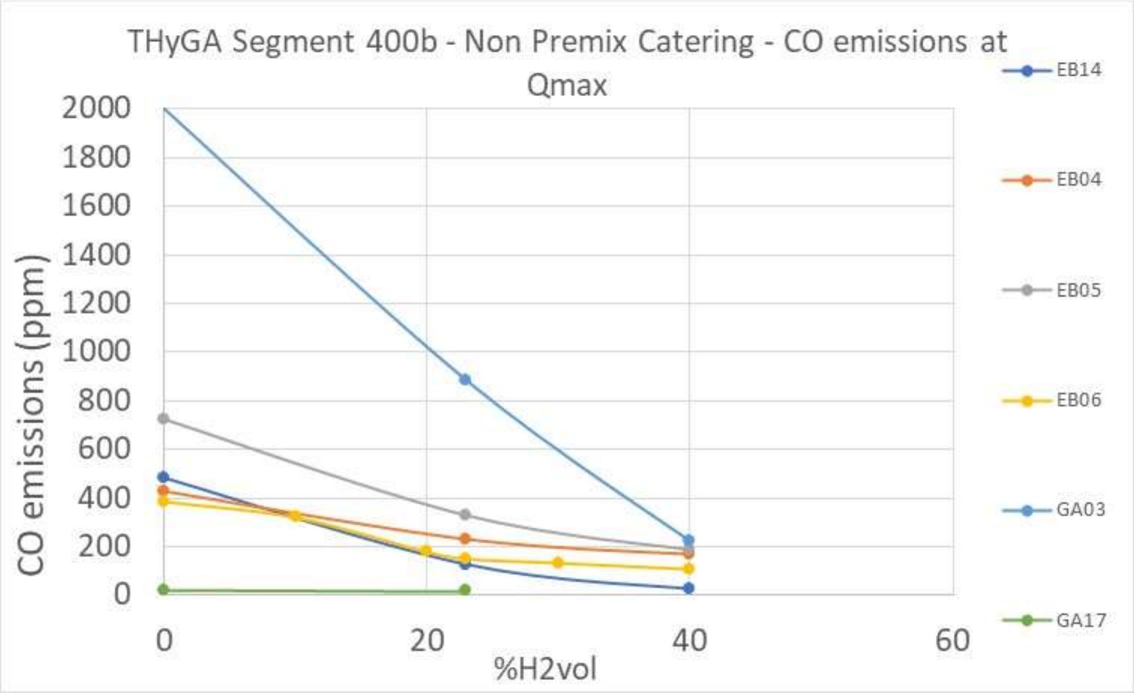


Figure 78: Segment 400b - CO emissions at Qmax.

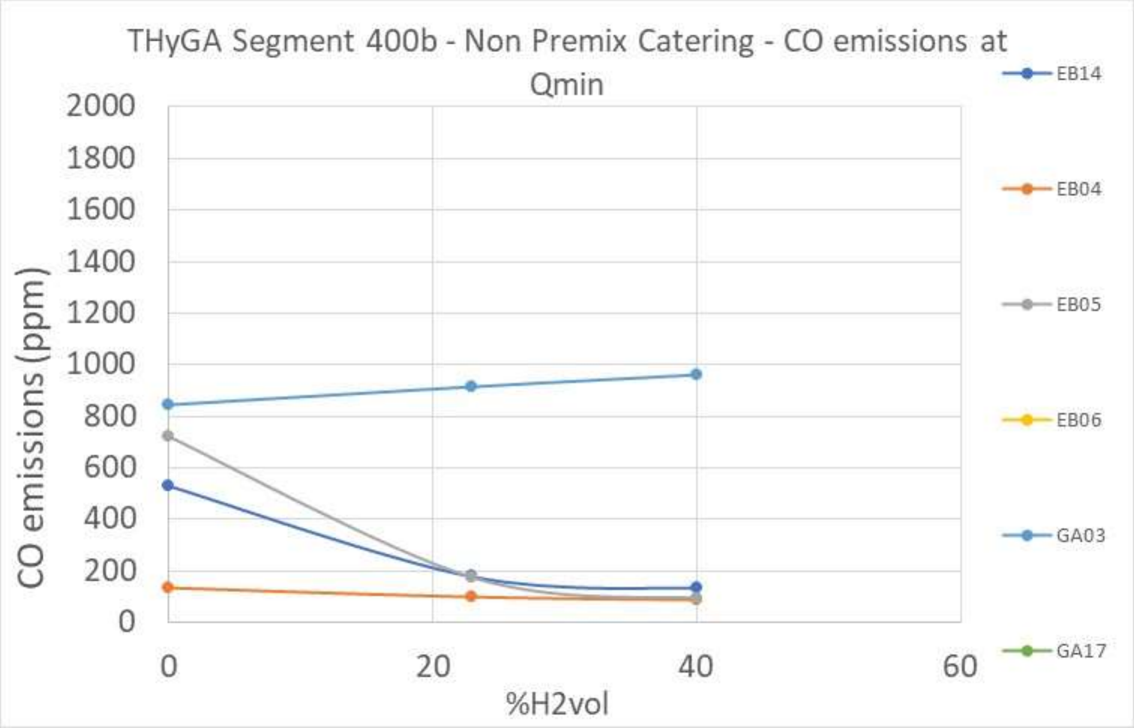


Figure 79: Segment 400b - CO emissions at Qmin.

2.9.4 Emissions

2.9.4.1 *Fully premix catering appliances (Segm. 400a)*

2.9.4.1.1 NOx emissions (dry air free)

We observe a general trend in decrease of CO and NO_x, apart from a few cases.

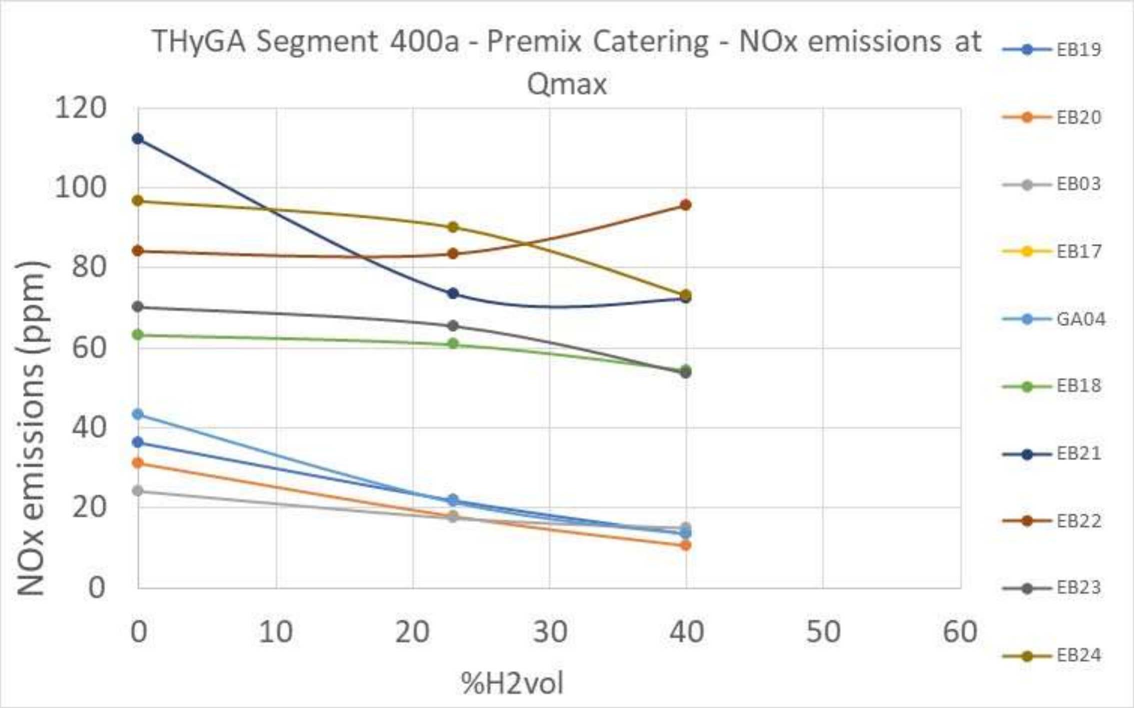


Figure 80: Segment 400a - NOx emissions at Qmax.

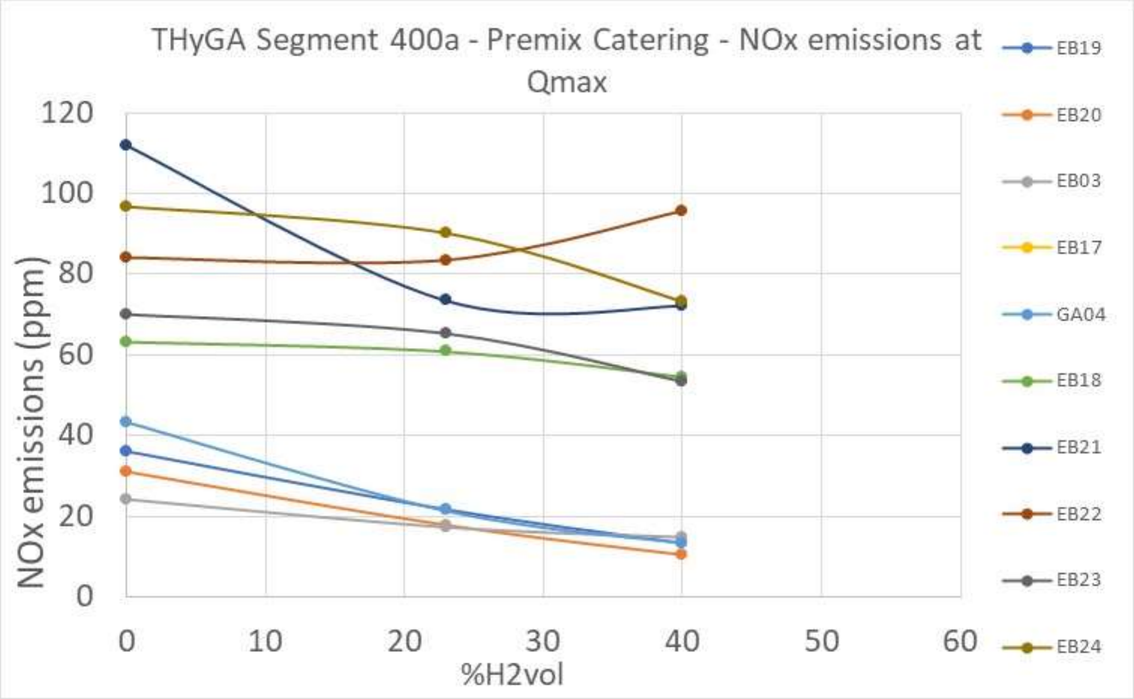


Figure 81:Segment 400a - NOx emissions at Qmin.

2.9.4.1.2 UHC (NOT dry air free)

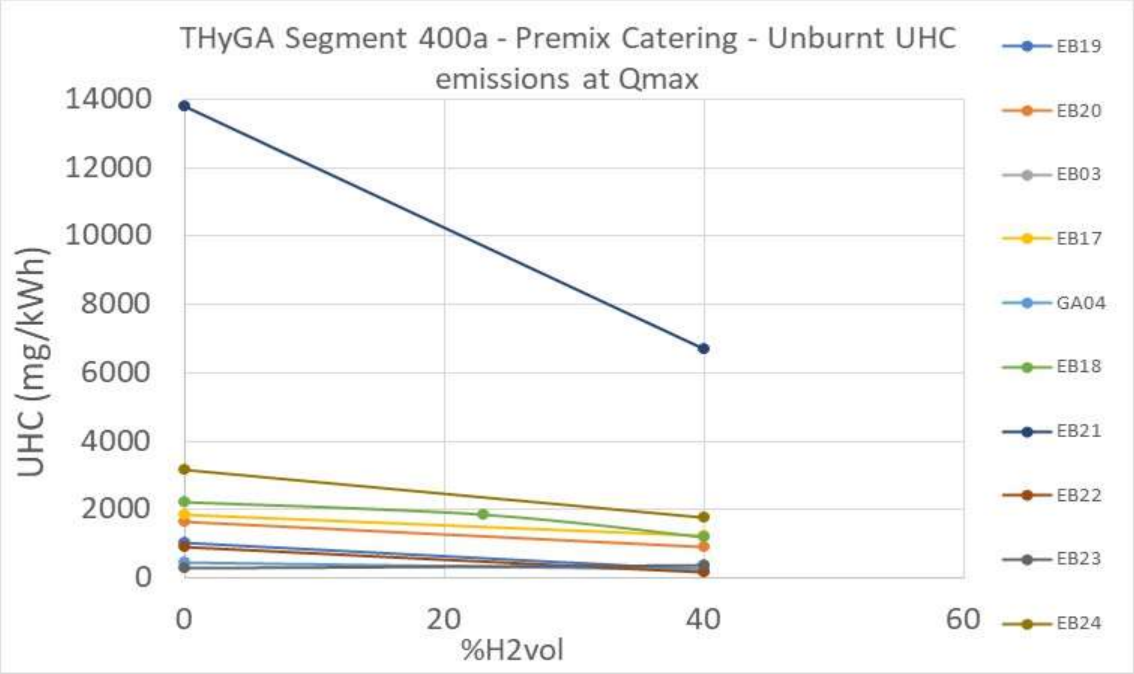


Figure 82: Segment 400a - NOx emissions at Qmax.

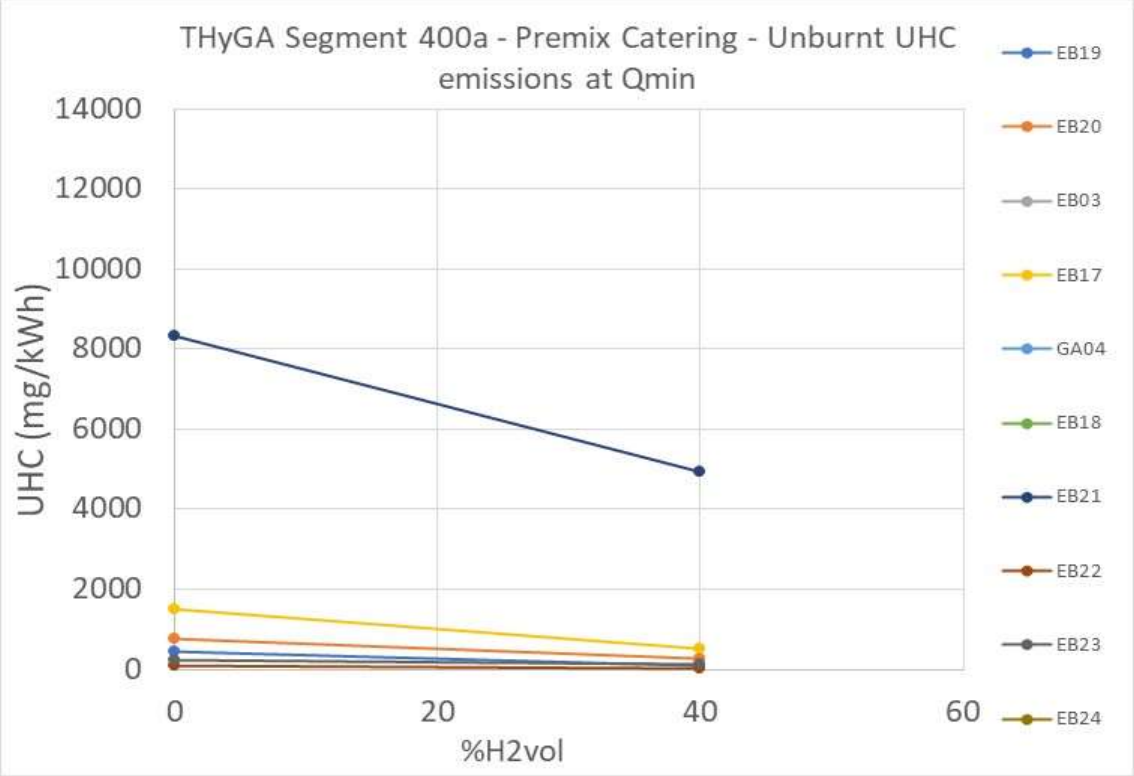


Figure 83: Segment 400a - NOx emissions at Qmin.

Note the quite high UHC for EB21. It can be due to big burner surface with 2 burners.

UHC is also discussed in the section 3.5.

2.9.4.2 *Not fully premix catering appliances (Segm. 400b)*

2.9.4.2.1 NOx emissions (dry air free)

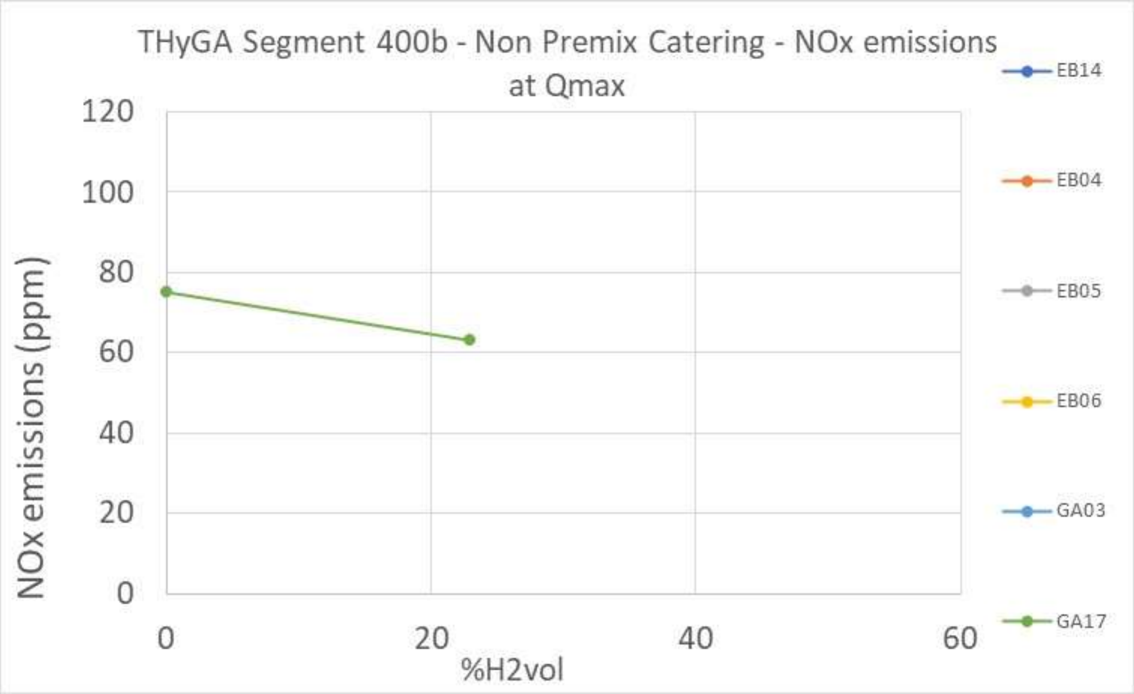


Figure 84: Segment 400b - NOx emissions at Qmax.

2.9.4.2.2 UHC (NOT dry air free)

UHC is discussed in section 3.5.

2.9.5 Efficiency

2.9.5.1 *Fully premix catering appliances (Segm. 400a)*

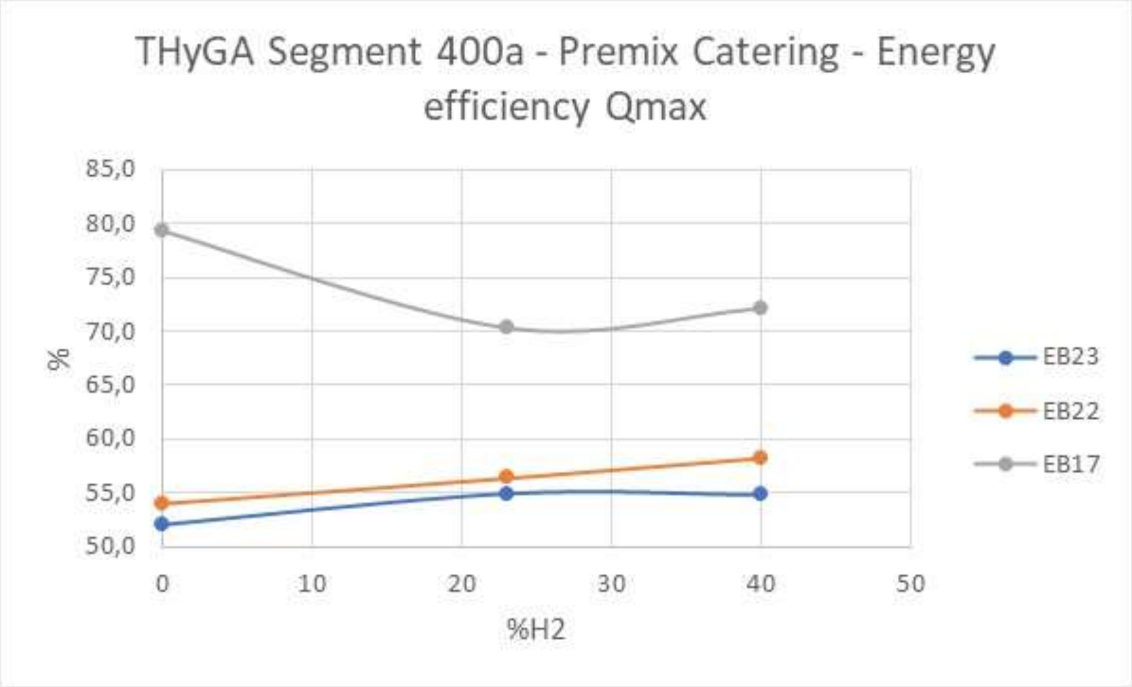


Figure 85: Segment 400a – Efficiency at Qmax

2.9.5.2 *Not fully premix catering appliances (Segm. 400b)*

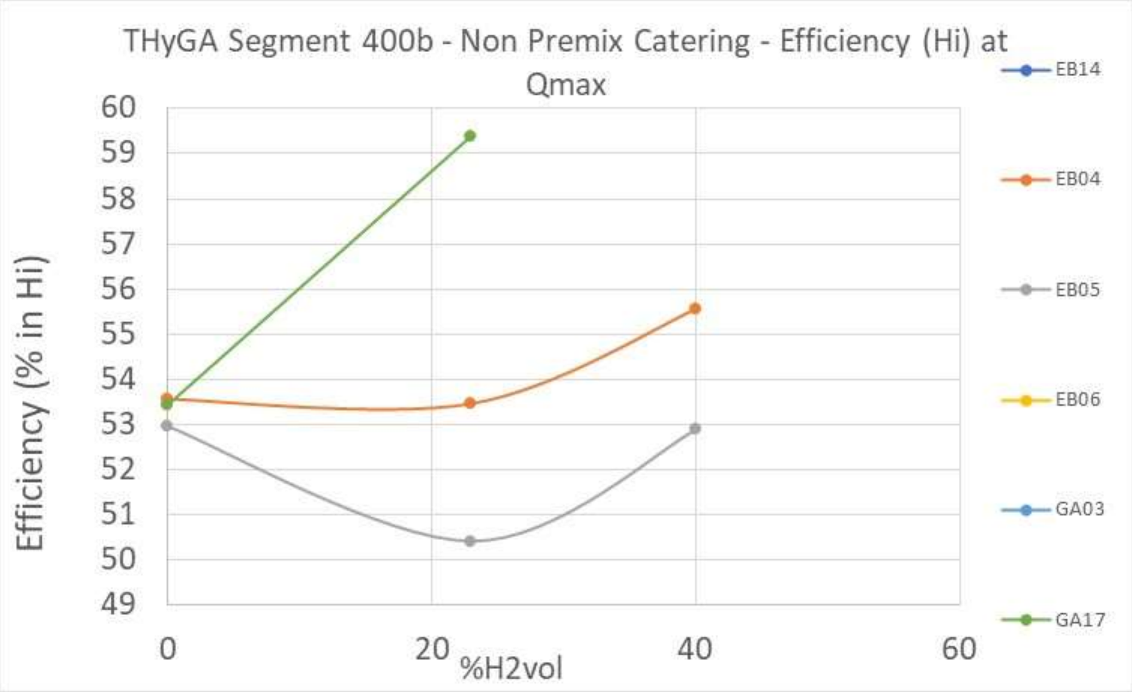


Figure 86: Segment 400b – Efficiency at Qmax.

2.9.6 Operational

Apart from the noise mentioned already for 40% H2, no operational issues are observed.

Catering full premix

No operational issues observed.

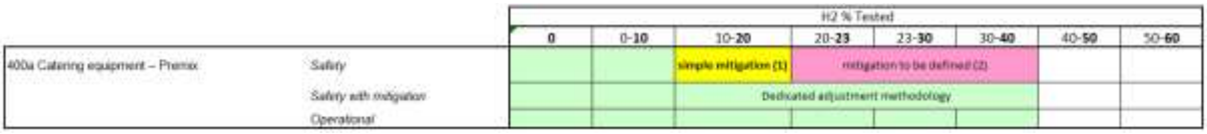
Catering not premix

No operational issues observed.

2.9.7 Conclusion for segments 400a and 400b

Catering full premix

Table 29: Conclusions for segment 400a.



		H2 % Tested							
		0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
400a Catering equipment – Premix	Safety	🟩	🟩	simple mitigation (1)	mitigation to be defined (2)				
	Safety with mitigation	🟩	🟩	Dedicated adjustment methodology					
	Operational	🟩	🟩	🟩	🟩	🟩	🟩		

Note that the above table doesn’t take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 400a, a total of 10 appliances were tested. The number of appliances having issues are indicated in the red cells of the “impact card” above. Note that not all appliances may have issues for the same tests, and not all tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

The main issue is related to adjustment of those premix appliances making them sensitive to Hydrogen already with 20% H2 in the grid (see the conclusions for segm. 100a on adjustment. As for the boilers, there are simple solutions to avoid such situation).

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

Catering not premix

Table 30: Conclusions for segment 400b.

	H2 % Tested							
	0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
400b Catering Safety	🟩	🟩	🟩	🟩	1	1	1	1
Operational	🟩	🟩	🟩	🟩	🟩	🟩	▨	▨

For segment 400b, a total of 6 appliances were tested. The number of appliances having issues are indicated in the red cells of the “impact card” above. Note that not all appliances may have issues for the same tests, and not all tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

Flash back issues starts with 30% H2 for one of the appliances tested.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in the section 3.3.

2.10 Space heaters (Segm. 500)

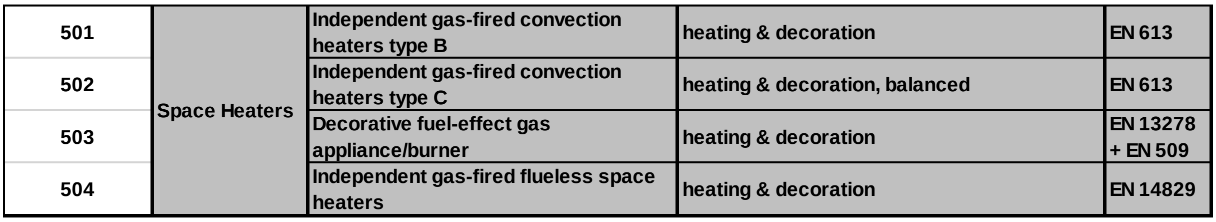
2.10.1 Appliances tested

Space heaters (Segm. 500) include **THyGA segments 501, 502, 503 and 504** (see Annex 2 for more details).

Table 31: Characteristics of the 4 space heaters tested.

Appliance ID	Segment	Qmin (kW)	Qmax (kW)
GA02	503	3.1	5.8
GA07	503	Not specified	10.2
GA08	504	3.3	10
GA06	507	NA	5.36

Table 32: Segmentation of the space heater category.



501	**Space Heaters**	**Independent gas-fired convection heaters type B**	**heating & decoration**	**EN 613**
502		**Independent gas-fired convection heaters type C**	**heating & decoration, balanced**	**EN 613**
503		**Decorative fuel-effect gas appliance/burner**	**heating & decoration**	**EN 13278 + EN 509**
504		**Independent gas-fired flueless space heaters**	**heating & decoration**	**EN 14829**

2.10.2 Pictures

Figure 87: Wall-hung gas convector (Dru – www.dru.nl) on the left, free standing closed glass fronted space heater on the right (www.wellstraler.be).

Figure 88: Built-in closed glass fronted fireplace (source: www.kalfire.com).

2.10.3 Safety

Table 33: Segment 500- Safety aspects

	Appliance ID		GA02	GA07	GA08	GA06
	Segment		503	503	504	507
	Qmin (kW)		3.1	Not specified	3.3	NA
	Qmax (kW)		5.8	10.2	10	5.36
	Combustion control feature (Y/N)		N	NA	N	N
At what level of H2 the problem may occur : reference gas + %H2 used	%H2 in test gas	0	X	X	X	X
		0-10	▨	▨	▨	▨
		10-20	▨	▨	▨	▨
		20-23	X	X	X	X
		23-30	X	X	X	X
		30-40	X	X	X	X
		40-50	X			
		50-60	X			
	1.1 Efficiency and emission CH4	CH4 + H2	X (60%)	X	X	X
	1.2 Efficiency and emission EU LOW	EU LOW + H2	X	X	X	
	1.3 Efficiency and emission G23	G23 + H2		X	X	X
CS	1.4 Cold start	CH4+40%H2	X	X	X	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X (60%)	X	X	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2				
FGP	1.7 Flue gas pipe length	CH4+30%H2		X	X	X
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X
FD	1.9 Impact H2 flame detection.		X	X	X	X
FB	1.10 Flash back		X (60%)	X	X	X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA	NA	NA
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA	NA	NA
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA	NA	NA
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA	NA	NA
DI	4.1 Delayed ignition test.	CH4+30%H2				
S	4.2 Soundness			X		X
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2		X	X	X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2			X	X
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA
W	4.6 Influence of wind			X		X
LT	4.7 Long time (limited time)	depends on manufacturer		X	X	
AUX	4.8 Fluctuation of the aux.			X	X	X
P	4.9 Fluctuation of pressure	CH4+40%H2	X	X	X	X
O	Other /Operational		X	X	X	

X	Test realized and no issues
▨	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

2.10.3.1 Overall observations and discussion on safety results

All appliances tested are fine up to at least 40%.

- There is a flashback occurrence for one of the appliances (GA02) at 60% H2. This happened during a hot start. "*Flashback occurred during the ignition test in warm condition with a* *mixture of 60% hydrogen. The device is equipped with an explosion hatch that catches this small explosion. No further damage to the device was observed."*

- For GA07 at the maximum load, the appliance operates safely for mixtures up to 40% H2. At the minimum load, the CO value exceeds 1000ppm. As the standard does not set requirements for combustion at minimum load this is not in contradiction with the certification. The issue with high CO value could in practice easily be solved by increasing the burner pressure for Qmin.
- For GA06 no flashback was observed during the test program.

Additional tests were done on this appliance. All the following tests did not show any specific issue with H2:

- Leakage test.
- Effect of room draught on burner.
- Effect of down draught.
- Combustion safety device (TTB) with positive effect of H2.

2.10.3.2 CO emissions (dry air free)

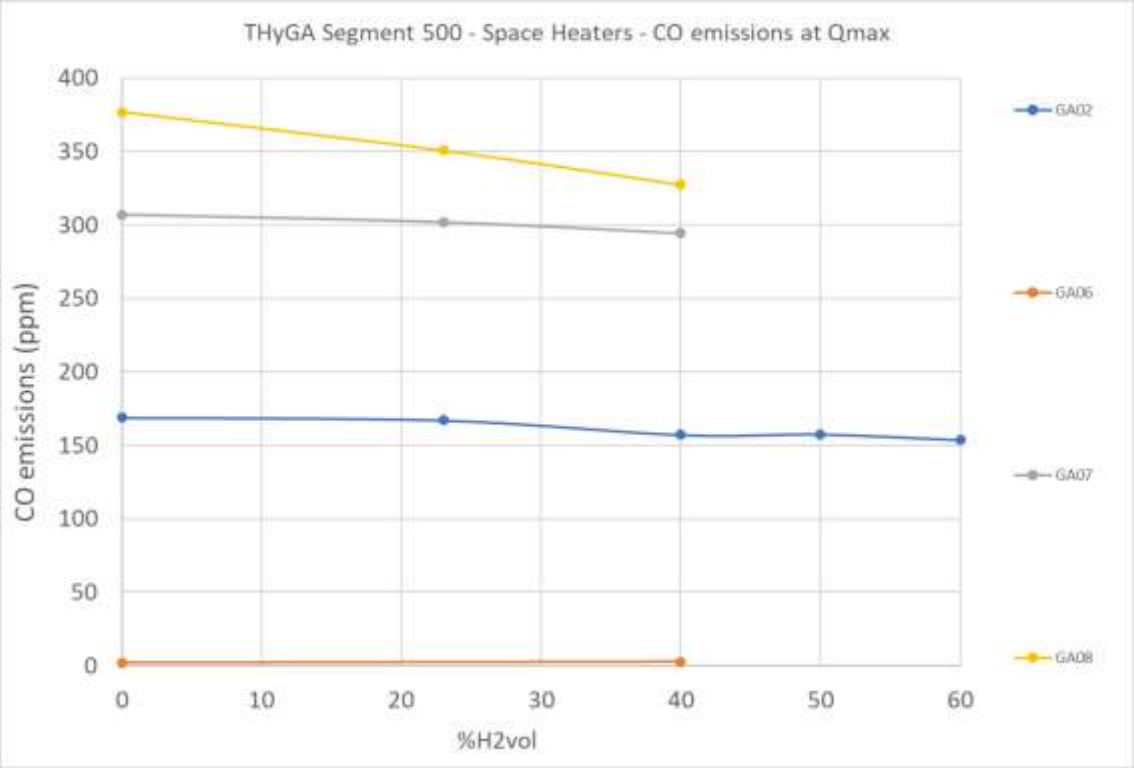


Figure 89: Segment 500 - CO emissions at Qmax.

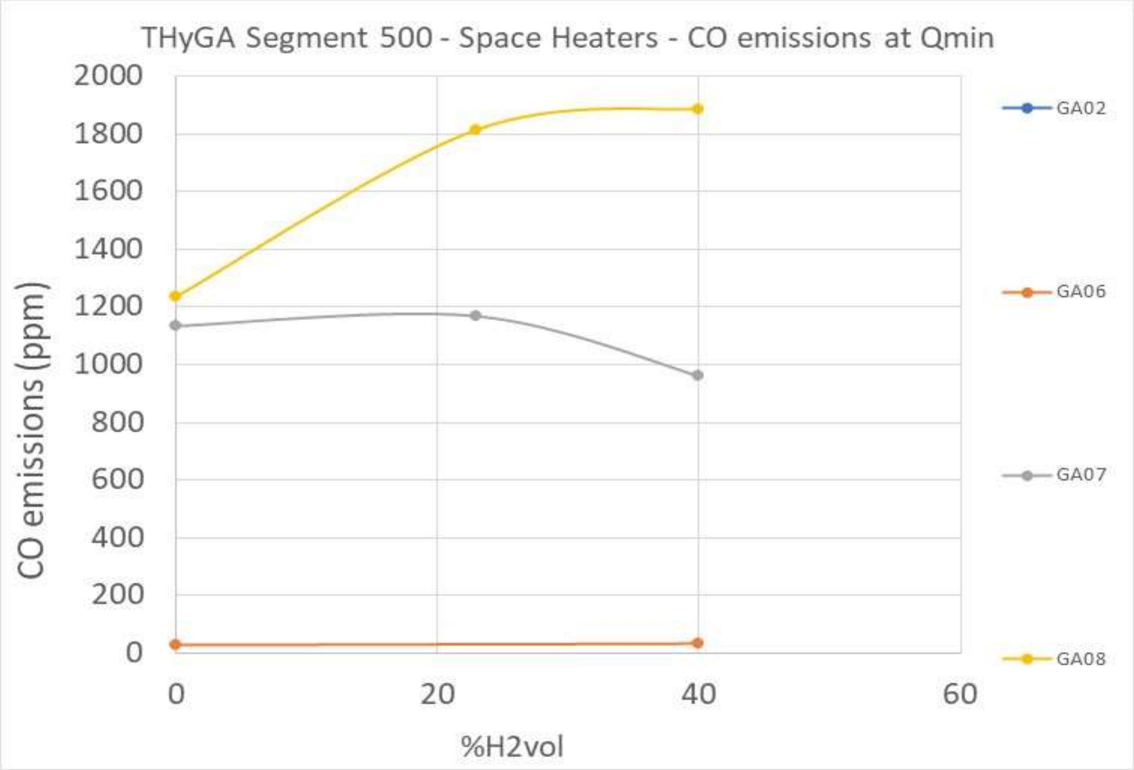


Figure 90: Segment 500 - CO emissions at Qmin.

2.10.4 Emissions

2.10.4.1 NOx emissions (dry air free)

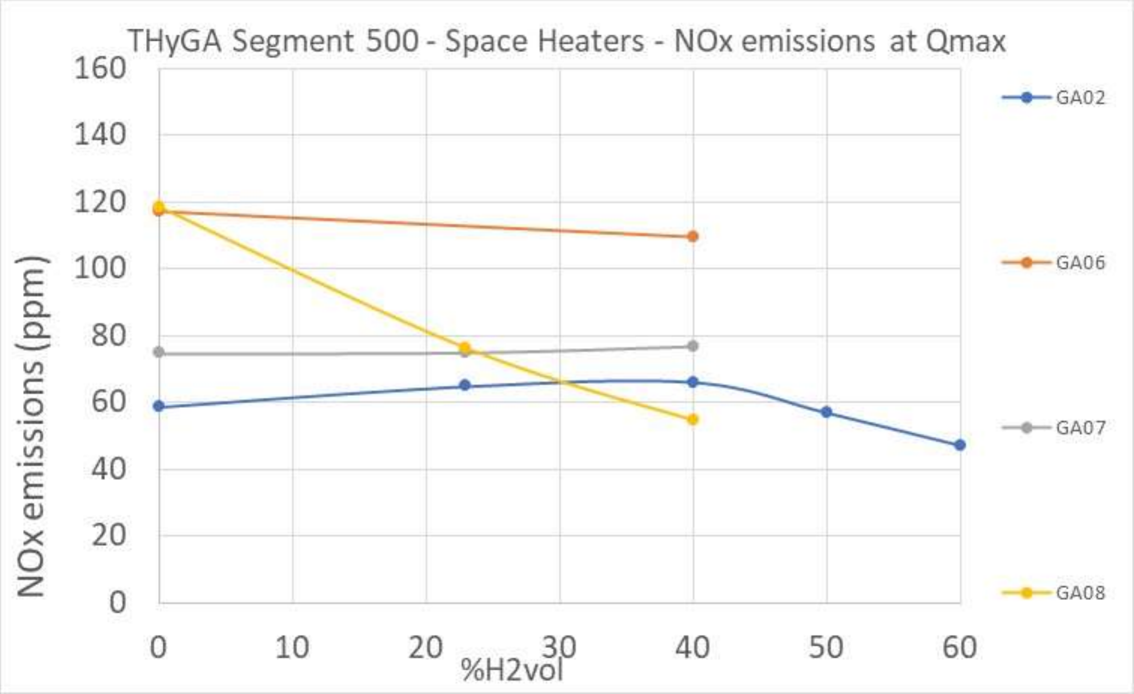


Figure 91: Segment 500 - NOx emissions at Qmax.

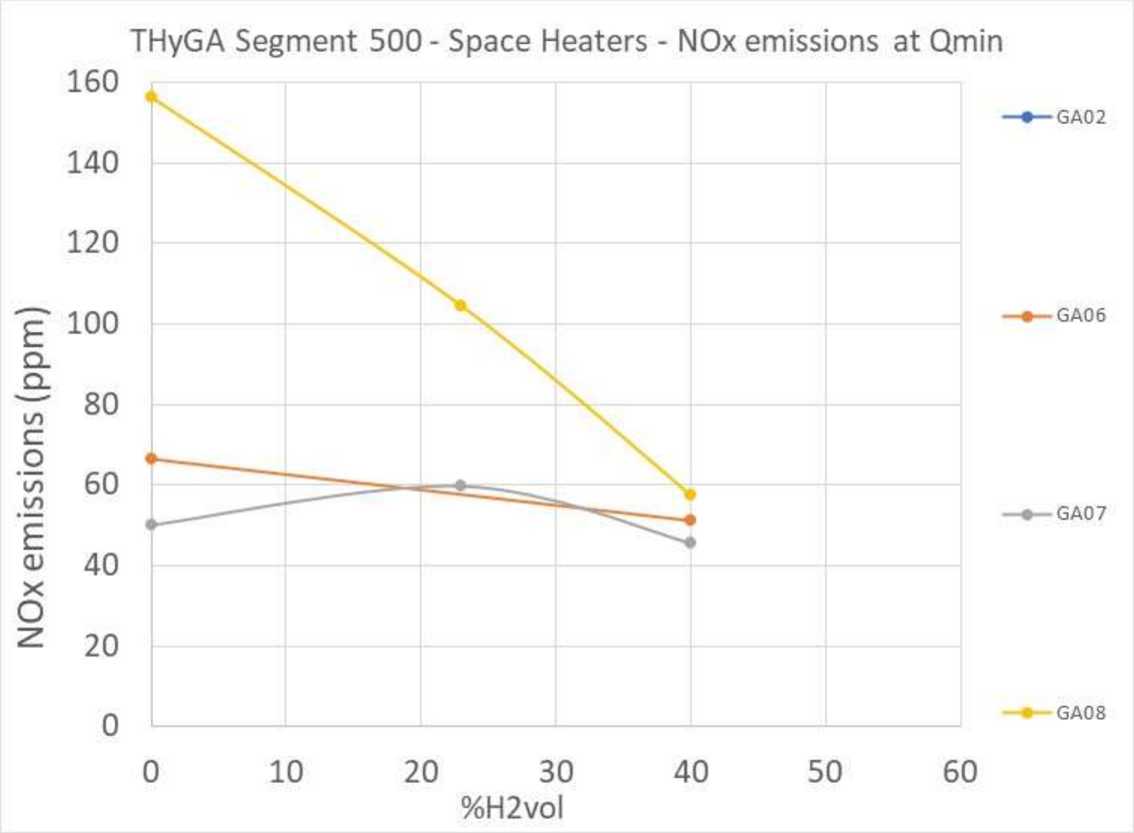


Figure 92: Segment 500 - NOx emissions at Qmin.

2.10.4.2 Unburned Hydrocarbons (UHC) and unburned hydrogen (UH)

UHC is discussed in section 3.5.

Fairly high concentrations are measured, both during the start/stop cycle and in a stabilised state. The high level of UHC in this kind of appliance is probably related to the the use of the decorative material (imitation of a burning real wood log) interfering with a clean combustion (see picture).

Figure 93: Example of fake wood in a gas fireplace (https://www.fairwaysfireplaces.co.uk/gas-fires/product/reflex-75t-icon).

2.10.5 Efficiency

Efficiency was not measured extensively for budget reasons (3-4 hours before appliance complete stabilisation).

However, the efficiency was measured here for two appliances showing the same trend (slight decrease of efficiency with H2%).

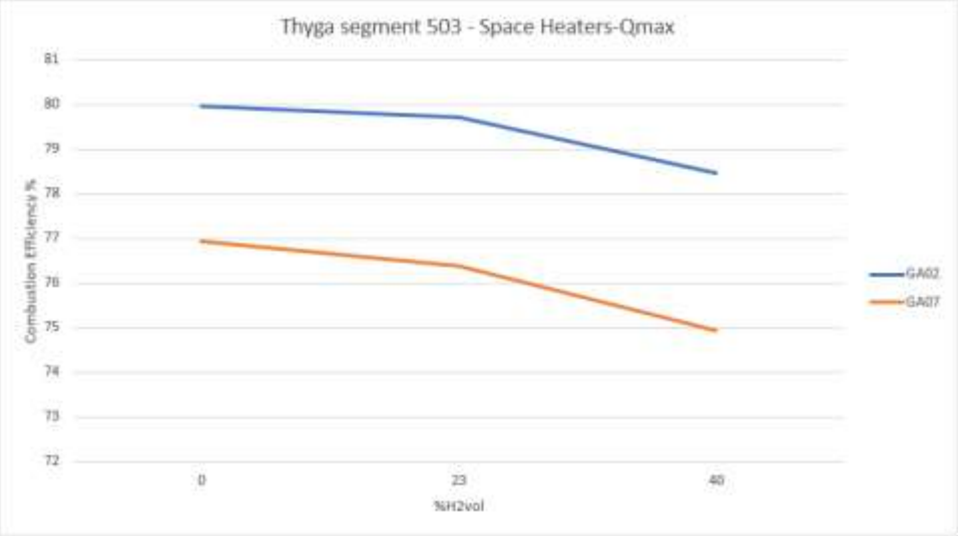


Figure 94: Segment 500 – Efficiency at Qmax

2.10.6 Operational

There is some impact of H2 on the flames.

Appearance of the flame:

It is observed that with white stones, the flame is blue and lower. This could be acceptable for people not used to it. After some time, it becomes yellow (like wood appliances).

Height of the flame

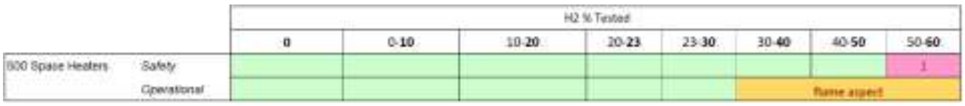
For GA08, when switching from G20-20mbar to a mixture with 40%H2-20mbar, it is clearly visible that the flame height becomes several centimeters smaller and at the same time more transparent. The manufacturer is convinced that, with a small adjustment, they can achieve the same flame pattern as with pure G20, but still consider the current pattern commercially acceptable.

Hot start

Issue was observed for high concentration of H2 (60%).

2.10.7 Conclusion for segment 500

Table 34: Conclusions for segment 500



		H2 % Tested							
		0	0-10	10-20	20-23	23-30	30-40	40-50	50-60
500 Space Heaters	Safety	🟩	🟩	🟩	🟩	🟩	🟩	🟩	1
	Operational	🟩	🟩	🟩	🟩	🟩	flame aspect		

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 500, a total of 4 appliances were tested. The number of appliances having issues are indicated in the red cells of the "impact card" above. Note that not all appliances may have issues for the same tests, and not all *tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.*

In this segment group, appliances can cope with up to 60% H2 where Flashback issues are observed.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

The test done on one of the appliances in this segment group shows issues for the test performed with 30% H2.

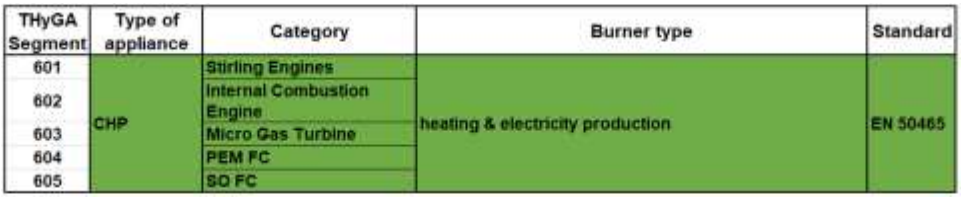
2.11 CHP (Segm. 600)

2.11.1 Appliances tested

Table 35: Characteristics of the 5 CHP tested.

Appliance ID	Segment	Qmin (kW)	Qmax (kW)
D11	602	30.5	49.6
GW09	602	9.7	19.5
EN20	603	9.4	20
GA12	604	NA	2
GA13	605	1.1	3.2

Table 36: Segmentation of the CHP category.



THyGA Segment	Type of appliance	Category	Burner type	Standard
601	CHP	Stirling Engines	heating & electricity production	EN 50465
602		Internal Combustion Engine		
603		Micro Gas Turbine		
604		PEM FC		
605		SO FC		

2.11.2 Pictures

Figure 95: Inhouse5000+ CHP (fuel cell) (https://www.inhouse-engineering.de/en/fuel-cell/chp/).

2.11.3 Safety

The following results were obtained:

Table 37: Segm 600 - Safety aspects

Appliance ID		D11	GW09	EN20	GA12	GA13
Segment		602	602	603	604	605
Qmin (kW)		30,5	9.7	9,4	NA	1,1
Qmax (kW)		49,6	19.5	20	2	3,2
Combustion control feature (Y/N)		Y	N	Y	NO	N
%H2 in test gas	**0**	X	X	X	X	X
	0-**10**		X	X	X	X
	10-**20**				X	X
	20-**23**	X	X	X	X	X
	23-**30**		X		X	X
	30-**40**	X	X			
	40-**50**		X			
	50-**60**					
1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X (30%)	X
1.2 Efficiency and emission EU LO	EU LOW + H2				X	
1.3 Efficiency and emission G23	G23 + H2		X		X	
1.4 Cold start	CH4+40%H2	X	X	X	X	
1.5 Hot start.	CH4+23% H2+40%H2(min)	X	X	X		
1.6 Low air temperature (- 10 C)	CH4 + H2					
1.7 Flue gas pipe length	CH4+30%H2					
1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X	X
1.9 Impact H2 flame detection.		X			X	X
1.10 Flash back		X	X	X	X	X
3.1 ADJUSTMENT A	EU HighEU Low+H2	X	NA	NA	NA	NA
3.2 ADJUSTMENT B	EU lowEU high+H2		NA	NA	NA	NA
3.3 ADJUSTMENT H	EU Low+H2EU high+H2		NA	NA	NA	NA
3.4 ADJUSTMENT G	EU Low+H2EU high+H2	X	NA	NA	NA	NA
4.1 Delayed ignition test.	CH4+30%H2					
4.2 Soundness						
4.3 Quick variation Qmin-Qmax	CH4+30%H2				X	X
4.4 Overheat. Meas. of temp.	CH4+30%H2					
4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA	NA
4.6 Influence of wind						
4.7 Long time (limited time)	depends on manufacturer					X
4.8 Fluctuation of the aux.						
4.9 Fluctuation of pressure	CH4+40%H2				X	X
Other /Operational					CO (30%)	

Note that for this group of segments the maximum H2 tested was only 23% (Micro Turbine) or 30% (the two Fuel cell appliances). This is due to manufacturer concern with testing those above the value given.

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

ICE Technology: Both D11 and GW09 systems run very well with up to at least 40%H2. No issues were observed at any time. The system also starts with 40%H2 without any problem. Short tests were made up to 60% H2 (D11).

The engine had a quieter operation with subjectively fewer vibrations when adding H2 (D11). Depending on initial setting the control system could max out when shifting from high quality gas to gas with lower calorific value. No safety issues were observed during the test.

Micro turbine EN20. The microturbine performed well between 0-23% H2. No flashback or damage to the turbine was observed. We did not test mixtures with more than 23%H2 because the manufacturer does not guarantee mixtures above this value.

Fuel cell PEM GA12. This PEM fuel cell functions correctly **with a hydrogen mixture of up to 25%.** At 30%H2 the CO value went too high, and the appliance went out (not in security, it stops working, a few hours later it starts up automatically). No flashback during the test program. If the H2 percentage becomes too high, it results in a higher CO concentration and the FC stops working.

Fuel cell SOFC GA13 The SOFC can basically operate with mixtures up to (and including) 30%H2, as long as the temperature of the stack is maintained.

CO emissions (dry air free)

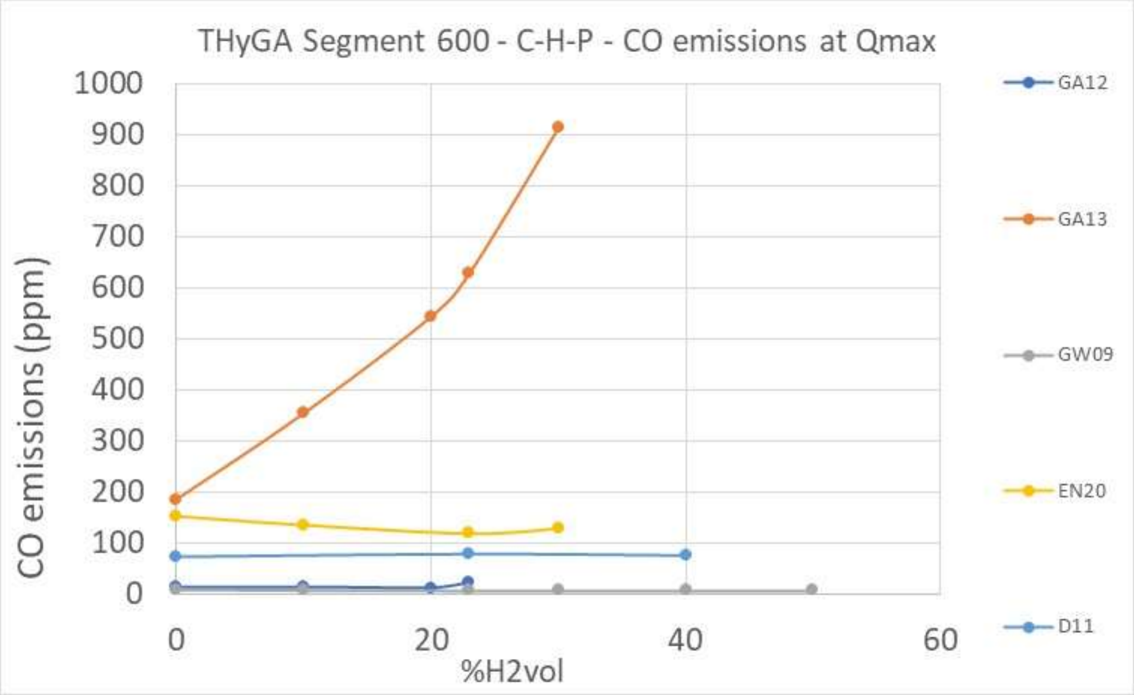


Figure 96: Segm 600 - CO emissions Qmax

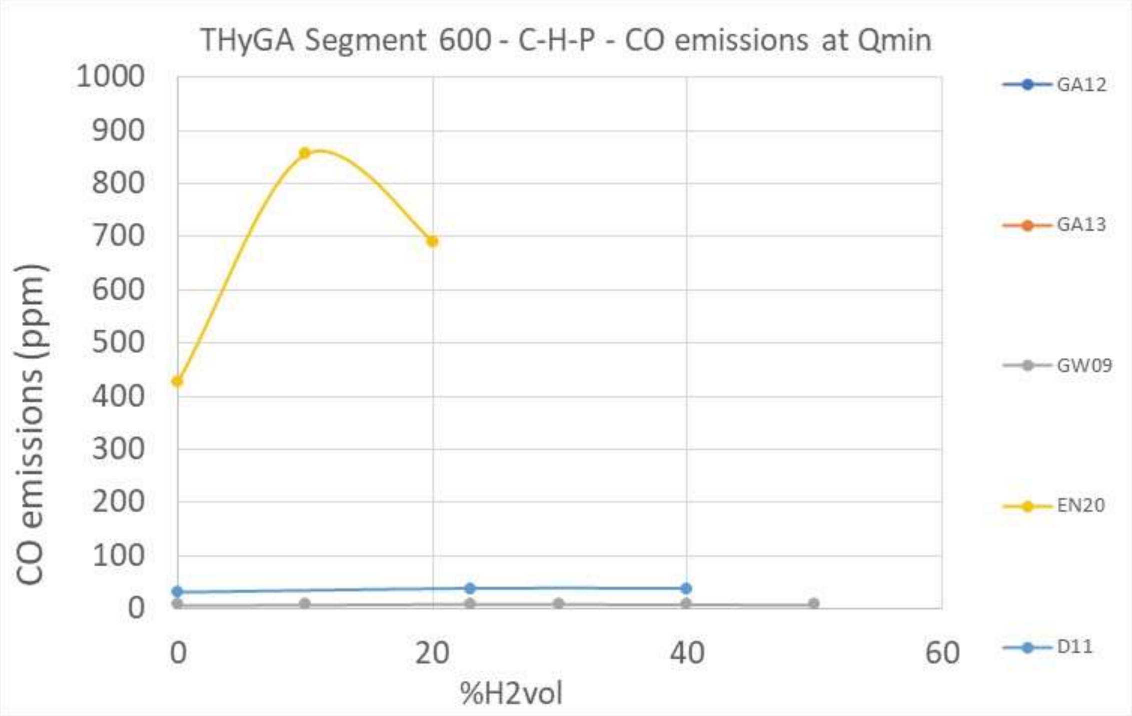


Figure 97: Segm 600 - CO emissions Qmin

2.11.4 Emissions

2.11.4.1 NOx (dry air free)

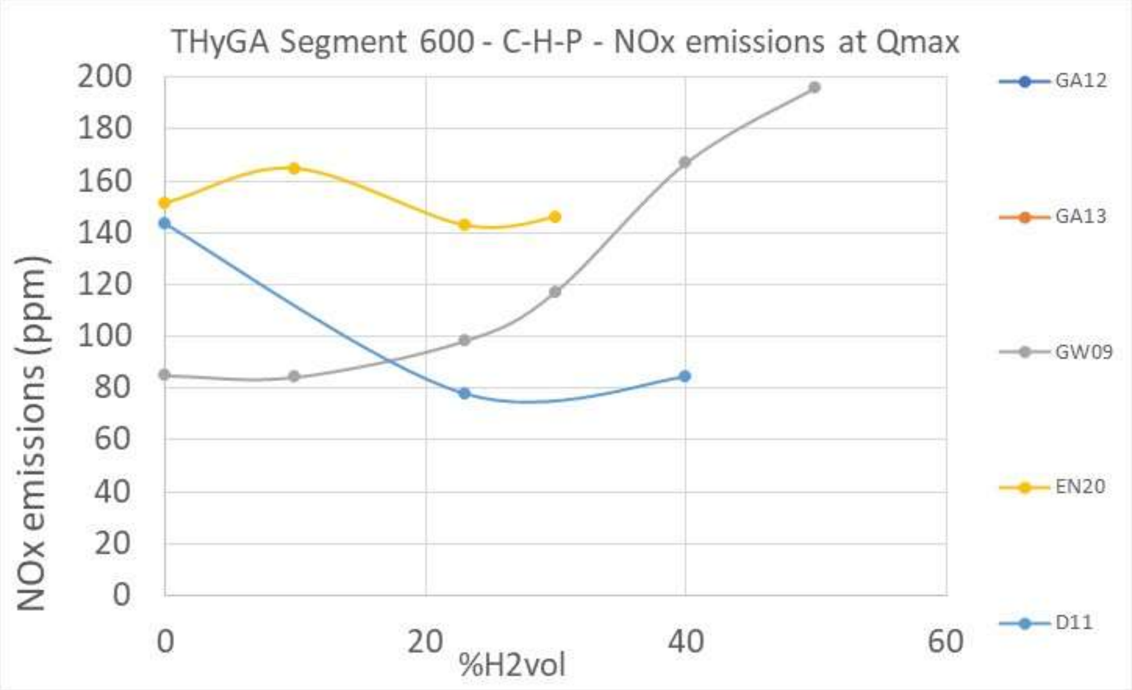


Figure 98: Segm 600 - NOx emissions Qmax

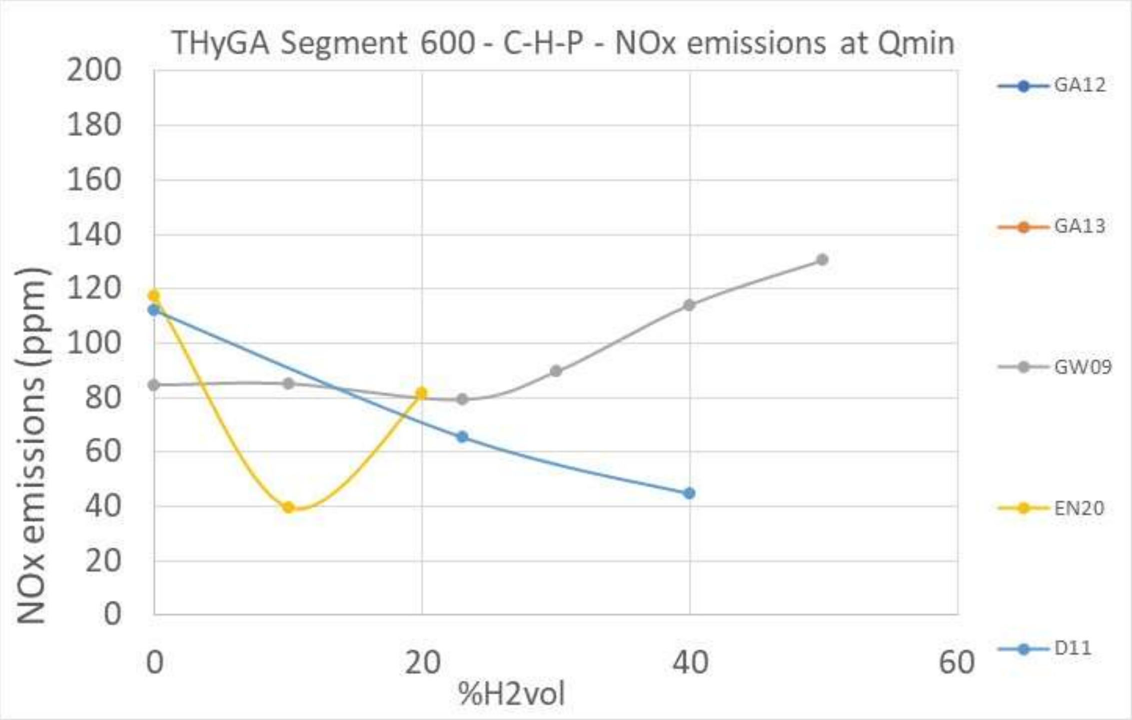


Figure 99: Segm 600 - NOx emissions Qmin

2.11.4.2 Unburned Hydrocarbons (UHC)

No measurement was made for this segment group.

2.11.5 Efficiency

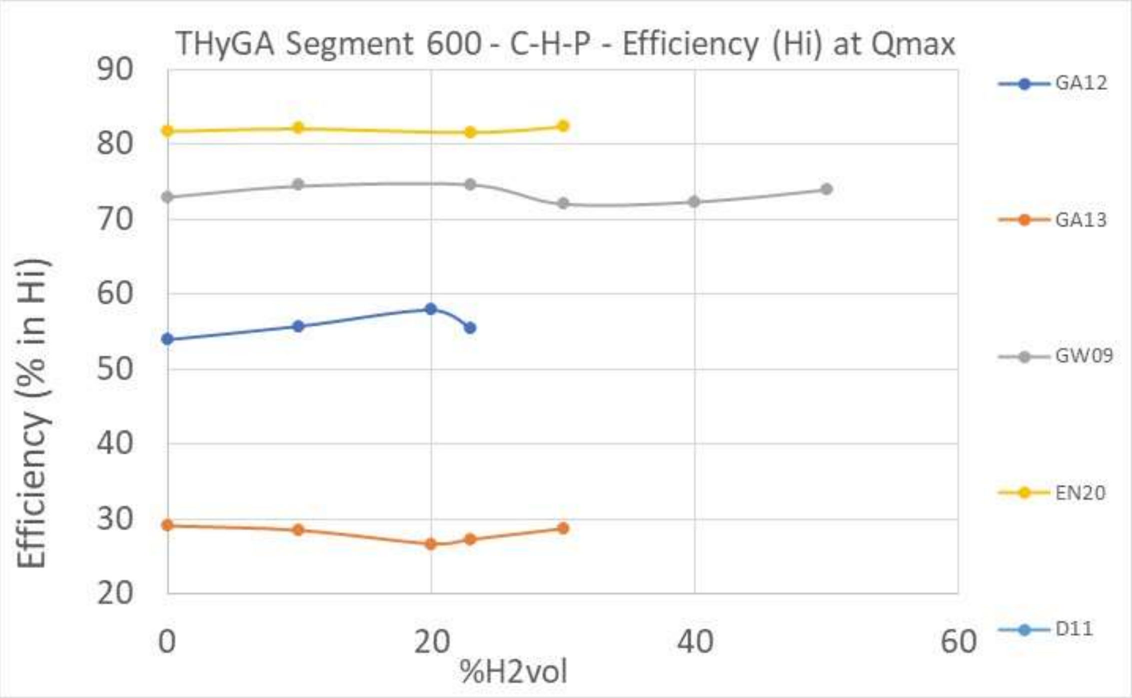


Figure 100: Segm 600 - Efficiency Qmax

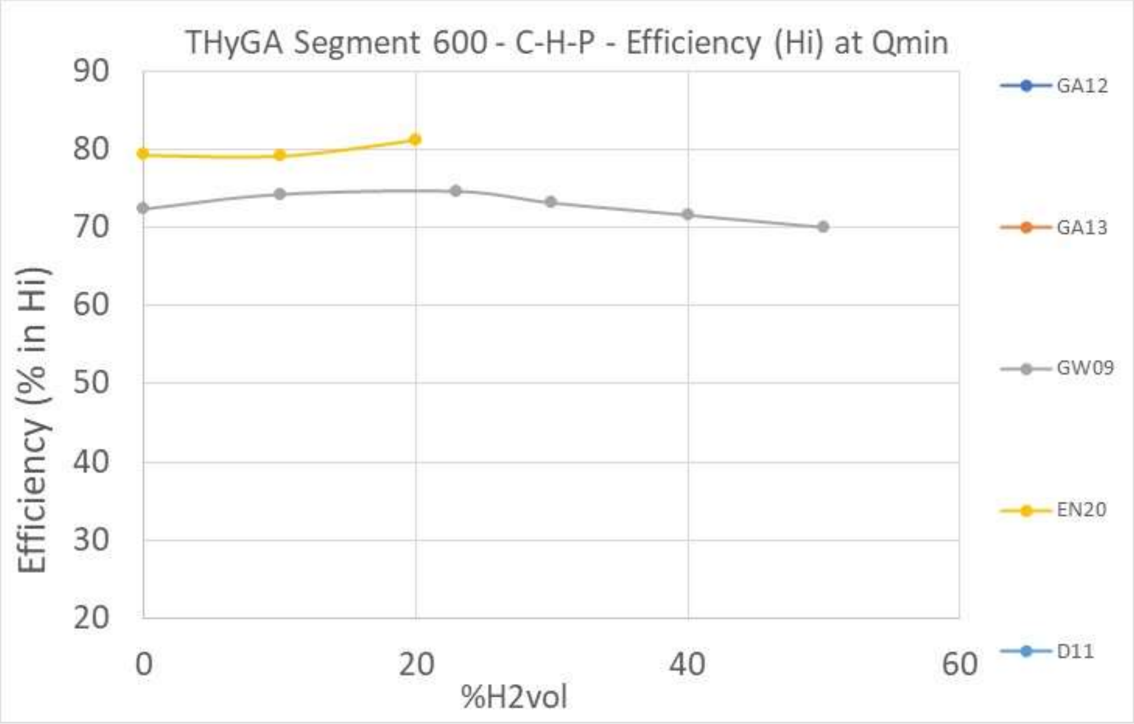


Figure 101: Segm 600 - Efficiency Qmin

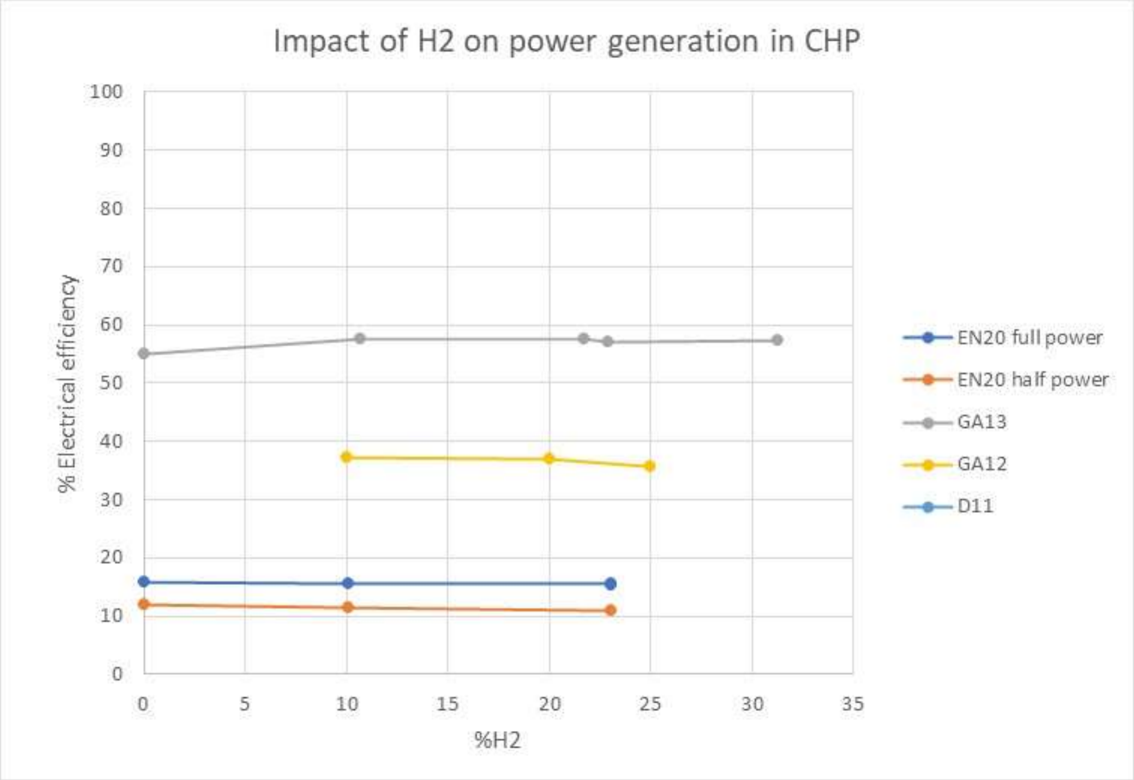


Figure 102: Impact of H2 on power generation in CHP

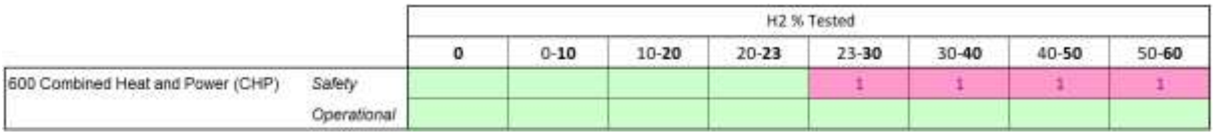
There is no impact of H2 on efficiency.

2.11.6 Operational

Apart from the issue mentioned for the Fuel cell PEM GA12 for which the CO value went too high resulting in the appliance going out, no other issue was reported.

2.11.7 Conclusion for segment 600

Table 38: Conclusions for segment 600



		H2 % Tested							
		0	0-10	10-20	20-23	23-30	30-40	40-50	50-60
600 Combined Heat and Power (CHP)	*Safety*	🟩	🟩	🟩	🟩	🟥 1	🟥 1	🟥 1	🟥 1
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 600, a total of 5 appliances were tested. Some has been tested only up to 23% H2.

One appliance (one of the Fuel cell appliances) has given high CO value already from 25% H2.

The number of appliances having issues are indicated in the red cells of the "impact card" above. Note that not all appliances may have issues for the same tests, and not all tests have been done on all appliances. For the details of issues observed, please check the extensive result table at the beginning of this section regarding this segment group.

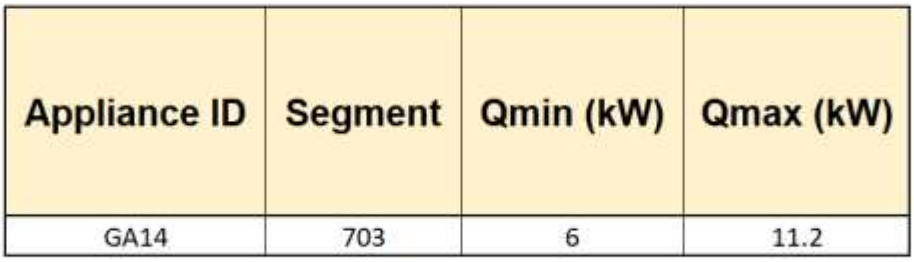
As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

2.12 Heat Pump (Segm. 700)

2.12.1 Appliances tested

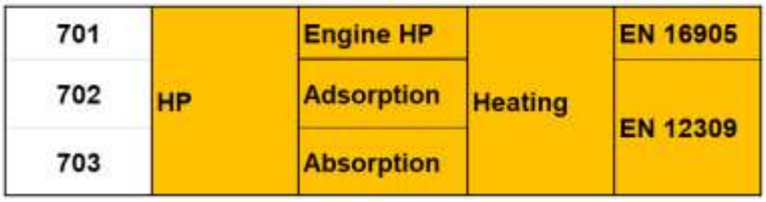
Only one appliance was tested (an adsorption heat pump).

Table 39: Characteristics of the tested heat pump



Appliance ID	Segment	Qmin (kW)	Qmax (kW)
GA14	703	6	11.2

Table 40: Segmentation of the heat pump category.

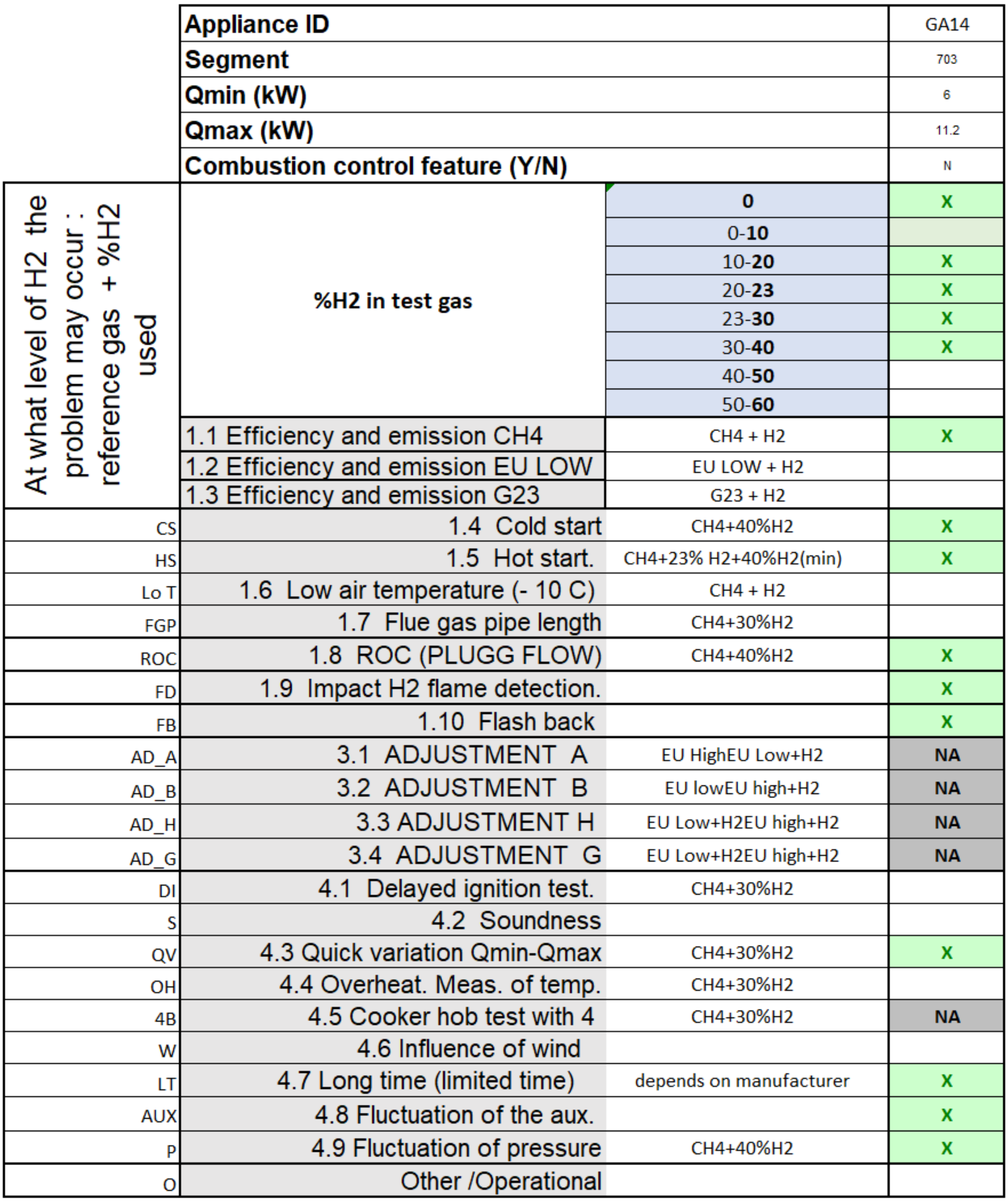


701	HP	Engine HP	Heating	EN 16905
702		Adsorption		EN 12309
703		Absorption		

2.12.2 Safety

The following results were obtained:

Table 41: Segm 700 - Safety aspects



	Appliance ID		GA14
	Segment		703
	Qmin (kW)		6
	Qmax (kW)		11.2
	Combustion control feature (Y/N)		N
At what level of H2 the problem may occur : reference gas + %H2 used	%H2 in test gas	0	X
		0-10	
		10-20	X
		20-23	X
		23-30	X
		30-40	X
		40-50	
		50-60	
	1.1 Efficiency and emission CH4	CH4 + H2	X
	1.2 Efficiency and emission EU LOW	EU LOW + H2	
	1.3 Efficiency and emission G23	G23 + H2	
CS	1.4 Cold start	CH4+40%H2	X
HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X
Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2	
FGP	1.7 Flue gas pipe length	CH4+30%H2	
ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X
FD	1.9 Impact H2 flame detection.		X
FB	1.10 Flash back		X
AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA
AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA
AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA
AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA
DI	4.1 Delayed ignition test.	CH4+30%H2	
S	4.2 Soundness		
QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X
OH	4.4 Overheat. Meas. of temp.	CH4+30%H2	
4B	4.5 Cooker hob test with 4	CH4+30%H2	NA
W	4.6 Influence of wind		
LT	4.7 Long time (limited time)	depends on manufacturer	X
AUX	4.8 Fluctuation of the aux.		X
P	4.9 Fluctuation of pressure	CH4+40%H2	X
O	Other /Operational		

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟥	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

The heat pump can handle mixtures up to and including 40% H2. We have not observed any issues including operation test for cold and hot start-up.

Due to unburned H2 in the environment caused by a leaking burner gasket, the test program was not fully completed at 40%H2.

CO emissions (dry air free)

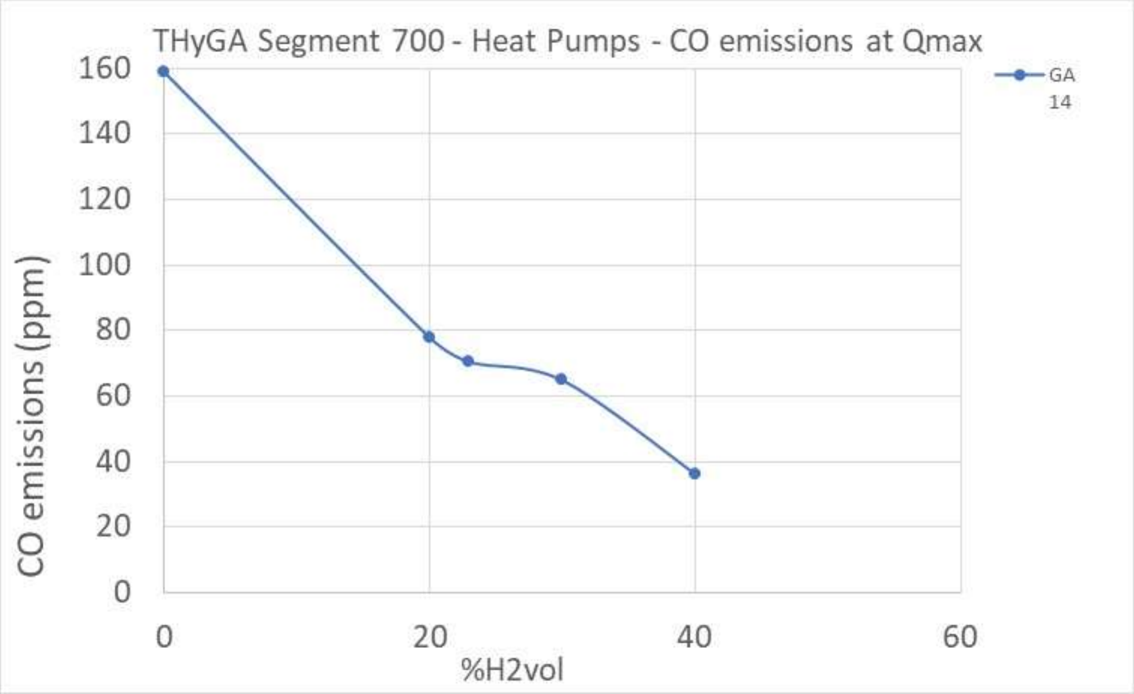


Figure 103: Segm 700 - CO emissions Qmax

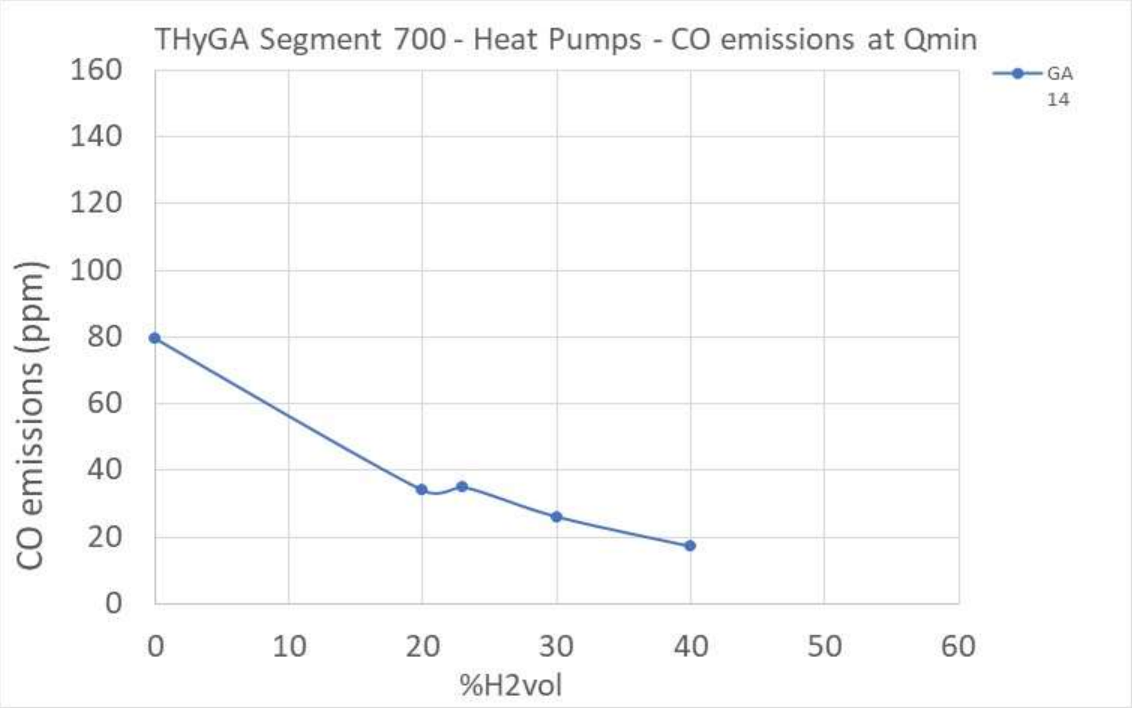


Figure 104: Segm 700 - CO emissions Qmin

2.12.3 Emissions

2.12.3.1.1 NOx (dry air free)

Both NO_x and CO are decreasing with H2.

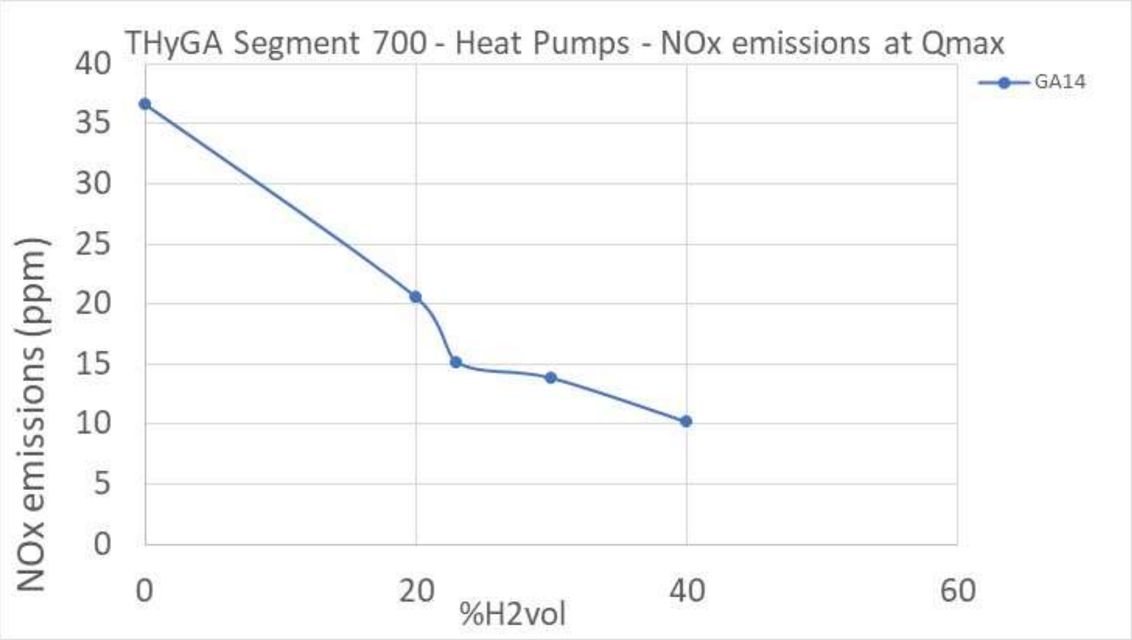


Figure 105: Segm 700 - NOx emissions Qmax.

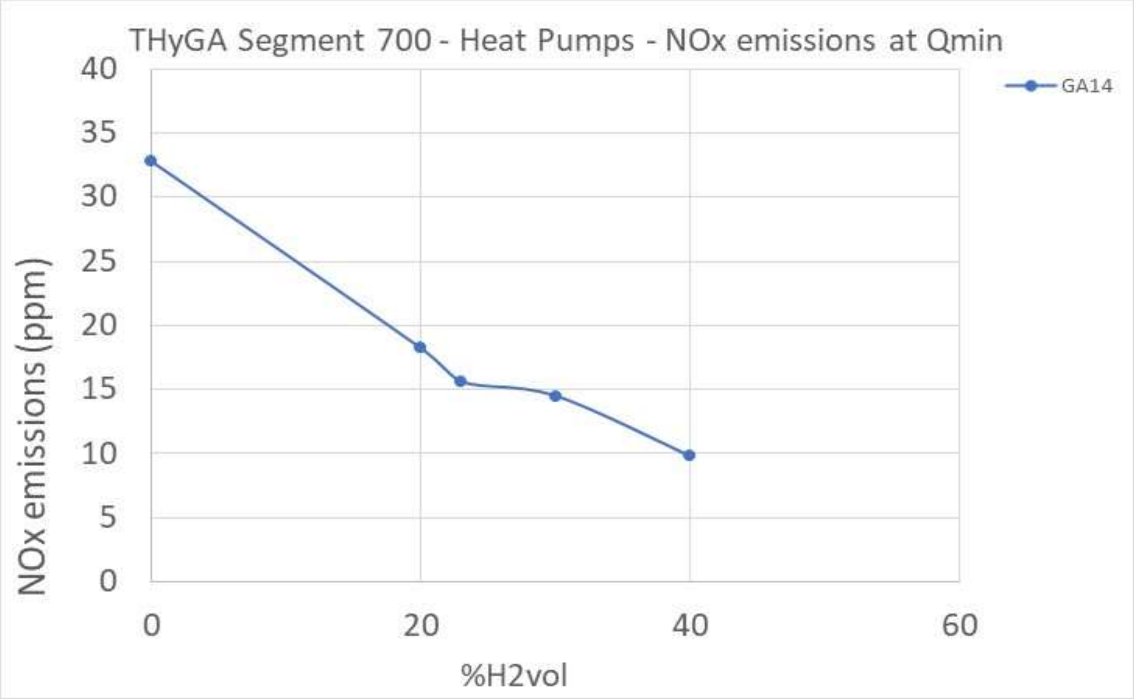


Figure 106: Segm 700 - NOx emissions Qmin.

2.12.4.2. Unburned Hydrocarbons (UHC)

No measurement were made for this segment group.

2.12.4 Efficiency

The efficiency measured at Qmax can be considered as constant. The "bump" for 23% H2 is most probably linked to testing issues.

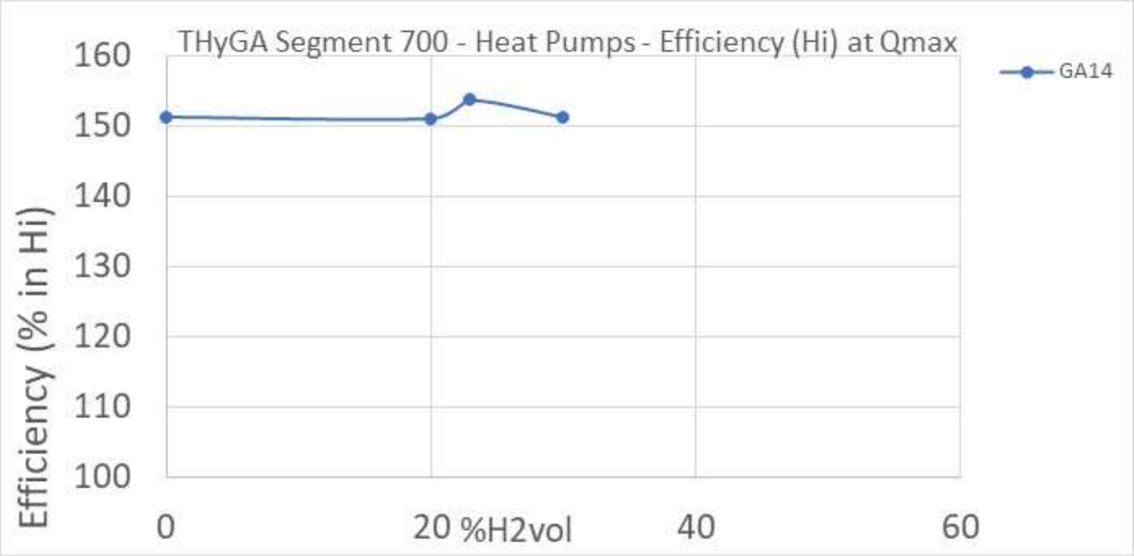


Figure 107: Segm 700 - Efficiency Qmax

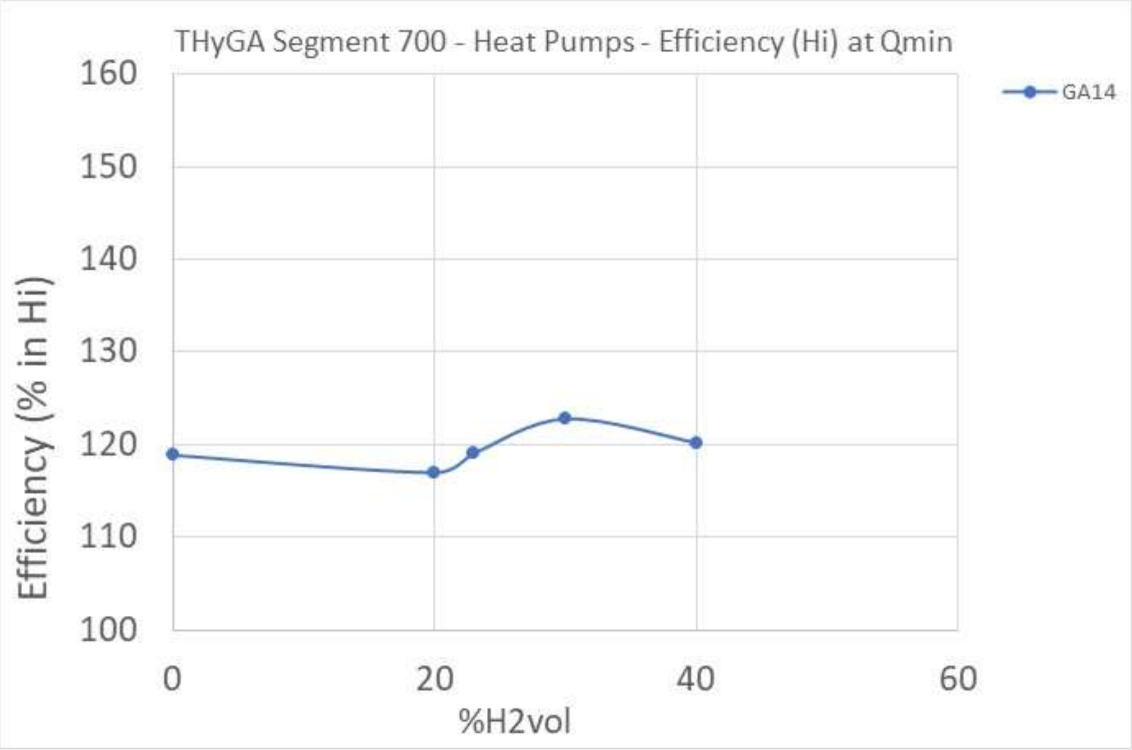


Figure 108: Segm 700 - Efficiency Qmin

2.12.5 Operational

No issues observed.

2.12.6 Conclusion for segment 700

Note that the conclusion below is based on a single test.

Table 42: Conclusions for segment 700

		H2 % Tested							
		0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
700 Gas Heat Pumps (GHP)	*Safety*	🟩	🟩	🟩	🟩	🟩	🟩		
	Operational	🟩	🟩	🟩	🟩	🟩	🟩		

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 700, only 1 appliance was tested.

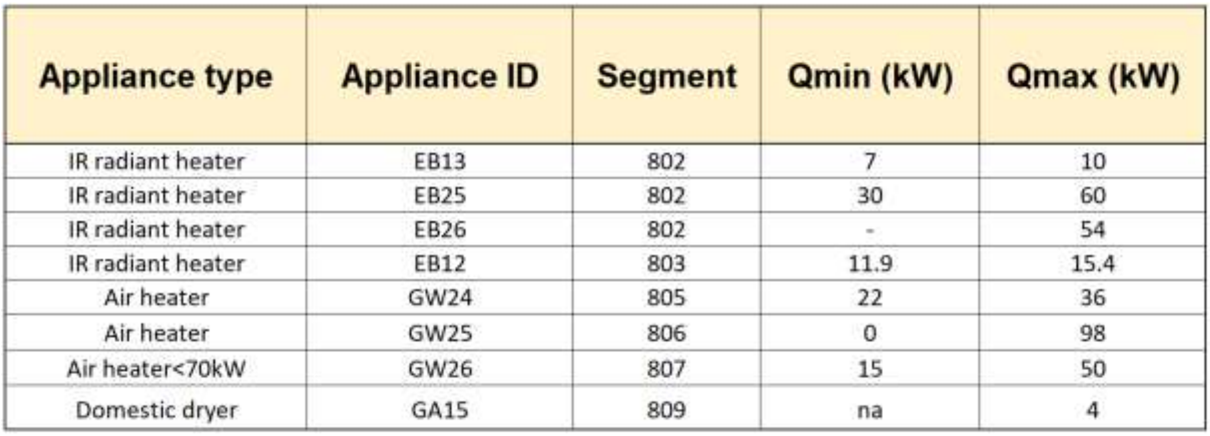
One heat pump was tested with up to 40% H2 and no issue was observed.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

2.13 Radiant heater & non dom. air heaters (Segm. 800)

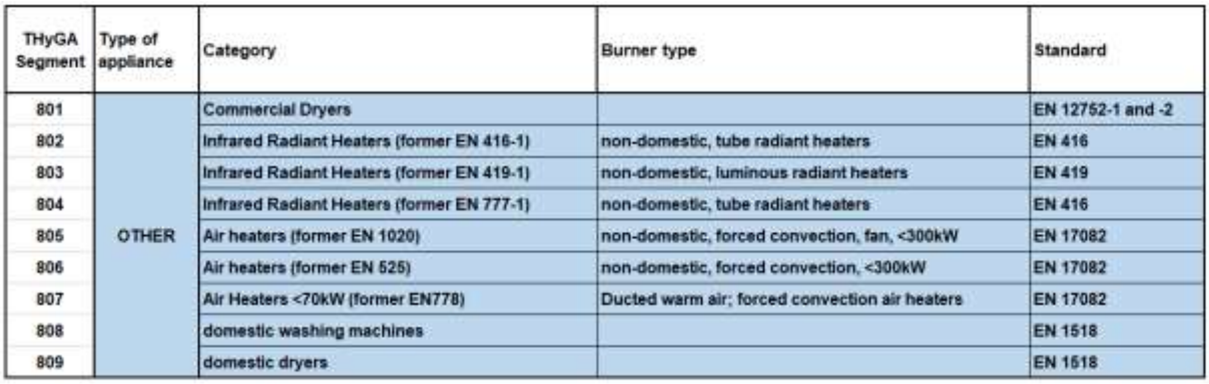
2.13.1 Appliances tested

Table 43: Characteristics of the 4 radiant heaters, 3 air heaters and domestic dryer that were tested.



Appliance type	Appliance ID	Segment	Qmin (kW)	Qmax (kW)
IR radiant heater	EB13	802	7	10
IR radiant heater	EB25	802	30	60
IR radiant heater	EB26	802	-	54
IR radiant heater	EB12	803	11.9	15.4
Air heater	GW24	805	22	36
Air heater	GW25	806	0	98
Air heater<70kW	GW26	807	15	50
Domestic dryer	GA15	809	na	4

Table 44: Segmentation of the dryers and heaters category



THyGA Segment	Type of appliance	Category	Burner type	Standard
801	OTHER	Commercial Dryers		EN 12752-1 and -2
802		Infrared Radiant Heaters (former EN 416-1)	non-domestic, tube radiant heaters	EN 416
803		Infrared Radiant Heaters (former EN 419-1)	non-domestic, luminous radiant heaters	EN 419
804		Infrared Radiant Heaters (former EN 777-1)	non-domestic, tube radiant heaters	EN 416
805		Air heaters (former EN 1020)	non-domestic, forced convection, fan, <300kW	EN 17082
806		Air heaters (former EN 525)	non-domestic, forced convection, <300kW	EN 17082
807		Air Heaters <70kW (former EN778)	Ducted warm air; forced convection air heaters	EN 17082
808		domestic washing machines		EN 1518
809		domestic dryers		EN 1518

2.13.2 Pictures

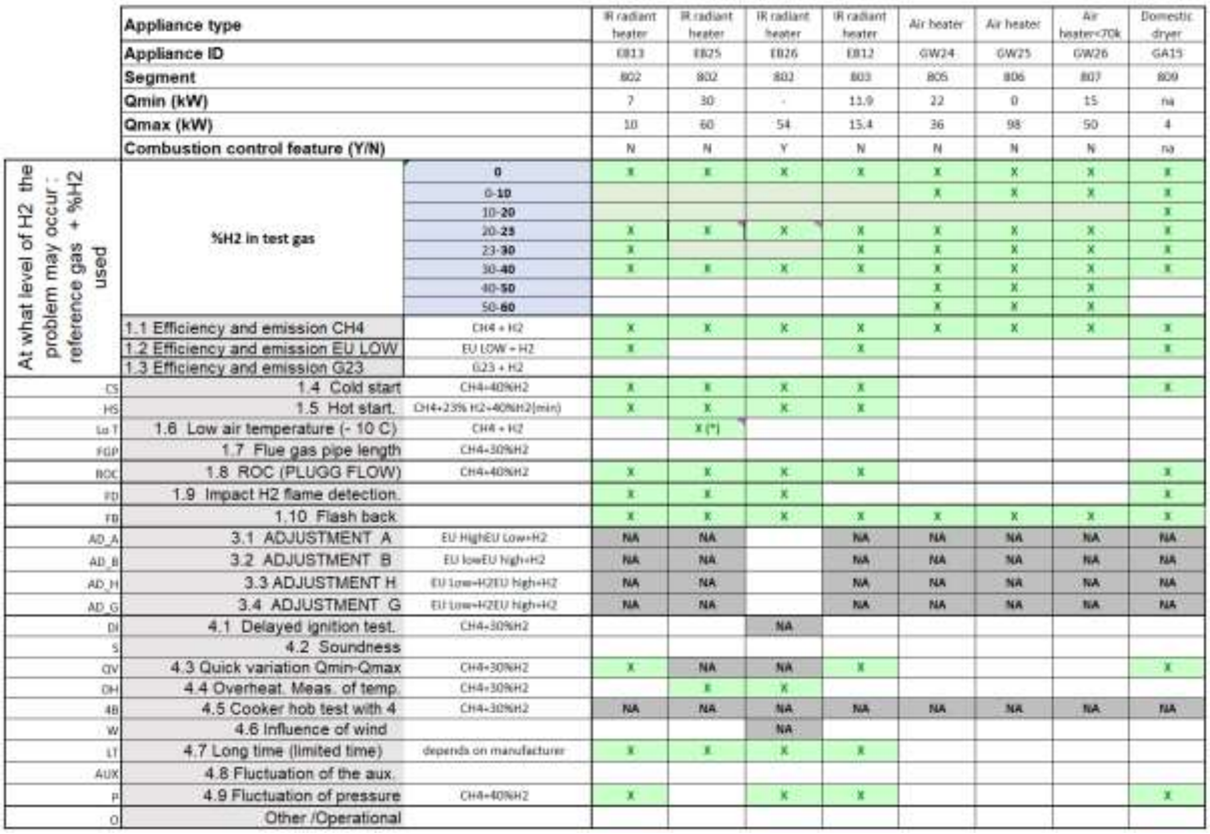
Figure 109 : Example for radiant tube heater [source: GoGaS Goch GmbH & Co. KG, Zum Ihnedieck 18, 44265 Dortmund].

Figure 110 : Example for radiant luminous heater [source: GoGaS Goch GmbH & Co. KG, Zum Ihnedieck 18, 44265 Dortmund].

2.13.3 Safety

The following results were obtained:

Table 45: Segm 800 - Safety aspects



		Appliance type		IR radiant heater	IR radiant heater	IR radiant heater	IR radiant heater	Air heater	Air heater	Air heater<70k	Domestic dryer
		Appliance ID		EB13	EB25	EB26	EB12	GW24	GW25	GW26	GA15
		Segment		802	802	802	803	805	806	807	809
		Qmin (kW)		7	30	-	11.9	22	0	15	na
		Qmax (kW)		10	60	54	15.4	36	98	50	4
		Combustion control feature (Y/N)		N	N	Y	N	N	N	N	na
At what level of H2 the problem may occur : reference gas + %H2 used		**%H2 in test gas**	**0**	X	X	X	X	X	X	X	X
			0-**10**					X	X	X	X
			10-**20**								X
			20-**25**	X	X	X	X	X	X	X	X
			23-**30**	X			X	X	X	X	X
			30-**40**	X	X	X	X	X	X	X	X
			40-**50**					X	X	X	
			50-**60**					X	X	X	
		1.1 Efficiency and emission CH4	CH4 + H2	X	X	X	X	X	X	X	X
		1.2 Efficiency and emission EU LOW	EU LOW + H2	X			X				X
		1.3 Efficiency and emission G23	G23 + H2								
	CS	1.4 Cold start	CH4+40%H2	X	X	X	X				X
	HS	1.5 Hot start.	CH4+23% H2+40%H2(min)	X	X	X	X				
	Lo T	1.6 Low air temperature (- 10 C)	CH4 + H2		X (*)						
	FGP	1.7 Flue gas pipe length	CH4+30%H2								
	ROC	1.8 ROC (PLUGG FLOW)	CH4+40%H2	X	X	X	X				X
	FD	1.9 Impact H2 flame detection.		X	X	X					X
	FB	1.10 Flash back		X	X	X	X	X	X	X	X
	AD_A	3.1 ADJUSTMENT A	EU HighEU Low+H2	NA	NA		NA	NA	NA	NA	NA
	AD_B	3.2 ADJUSTMENT B	EU lowEU high+H2	NA	NA		NA	NA	NA	NA	NA
	AD_H	3.3 ADJUSTMENT H	EU Low+H2EU high+H2	NA	NA		NA	NA	NA	NA	NA
	AD_G	3.4 ADJUSTMENT G	EU Low+H2EU high+H2	NA	NA		NA	NA	NA	NA	NA
	DI	4.1 Delayed ignition test.	CH4+30%H2			NA					
	S	4.2 Soundness									
	QV	4.3 Quick variation Qmin-Qmax	CH4+30%H2	X	NA	NA	X				X
	OH	4.4 Overheat. Meas. of temp.	CH4+30%H2		X	X					
	4B	4.5 Cooker hob test with 4	CH4+30%H2	NA	NA	NA	NA	NA	NA	NA	NA
	W	4.6 Influence of wind				NA					
	LT	4.7 Long time (limited time)	depends on manufacturer	X	X	X	X				
	AUX	4.8 Fluctuation of the aux.									
	P	4.9 Fluctuation of pressure	CH4+40%H2	X		X	X				X
	O	Other /Operational									

(*) Test 1.6 has been carried out at 0°C.

X	Test realized and no issues
🟩	Test has not been done with this %H2, but at lower and higher %H2, we consider "no issue"
X	Test realized and issue
🟪	Test has not been done with this %H2, but at lower and higher %H2, we consider "issue"
X	Potential issue (noise, atypic behavior) but not linked to safety
🟨	Test has not been done with this %H2, but at lower and higher %H2, we consider "potential issue"
NA	Test non applicable
	Not tested

Overall observations on safety results

All appliances (radiant heaters, air heaters, tumble dryers) performed well up to 40% and some up to 60%.

CO (dry air free)

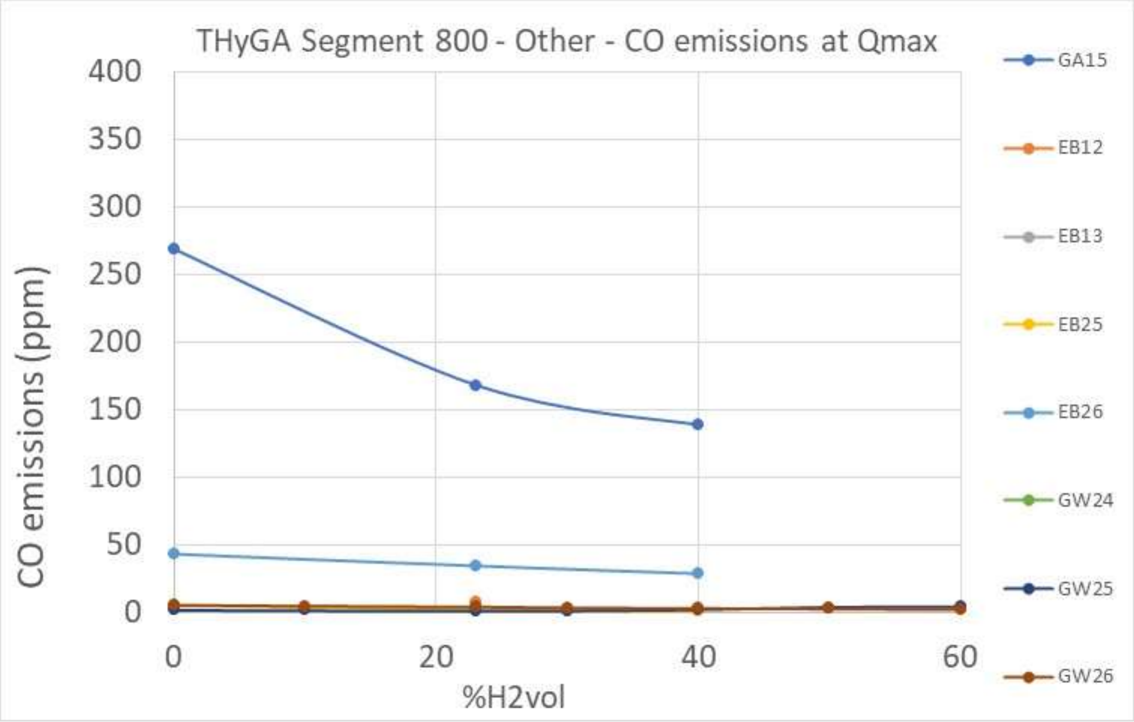


Figure 111: Segm 800 - CO emissions Qmax.

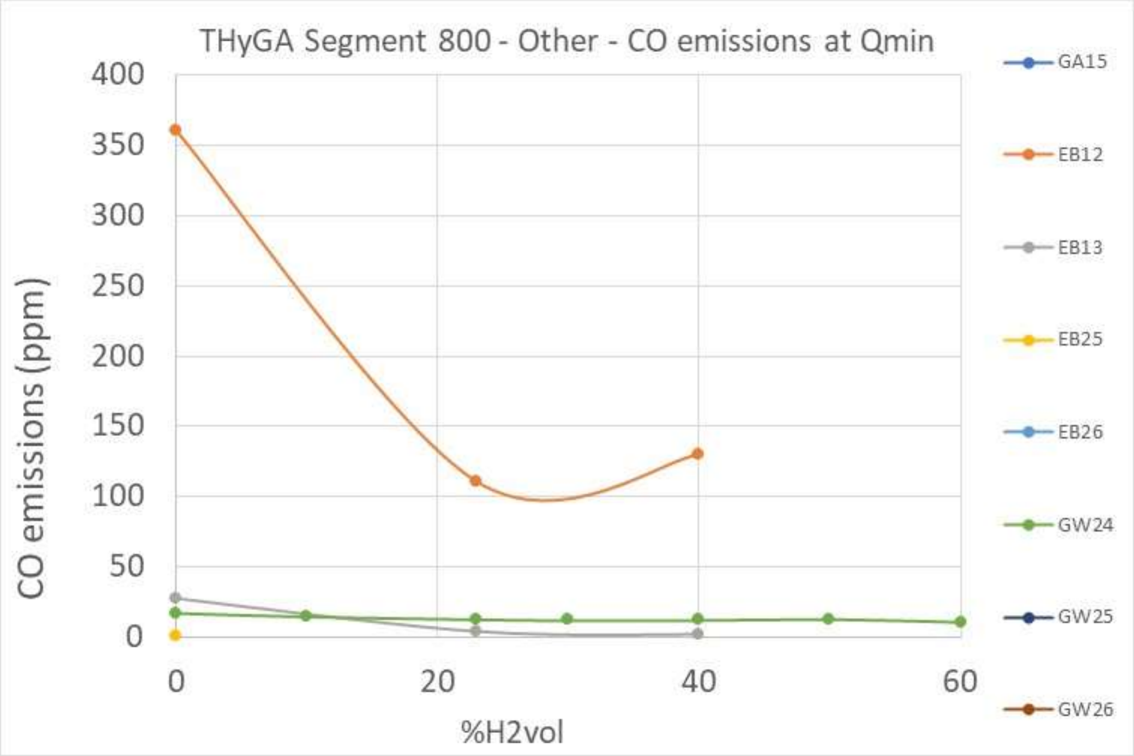


Figure 112: Segm 800 - CO emissions Qmin.

2.13.4 Emissions

2.13.4.1.1 NOx (dry air free)

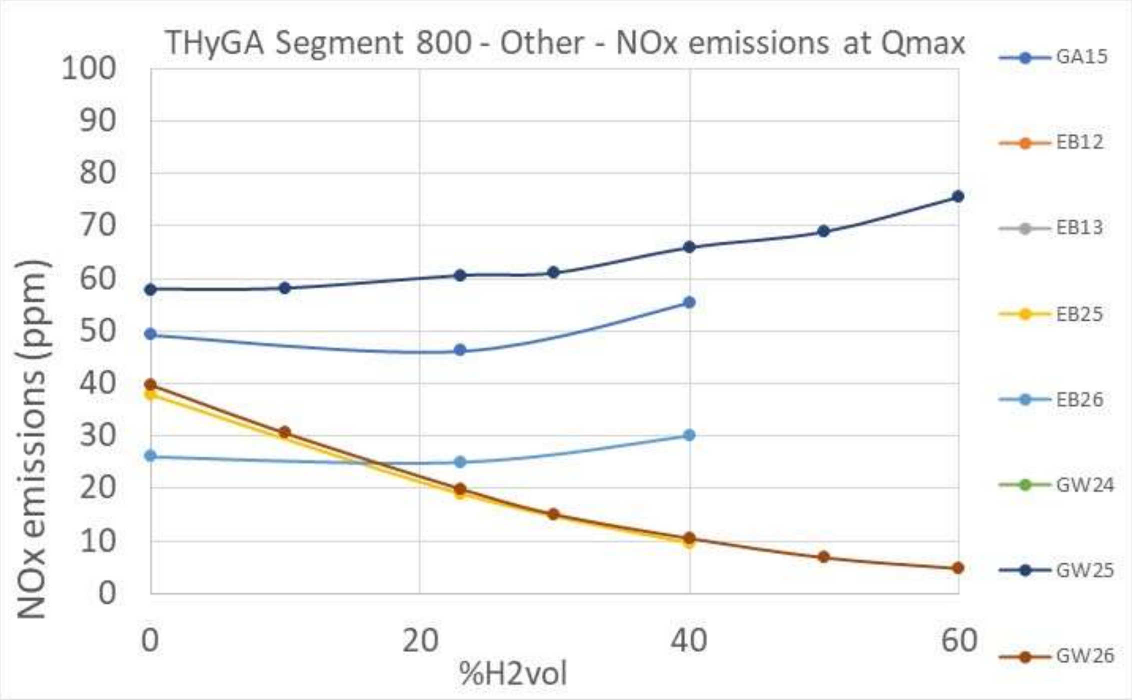


Figure 113: Segm 800 - NOx emissions Qmax.

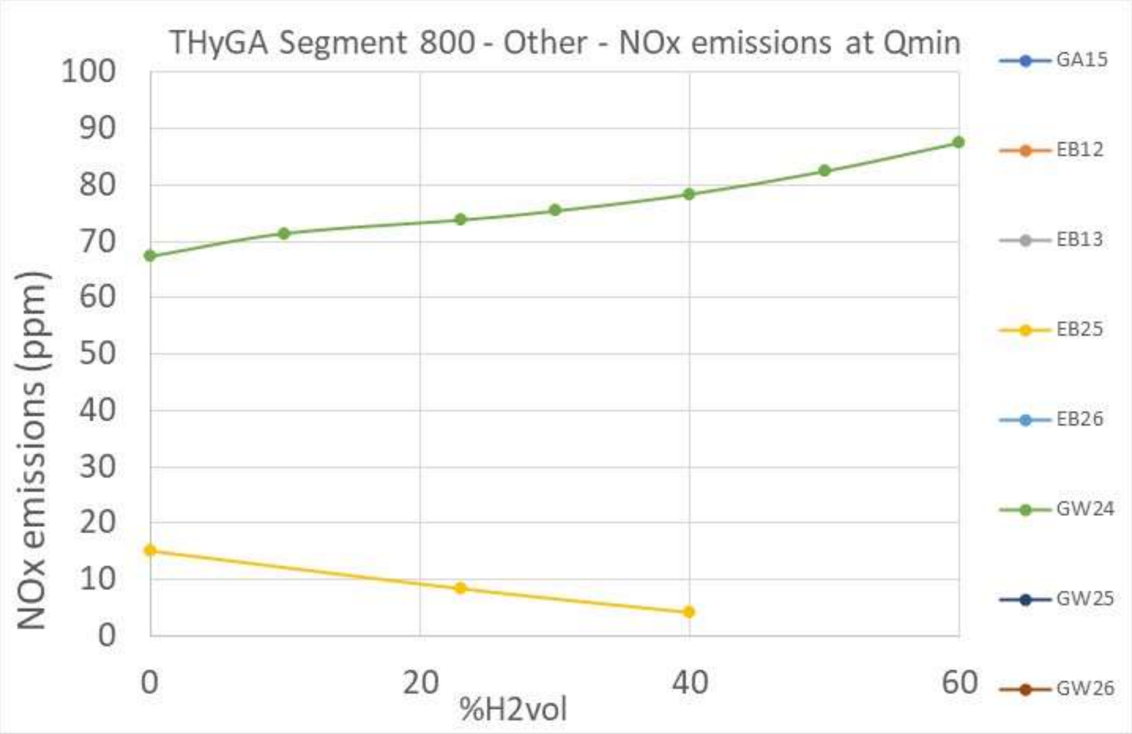


Figure 114: Segm 800 - NOx emissions Qmin.

2.12.4.2. Unburned Hydrocarbons (UHC)

See section 5.4.

2.13.5 Efficiency

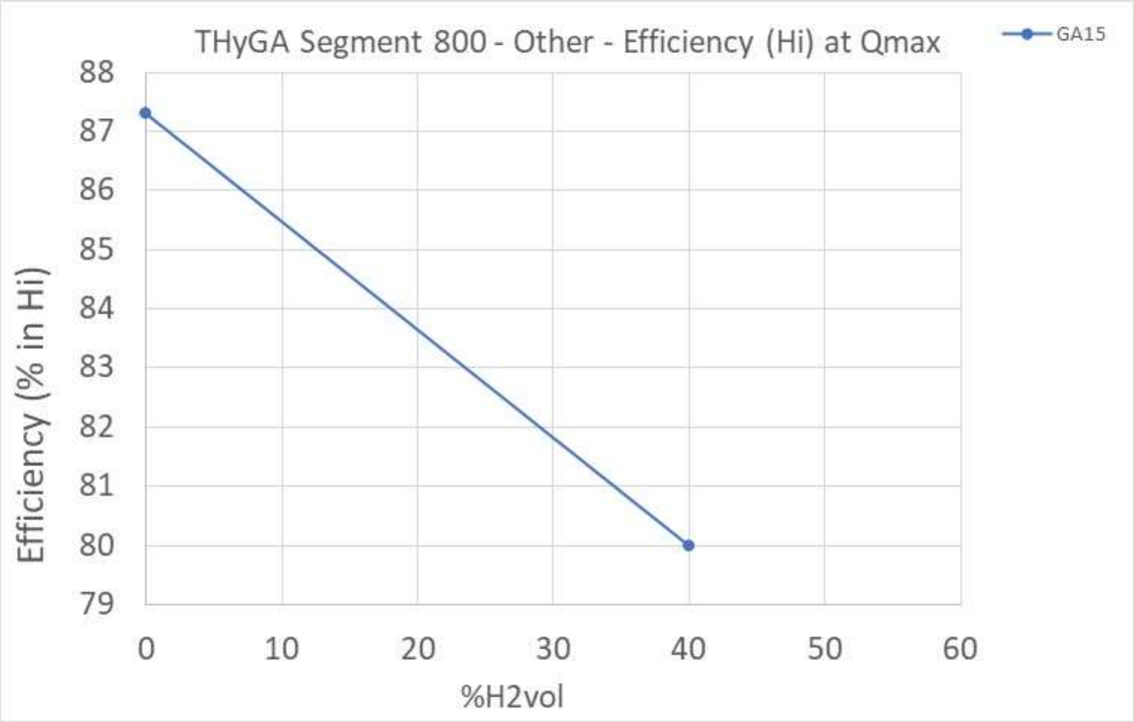


Figure 115: Segm 800 - Efficiency Qmax

Here we see a decrease in efficiency.

2.13.6 Operational

No operational issues were observed.

2.13.7 Conclusion for segment 800

Table 46: Conclusions for segment 800

		H2 % Tested							
		0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
800 Radiant heater & commercial a	*Safety*	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Note that the above table doesn't take into account the delayed ignition with H2 blends. See the specific section on this topic.

For segment 800, a total of 8 appliances were tested. The number of appliances having issues are indicated in the red cells of the "impact card" above.

No safety issue was observed with those appliances tested with up to 40% H2 (some with 60%).

High CO values with CH_4 were observed on one appliance and the addition of H2 has the effect of decreasing the emissions.

As mentioned, it is important to keep in mind that the table and results above do not consider the results obtained at the end of the project on delayed ignition. Delayed ignition is discussed extensively in section 3.3.

3 Horizontal analysis of the results for some parameters

3.1 Impact of hydrogen on the heat input (for all segments)

3.1.1 Introduction, qualitative analysis

Obviously, H2 impacts the Wobbe index and calorific value of the gas, and this will result in a decrease of the heat input unless compensated. However, in practice, the flow of gas may just be increased (e.g. by increasing the pressure) and can thus be compensating some of the decrease in energy brought to the appliance. This scenario was not tested, as most of the end-users (in domestic sector) will not have the possibility to interact with the appliances if H2 is injected in the grid.

The heat input reduction may be a sensitive parameter for some utilizations, and ultimately some of the end users may complain about the appliances no longer providing the service they bought it for. The main consequences:

- For cooking, it will increase the heating time.
- For hot water production it will reduce the amount of produced hot water in an equivalent time, potentially bringing discomfort.
- For heating appliances like boilers, it should not be a problem as those are generally oversized. However, it can be an issue for appliances chosen to just cover the maximum heat demand without oversizing. In this case, the appliances may not be able to cover the heat need in the coldest winter days.

3.1.2 Impact of H2 on Hi, density and Wobbe (theoretical)

The following impact is calculated with the THyGA datasheet:

Table 47: Absolute impact of H2 on Hi, density and Wobbe (15C/15C)H2.

CH4	H2	Ws	d	Hi	Hs
Vol.(-)	Vol.(-)	[MJ/m³]	(-)	[MJ/m³]	[MJ/m³]
100	0	53.47	0.56	35.82	39.84
90	10	52.17	0.51	33.31	37.13
80	20	50.87	0.46	30.81	34.43
70	30	49.58	0.41	28.31	31.72
60	40	48.30	0.36	25.80	29.02
50	50	47.08	0.31	23.30	26.31
40	60	45.96	0.26	20.79	23.61
0	100	48.46	0.07	10.78	12.79

Table 48: Relative impact of H2 on Hi, density and Wobbe.

CH4	H2	Ws	d	Hi	Hs
Vol.(-)	Vol.(-)	%	%	%	%
100	0	100%	100%	100%	100%
90	10	98%	91%	93%	93%
80	20	95%	83%	86%	86%
70	30	93%	74%	79%	80%
60	40	90%	65%	72%	73%
50	50	88%	56%	65%	66%
40	60	86%	48%	58%	59%
0	100	91%	13%	30%	32%

As seen on Figure 116 and Figure 117 the relative variation of Wobbe and Hi is very much different from each other: The Hi decreases stronger than the Wobbe Index (linear), while the Wobbe Index (not linear) shows "only" a reduction by 16% at 60% H2 (compared to 42% for the Hi).

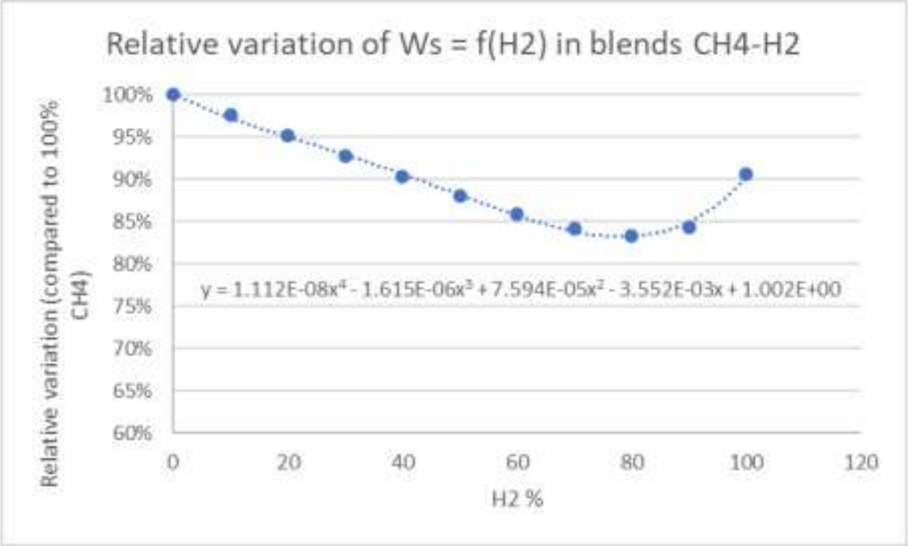


Figure 116: Relative variation of Ws = f(H2) in blends CH4-H2.

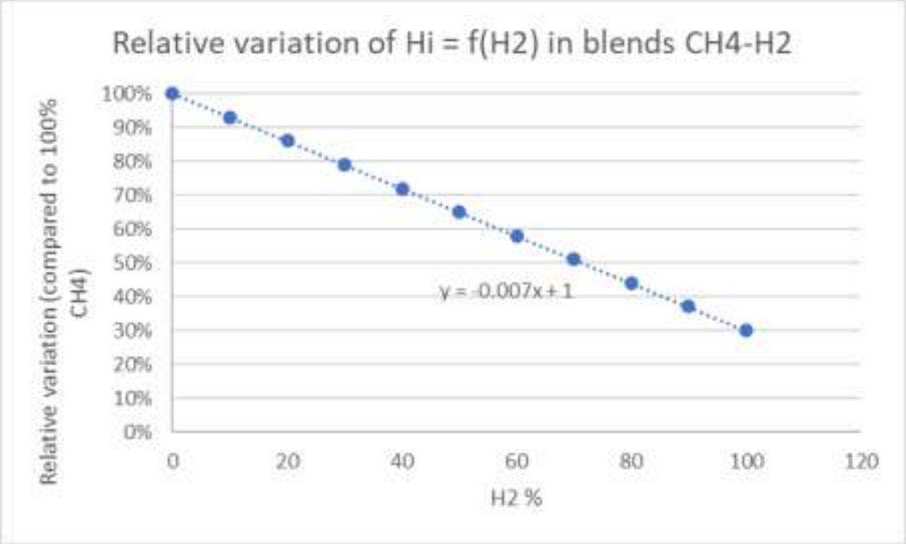


Figure 117: Relative variation of Hi = f(H2) in blends CH4-H2.

3.1.3 Variation measured of heat input when adding H2 in CH4

When plotting the heat input (Qtest) against the Wobbe index for the appliances tested, we see a rather linear evolution.

3.1.3.1 Boilers

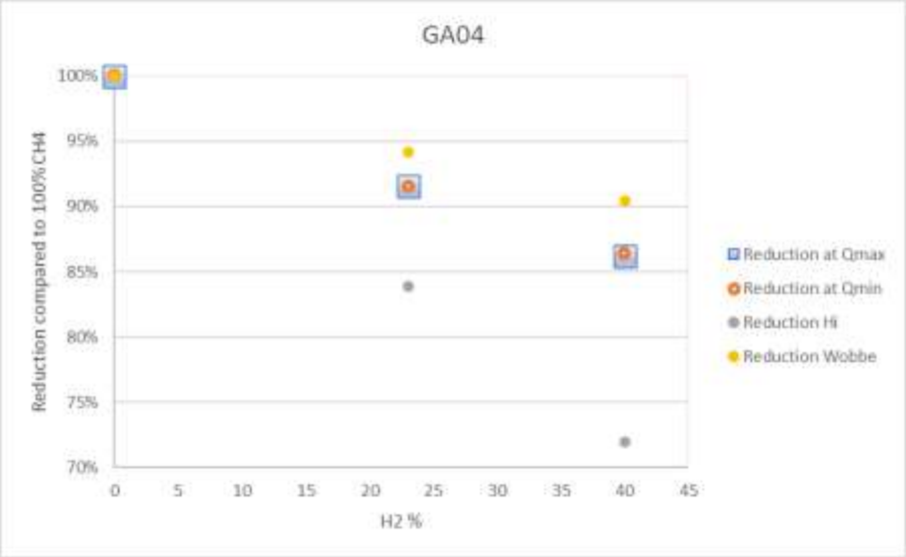


Figure 118: Heat input variation withe %H2 – GA04.

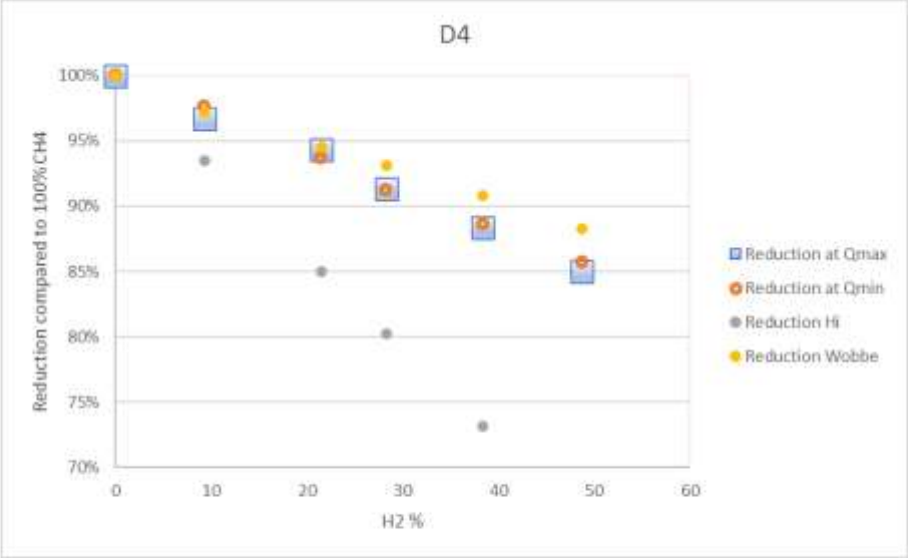


Figure 119: Heat input variation withe %H2 – D4.

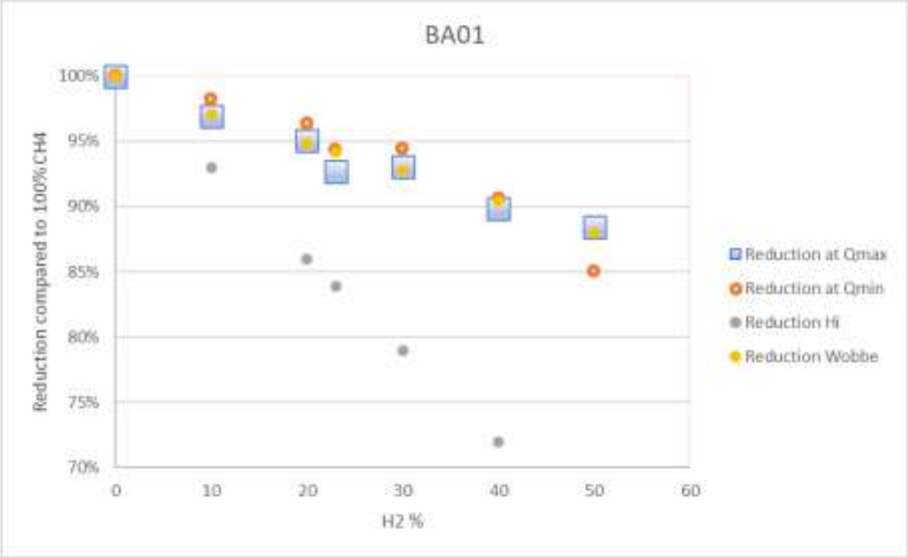


Figure 120: Heat input variation withe %H2 – BA01.

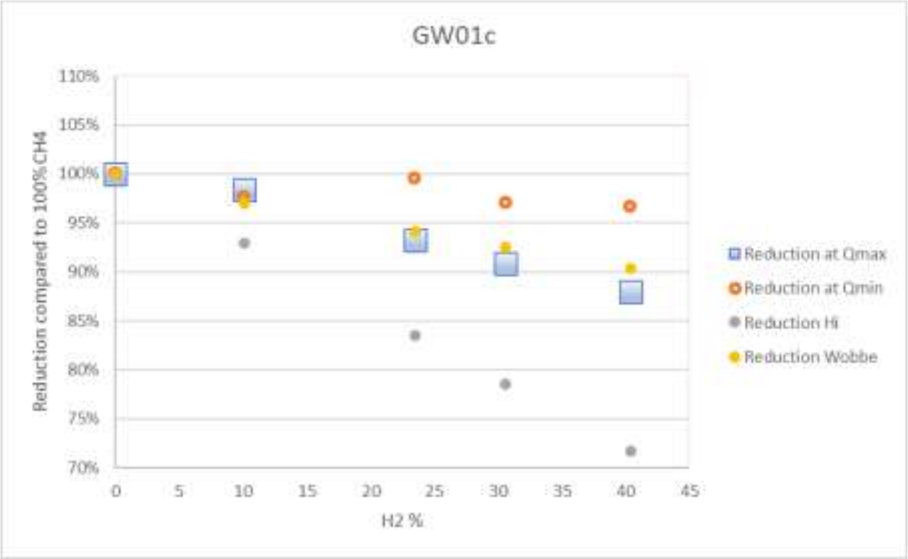


Figure 121: Heat input variation withe %H2 – GW01c.

The result above is rather strange at **Qmin**, the laboratory has indicated that the result observed could be due to the uncertainty of measurement.

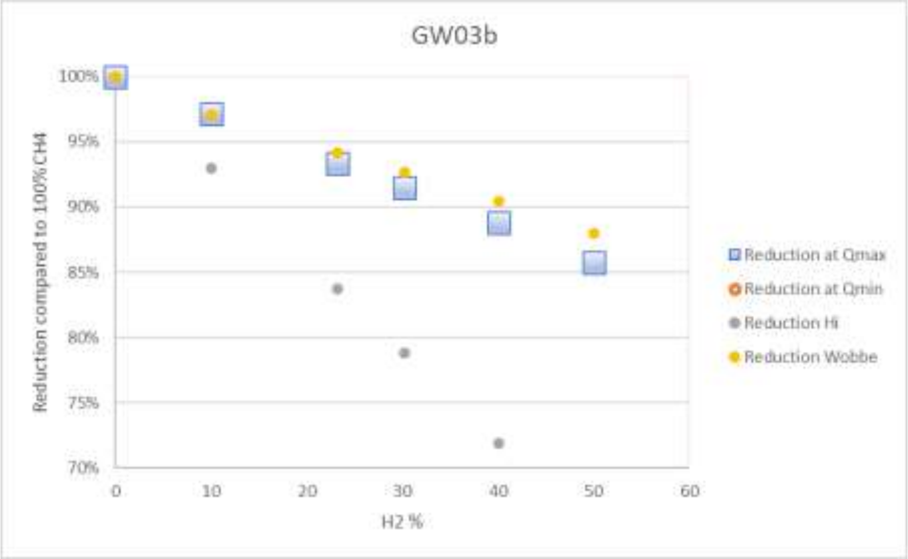


Figure 122: Heat input variation withe %H2 – GW03b.

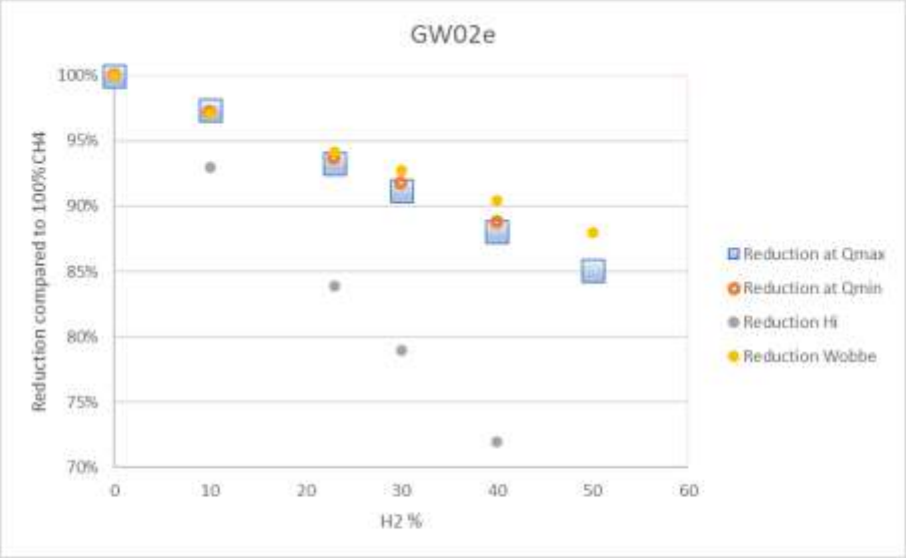


Figure 123: Heat input variation withe %H2 – GW02e.

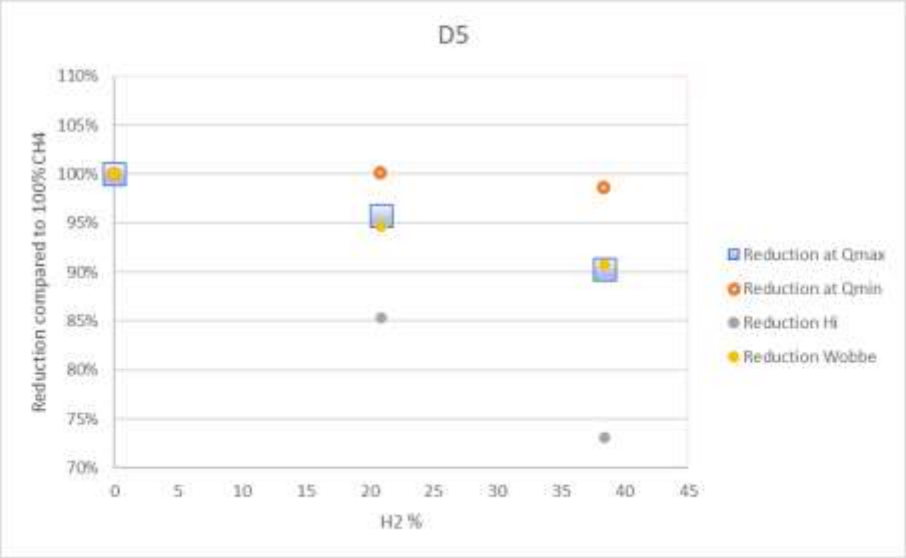


Figure 124: Heat input variation withe %H2 –D.

There is almost no reduction of heat input for the minimum of the modulation range.

3.1.3.2 Water heater

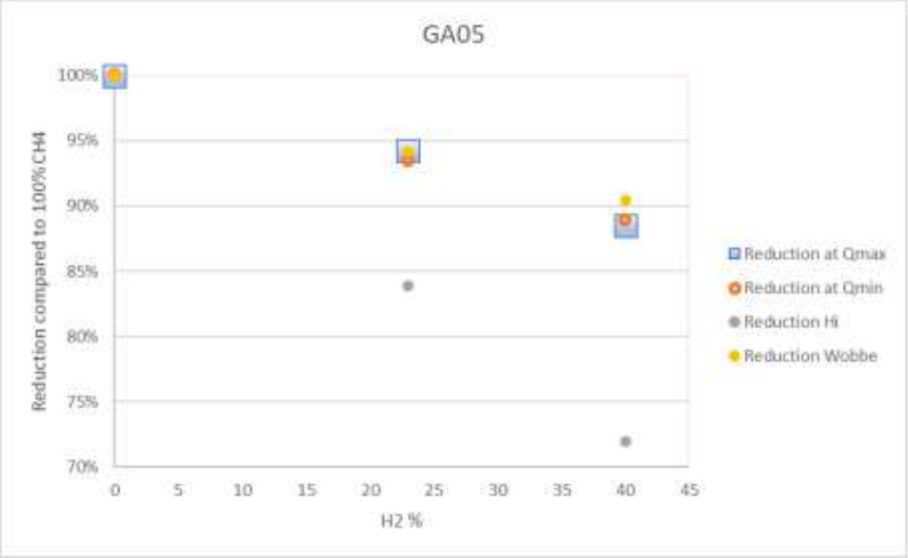


Figure 125: Heat input variation withe %H2 – GA05.

3.1.3.3 Cooker hob

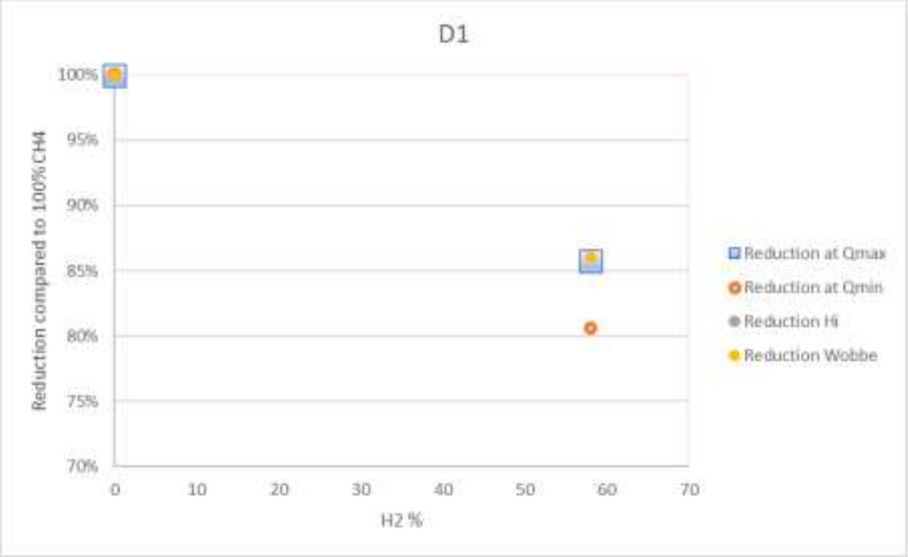


Figure 126: Heat input variation withe %H2 – D1.

For the cooker D1, we have quite a small value for the flow measured, and therefore a large uncertainty.

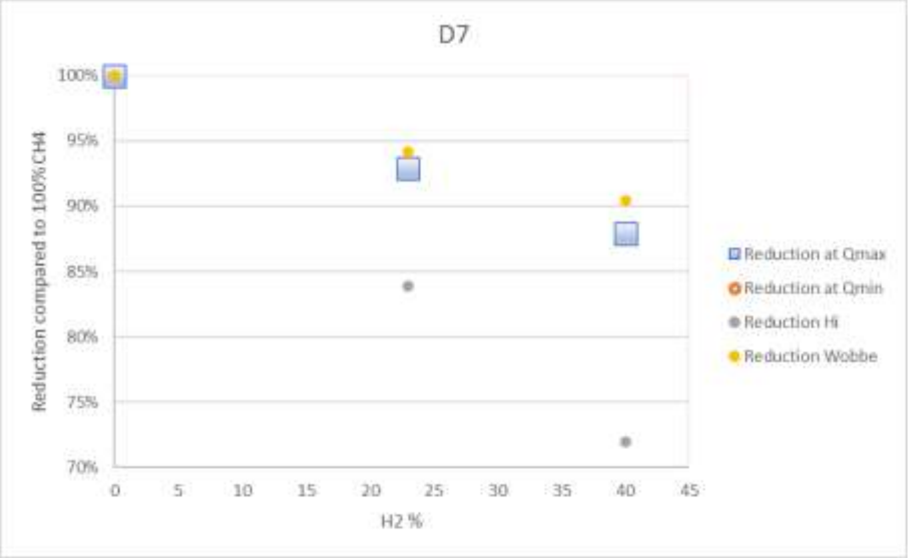


Figure 127: Heat input variation withe %H2 – D7.

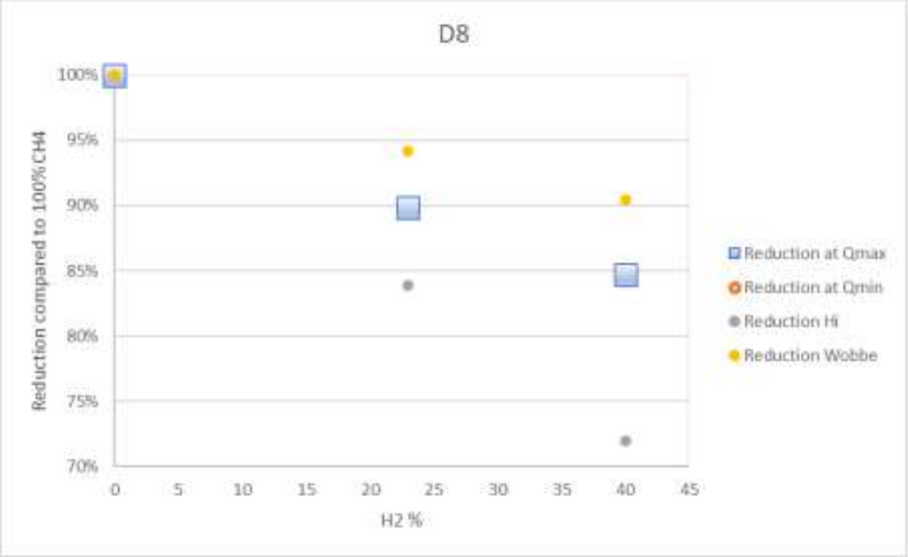


Figure 128: Heat input variation withe %H2 – D8.

3.1.3.4 Oven

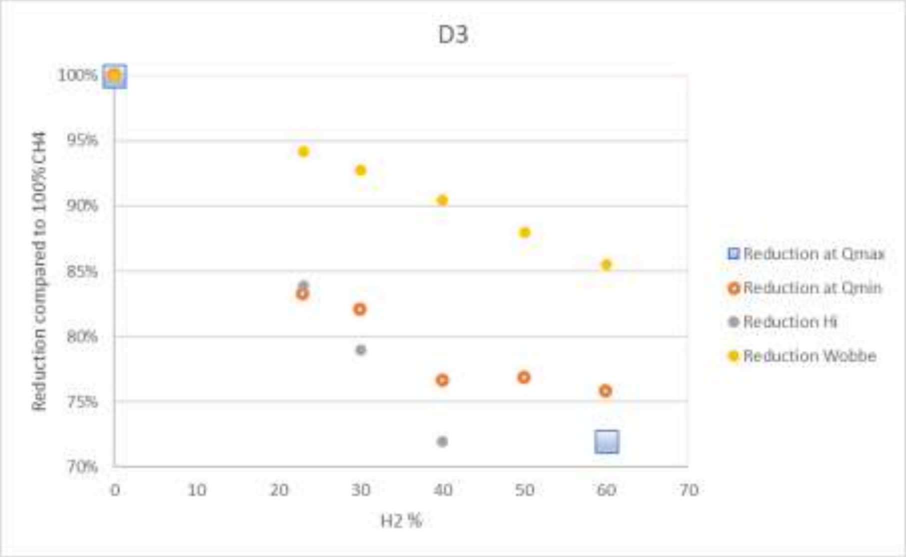


Figure 129: Heat input variation withe %H2 – D3.

The results seem to follow more closely the variation of the calorific value in this case. The duration of the test may have an influence on the results.

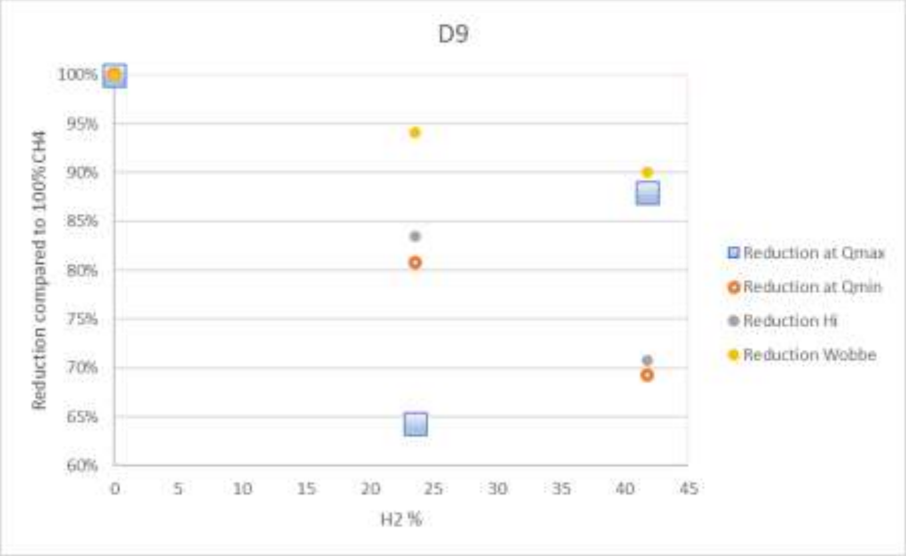


Figure 130: Heat input variation withe %H2 – D9.

For this appliance, the Qmax point at 23% shall be considered as an outlier (after checking with the laboratory, we couldn't find the reason for the results shown and the high variation observed).

3.2 Impact of hydrogen on parameters that are depending on the heat input

The heat input will directly impact some performances aspects like energy delivered or heating time. This is especially important for cooking. The measurement of cooking time to heat the same quantity of water was measured for the cooking hob D7.

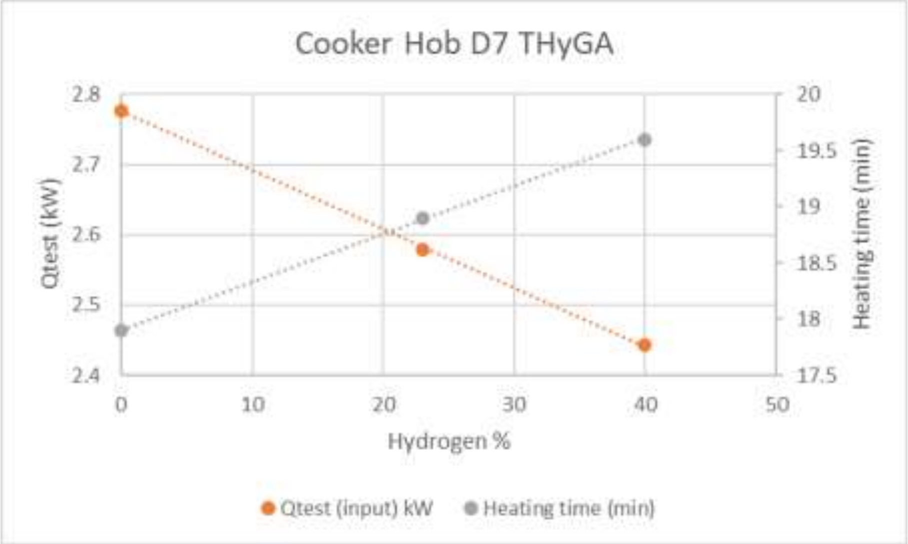


Figure 131: Heat input variation withe %H2 and its impact of heating time – D7.

The heating time is a linear function of the % of H2, the heating time of a standard pan with water (time to boil) is increased here from about 18 minutes (at 0% H2) to 19.5 minutes with 40% H2.

3.3 Delayed ignition

3.3.1 Introduction

Delayed ignition tests have been performed on 3 appliances at the manufacturers' facilities (a representative of the THyGA test labs was present for the first 2 tests):

1. a room sealed condensing gas boiler equipped with a fully premixing burner (segment 108 – standards EN 15502-1:2021 and EN 15502-2-1:2022) tested by the manufacturer (the appliance tested was the same model as EB01)
2. a room sealed glass-fronted live fuel effect gas fire equipped with a partially premixing burner (segment 502 – standard EN 613:2021).
3. additionally, a manufacturer has voluntarily shared his delayed ignition test results on an open flued low-NOx gas boiler equipped with a partially premixing burner (segment 102 – standards EN 15502-1:2021 and EN 15502-2-2:2014).

The tests were carried out according to the corresponding test conditions and requirements as stated in the concerned product standard(s).

<u>Room sealed condensing gas boiler (segment 108</u>

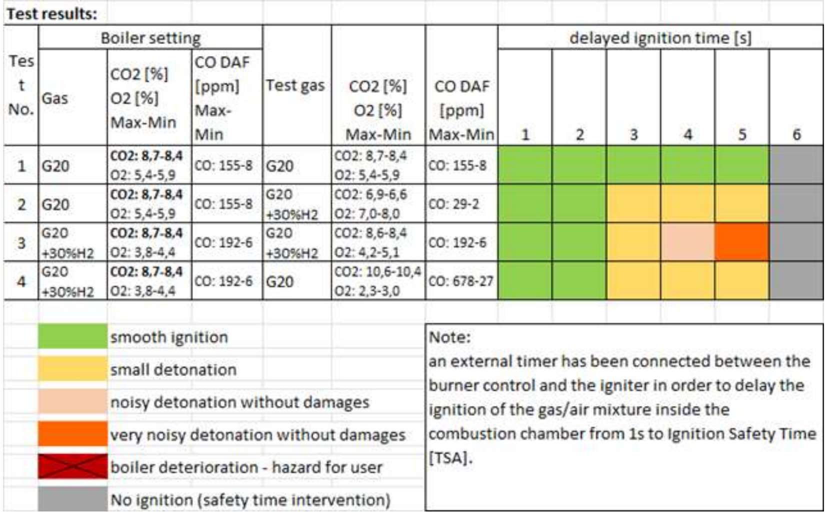
This appliance, with a heat input of 30 kW, has been tested on delayed ignition

- with the ignition delay increasing in steps of 1 s up to the safety time of 5 s,

- supplied with CH_4 (G20) and a mixture containing 70% CH4 + 30% H2 for 2 different combustion settings, respectively, i.e. adjusted to nominal settings on G20 and to nominal settings on a mixture containing 70% CH4 + 30% H2.

The following table gives an overview of the test results:

Table 49: Delayed ignition test results for a room sealed condensing boiler.



Test results:

Test No.	Boiler setting			Test gas	CO2 [%] O2 [%] Max-Min	CO DAF [ppm] Max-Min	delayed ignition time [s]					
	Gas	CO2 [%] O2 [%] Max-Min	CO DAF [ppm] Max-Min				1	2	3	4	5	6
1	G20	**CO2: 8,7-8,4** O2: 5,4-5,9	CO: 155-8	G20	CO2: 8,7-8,4 O2: 5,4-5,9	CO: 155-8	🟩	🟩	🟩	🟩	🟩	▒
2	G20	**CO2: 8,7-8,4** O2: 5,4-5,9	CO: 155-8	G20 +30%H2	CO2: 6,9-6,6 O2: 7,0-8,0	CO: 29-2	🟩	🟩	🟨	🟨	🟨	▒
3	G20 +30%H2	**CO2: 8,7-8,4** O2: 3,8-4,4	CO: 192-6	G20 +30%H2	CO2: 8,6-8,4 O2: 4,2-5,1	CO: 192-6	🟩	🟩	🟨	▨	🟧	▒
4	G20 +30%H2	**CO2: 8,7-8,4** O2: 3,8-4,4	CO: 192-6	G20	CO2: 10,6-10,4 O2: 2,3-3,0	CO: 678-27	🟩	🟩	🟨	🟨	🟨	▒

🟩 smooth ignition
🟨 small detonation
▨ noisy detonation without damages
🟧 very noisy detonation without damages
☒ boiler deterioration - hazard for user
▒ No ignition (safety time intervention)

Note:
an external timer has been connected between the burner control and the igniter in order to delay the ignition of the gas/air mixture inside the combustion chamber from 1s to Ignition Safety Time [TSA].

3.3.2 Findings

Adding H2 to the gas supplied to an appliance without changing settings leads to a small detonation at the ignition with 30% of H2, however the concerned boiler did still ignite without deterioration to the product or possible safety issues for the user.

Adjusting the boiler to nominal settings on the mixture obviously leads to a more violent ignition (very noisy detonation), also when supplied with CH_4, as more energy is released before ignition with 30% of H2, the concerned boiler did still ignite without deterioration to the product or possible safety issues for the user.

With on-site adjustment as currently practiced in a number of countries, the worst case, i.e. adjustment to nominal settings on the natural gas with the lowest possible Wobbe index containing the maximum H2 concentration (30% in the above test), safe delayed ignition would still have to be checked with the EU High gas and EU High gas + 30% H2.

If any mitigating measures are needed, the next measures may be applied:

- reduce the ignition safety time (by replacing the burner control by one with a shorter safety time).
- avoid (inappropriate) on-site adjustment.

<u>Room sealed (type C31), glass-fronted live fuel effect gas fire (segment 502)</u>

This appliance, with a heat input of 12 kW, has been tested on delayed ignition.

- with the test repeated progressively delaying the ignition stepwise up to

  - the safety time declared by the manufacturer (in this case 15 s) for the version with direct ignition of the main burner.
  - 45 s for the version with pilot flame.
- supplied respectively with CH4 (G20) and mixtures of CH4 and H2 containing resp. 23%, 30% and 40% H2 always adjusted to nominal settings on G20 (cf. appliance is not adjustable).

The following table gives an overview of the test results:

Table 50: Delayed ignition test results for a rom sealed (type C31), glass-fronted live fuel effect gas fire.

Appliance version with direct ignition of main burner

Test results:

Test	Settings gas	Test gas	delayed ignition time [s]				
			1	5	10	15	20
1	G20	G20	🟩	🟩	🟩	🟩	▩
2	G20	G20 +23% H2	🟩	🟩	🟩	🟩	▩
3	G20	G20 +30% H2	🟩	🟩	🟩	🟩	▩
4	G20	G20 +40% H2	🟩	🟩	🟩	🟩	▩

Appliance version with pilot flame

Test results:

Test	Settings gas	Test gas	delayed ignition time [s]								
			1	5	10	15	20	30	35	40	45
1	G20	G20	🟩	🟩	🟩	🟠	🟧	🟧	🟧	🟧	🟧
2	G20	G20 +23% H2	🟩	🟩	🟩	🟩	🟠	🟧	🟧	🟧	🟧
3	G20	G20 +30% H2	🟩	🟩	🟩	🟩	🟠	🟧	🟧	🟧	☒
4	G20	G20 +40% H2	🟩	🟩	🟩	🟠	🟧	🟧	🟧	🟧	☒

🟩	smooth ignition
🟨	small detonation
🟠	noisy detonation without damages
🟧	very noisy detonation without damages
☒	appliance deterioration - hazard for user
▩	no ignition

Figure 132: Experimental setting for the delayed ignition test.

Findings

- the version with direct ignition of the main burner and safety time of 15 s shows no issues and has a smooth ignition up to the maximumH2 concentration of 40% tested.
- the version with the pilot flame (cross-lighting time between pilot and main burner):
  - with CH_4 (G20), it starts making very noisy detonation from 20 s but without deterioration or possible hazards to the user, when repeating the test shortly afterwards (3 min) the lighting of the main burner only occurred after 34 s,
  - with H2 added (23% and 30%), it seems to light a little bit easier with the very noisy detonation only starting at 30 s,
  - with 30% and 40% of H2 the glass front panel broke, and the pieces ejected, when lighting of the main burner only occurred after 45 s with obviously possible hazards to the user.
- the delayed ignition results showed to depend much on the temperature in the system and the draught in the evacuation system,
- the manufacturer indicated that the shortest flue gas evacuation configurations are most critical.

Partially premix Low NOx burner type B11BS (segment 102)

When performing the delayed ignition test with 20% H2 added to CH_4, the ignition of the accumulated unburnt gas leads to flame creation at the injectors (= similar to what may happen due to light-back). This was observed on 2 open flued low-NOx gas boilers equipped with a partially premixing burner (segment 102 **without fan**).

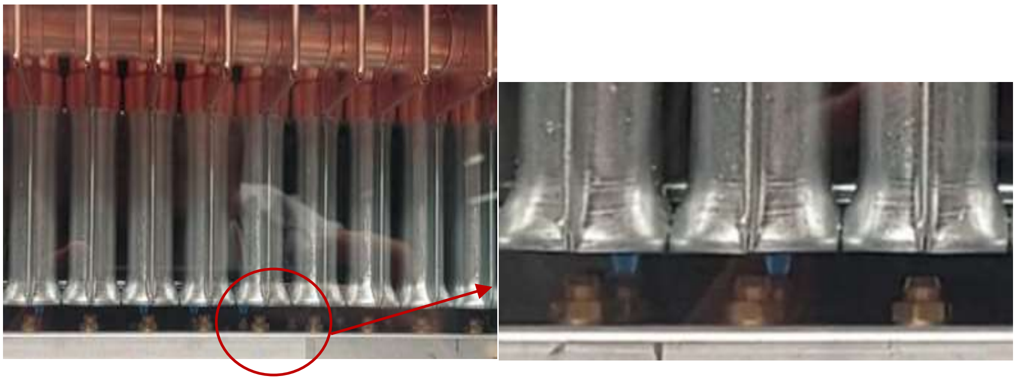


Figure 133: Flame creation at the injectors during the delayed ignition test.

Details of the test on 1 appliance: the phenomenon started after an ignition delay of only 3s when supplied with 20% and even 10% H2 while this does not occur with methane (G20).

3.3.3 Additional tests from a manufacturer (received at the very end of the reporting)

Seg 101: partially premix type B11BS

The delayed ignition tests gave a positive result with 15 % H2 or less.

With 20% H2 the explosion generated during the delayed ignition is able to ignite the gas directly at the injectors. It doesn't seem a light-back, but the result is the same.

The phenomenon started after an ignition delay of 6 s.

A mitigation measure could be a reduction of the TSA < 5 s (normally the burner control should be replaced in case the mitigation is needed).

Note: Because of the high NOx values these appliances can no longer be placed on the EU market according to Ecodesign regulation since 2018.

3.3.4 Delayed ignition for cooking appliances

In the cooker standards (EN 30 family) includes tests to check the accumulation of unburnt gas in the space where the appliance is installed or within the appliance (e.g. oven), mainly checking that ignition occurs smoothly within 5 seconds.

In addition to the above, the user manual must include instructions to the user, in case the ignition is not occurring normally, such as for example:

"The device shall not be operated for more than 15 s. If after 15 s the burner has not lit, stop operating the device and open the compartment door and/or wait at least 1 min before attempting a further ignition of the burner."

For **cooking appliances with automatic burner control systems**, the standard includes a test to check that there is no dangerous accumulation in case of several consecutive automatic re-ignition attempts.

Ignition (if any) is checked up to the last second of the third automatic ignition attempt and it's verified

- there is no damage to or distortion of the appliance;
- the compartment door, if any, does not open itself;
- no flame is emitted from the front of the appliance.

3.3.5 General conclusions on delayed ignition

In case of delayed ignition, relevant hydrogen concentrations in natural gas leads to more violent ignition.

- **For concentrations up to 20% H2, the impact has proven not to be detrimental or dangerous on the tested appliances equipped with a fan in the combustion circuit**, but…
- **… inappropriate onsite adjustment, if possible, may increase the risk on an unacceptable impact** (material deterioration and/or user hazard) of delayed ignition due to accumulation of a flammable mixture with a higher energy content.

Appliances equipped with specific partially premixing burners without a fan in the combustion circuit (i.e. appliance type B11BS) used in certain types of boilers and water heaters seem to be sensitive to delayed ignition. No light-back occurs, but the unburned gas accumulates also downstream of the burner. When this accumulated unburned gas is lighted it creates a flame at the injector.

Impacted segments:

- 101: open flued boiler (former EN 297) - partial premix/conv. **without fan**
- 102: open flued boiler (former EN 297) - partial premix **without fan** – low NOx version
- 104: room sealed boiler (former EN 483) - partial premix/conv. **without fan**
- 105: room sealed boiler (former EN 483) - partial premix/conv. **without fan** – low NOx version
- 201: open flued instantaneous water heater (former EN 26) - partial premix/atm. **without fan**
- 203: open flued accumulation water heater (former EN 89) - partial premix/atm. **without fan**

- Segment family 500 **without fans**

Note: According to our best knowledge, the products identified with segments 104 and 105 are probably non-existing or very rare on the market. However, both are covered/foreseen in the EN 1749 standard and not excluded by the EN15502-2-1 standard.

Based on the above findings it seems recommended

- to reconsider the test method and conditions to take in account reasonably foreseeable worst cases,
- to reassess the delayed ignition risk systematically for appliances not specifically designed for natural gas containing relevant H2 concentrations, especially when on-site adjustment is allowed/possible.

If any mitigating measures are needed, the next measures may be applied:

- reduce the ignition safety time (by replacing the burner control by one with a shorter safety time),
- avoid (inappropriate) on-site adjustment.

3.4 Flame detection - Ionisation current

All figures in this section are giving the ionization in **micro-**Ampere (µA).

For some appliances, the signal is much higher than the other ones. The origin of the signal is not clearly identified, but it is probably not ionization.

For several appliances the signal is very low, but it is probably not ionization either.

For most of the appliances, the signal is between few 4 µA and about 20 µA.

The signal is rather constant except for one appliance (see comment Nr. 2 above).

The signal at Qmin can be higher or lower compared to the signal at Qmax.

In conclusion we can say that the ionization current is not very much impacted by H2 (in the range of H2 tested). The signal seems to stay stable and above the threshold needed for the flame detection.

In conclusion we can say that it can be used for flame detection with blends up to 60% H2 and maybe more (but we have not tested more).

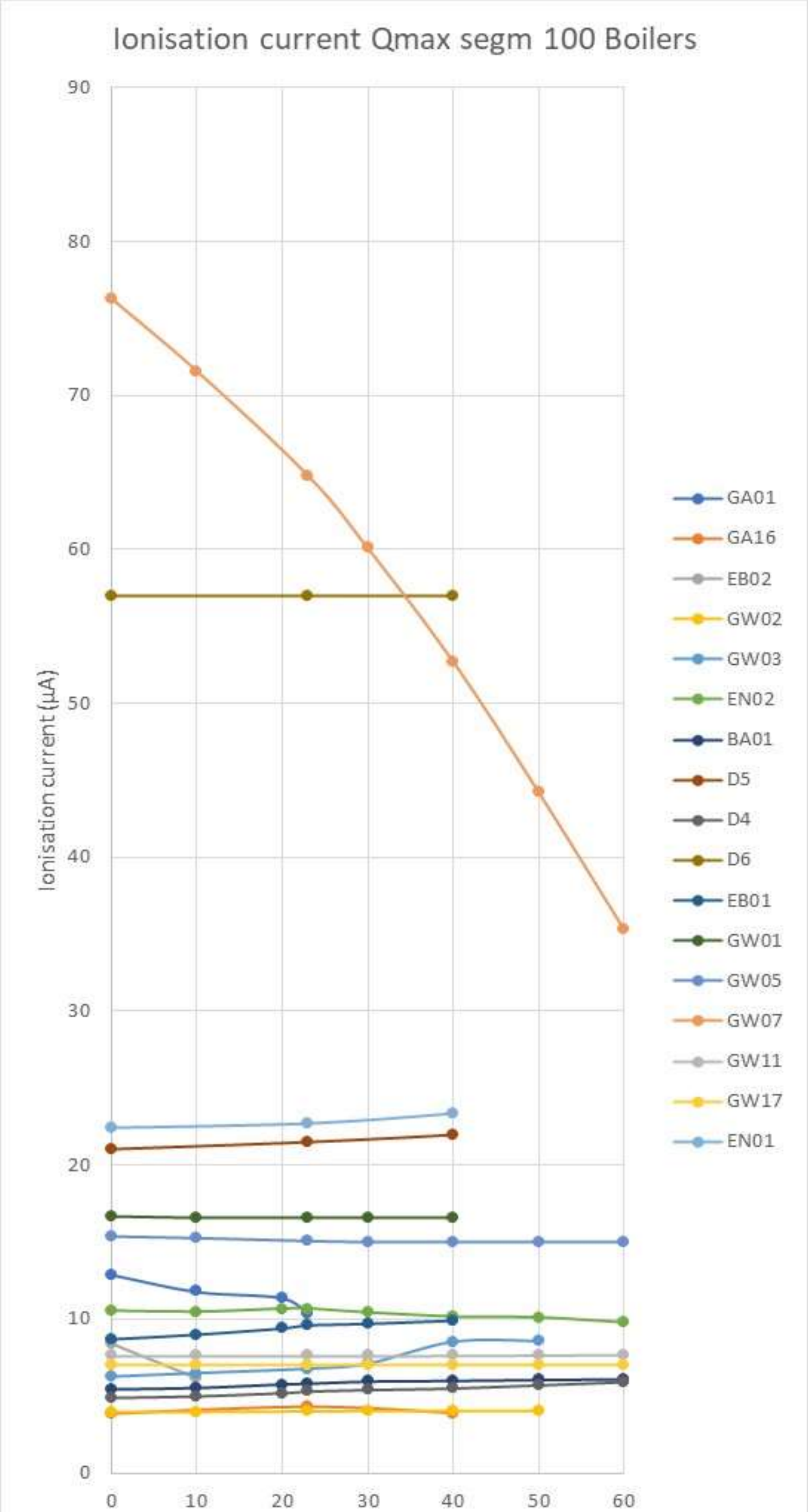


Figure 134: Segm 100 - Ionisation current Qmax

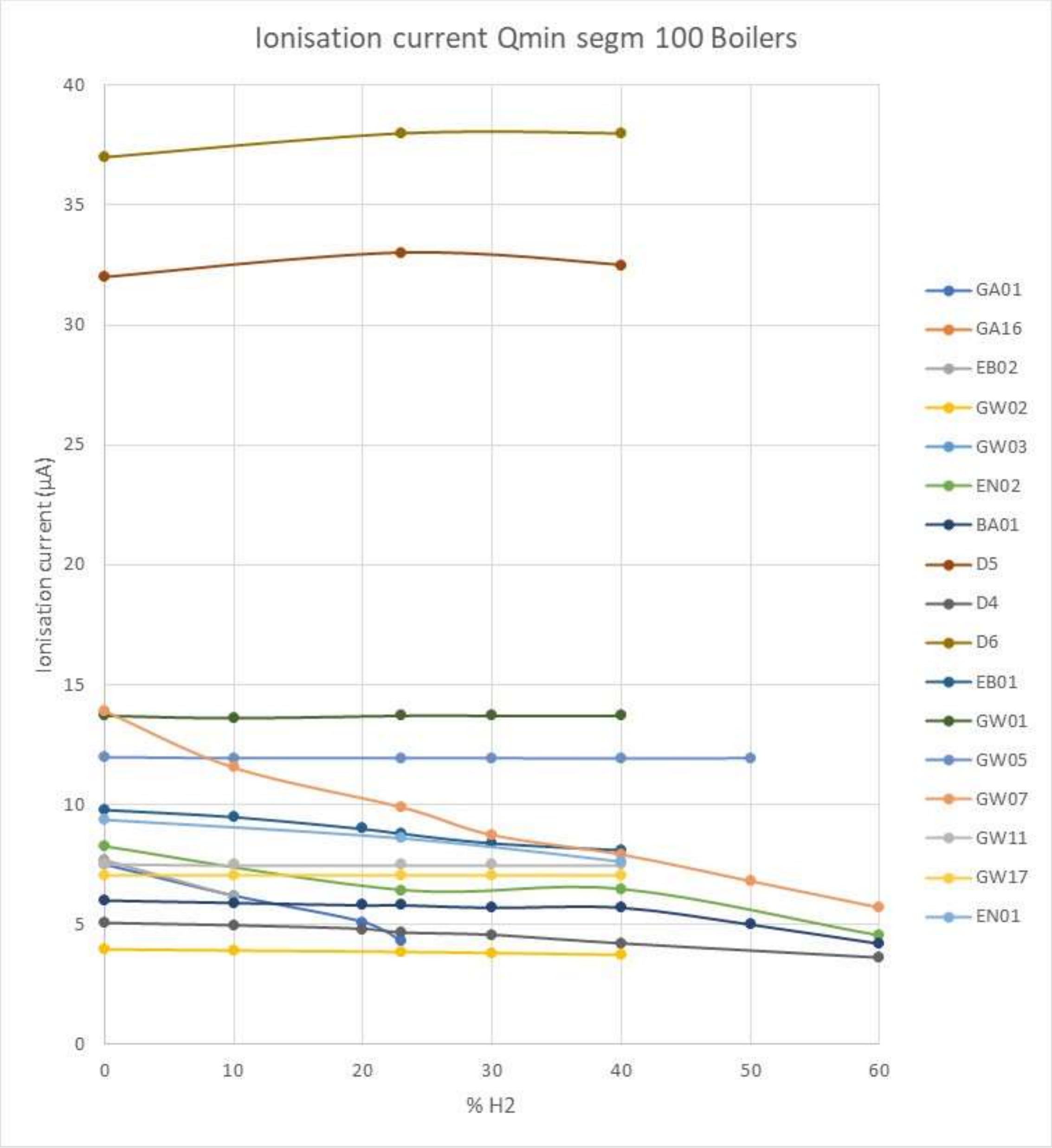


Figure 135: Segm 100 - Ionisation current Qmin

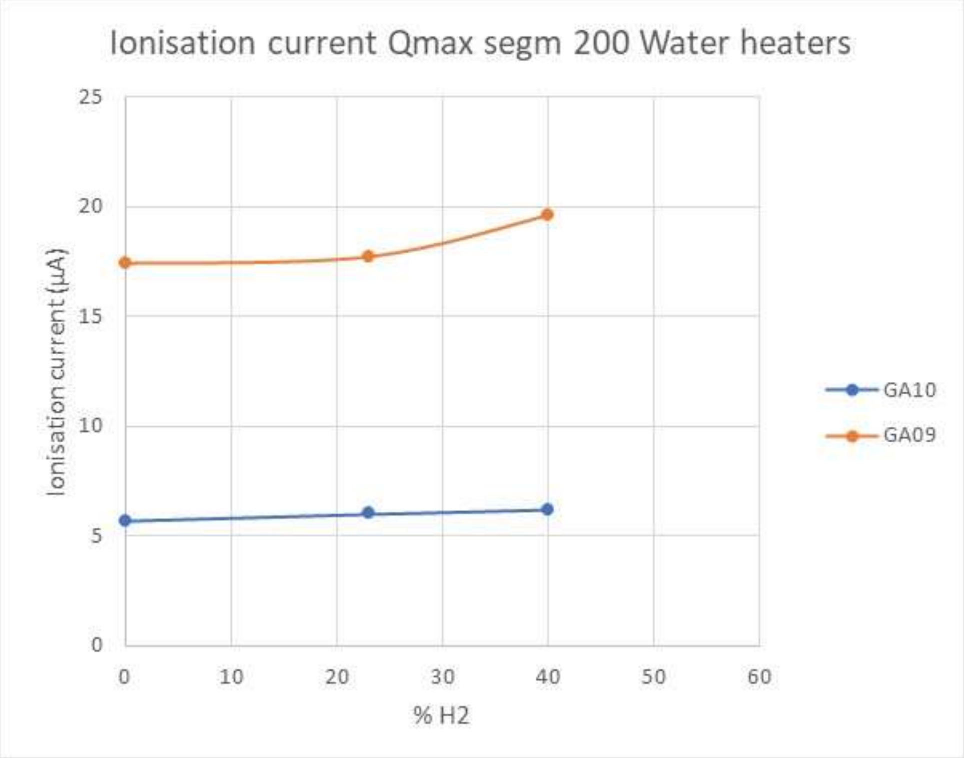


Figure 136: Segm 200 - Ionisation current

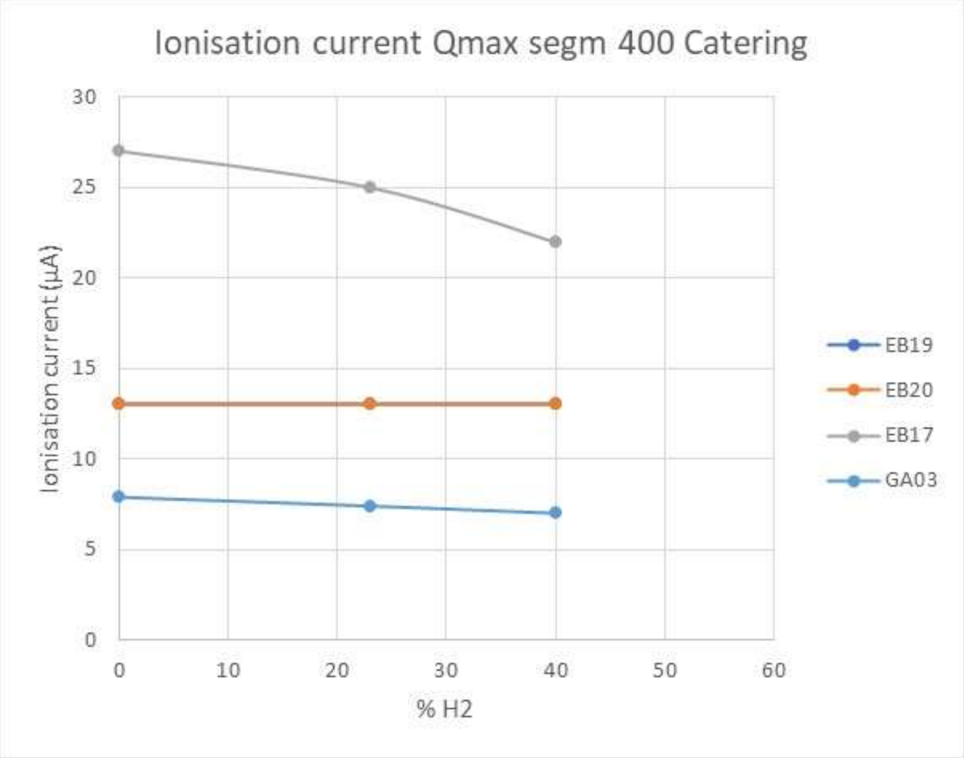


Figure 137: Segm 400 - Ionisation current Qmax

Figure 138: Segm 400 - Ionisation current Qmax

Figure 139: Segm 800 - Ionisation current Qmax

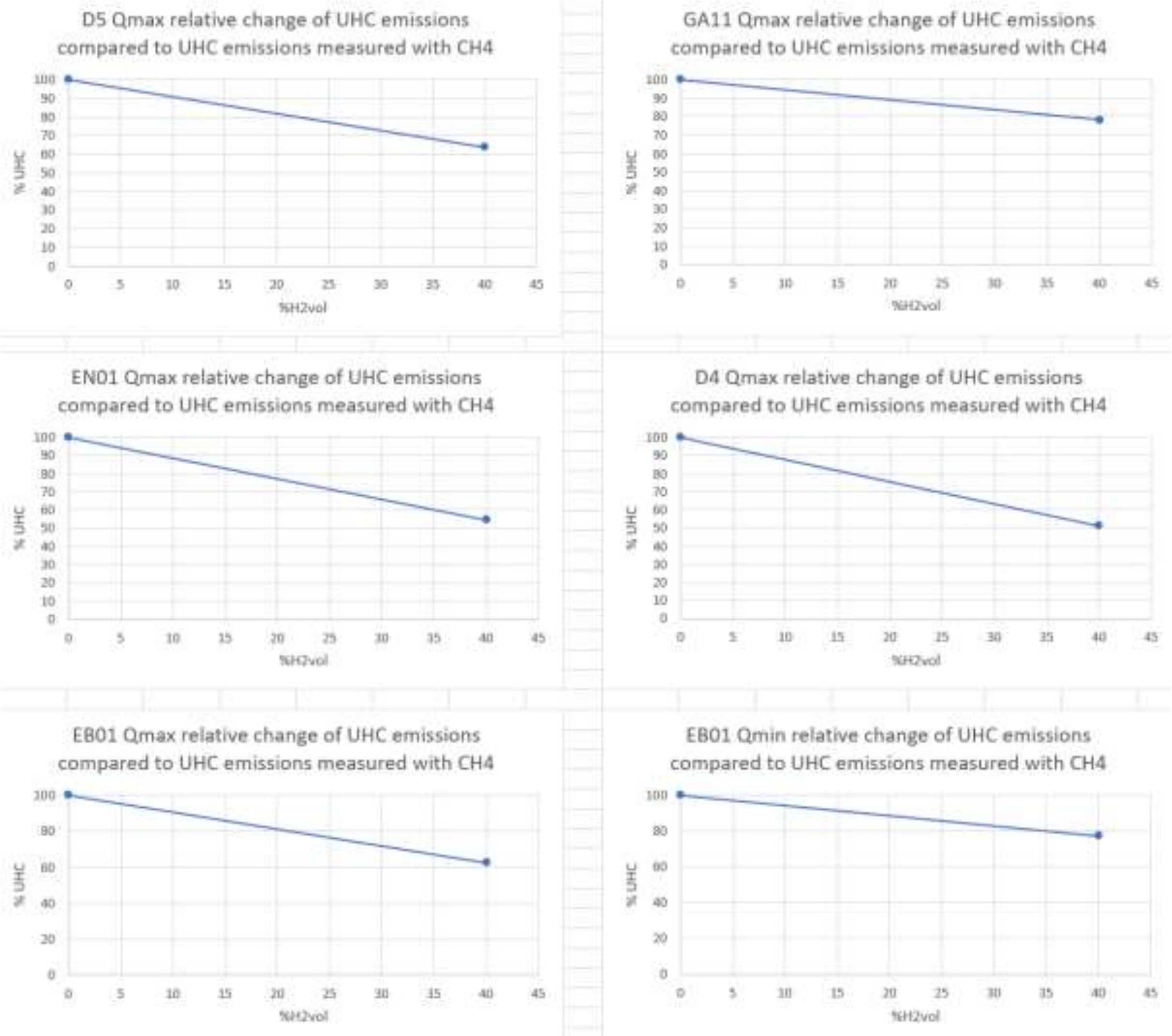
3.5 UHC and H2 emissions

3.5.1 UHC emissions

In this section we are looking at UHC emissions. As the test are conducted with CH4 / H2 mix, the UHC emissions are CH4 emissions (no other hydrocarbons).

The emissions are measured in ppm and recalculated on dry-air free flue gas. Following that, for comparison's sake, we have expressed the emissions in % of emission measured with CH4 without H2.

100a Fully premix boilers


D5 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

GA11 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

EN01 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

D4 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

EB01 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

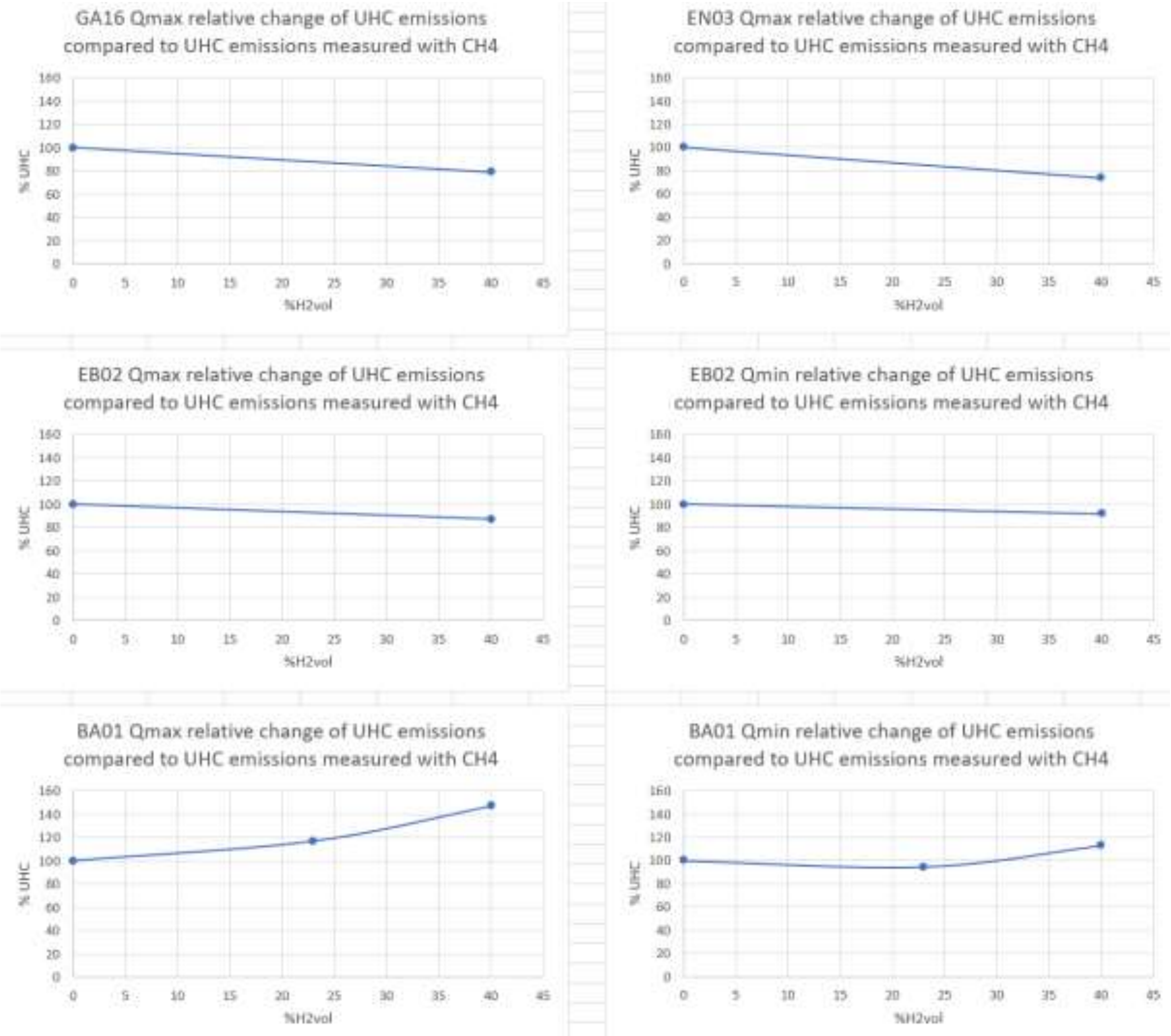
EB01 Qmin relative change of UHC emissions compared to UHC emissions measured with CH4

Figure 140: Segm 100a - UHC emissions

For fully premix boilers the addition of H2 reduces the amount of UHC produced.

The reduction of CH4 emission for those appliances is in the magnitude of CH4 replaced by hydrogen.

100b Not fully premix boilers and burners


GA16 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

EN03 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

EB02 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

EB02 Qmin relative change of UHC emissions compared to UHC emissions measured with CH4

BA01 Qmax relative change of UHC emissions compared to UHC emissions measured with CH4

BA01 Qmin relative change of UHC emissions compared to UHC emissions measured with CH4

Figure 141: Segm 100b - UHC emissions.

For non-fully premix boilers the addition of H2 does not have a clear impact on the evolution of UHC. We can conclude that the addition of hydrogen will increase the relative part of unburned CH4.

200 Water heaters

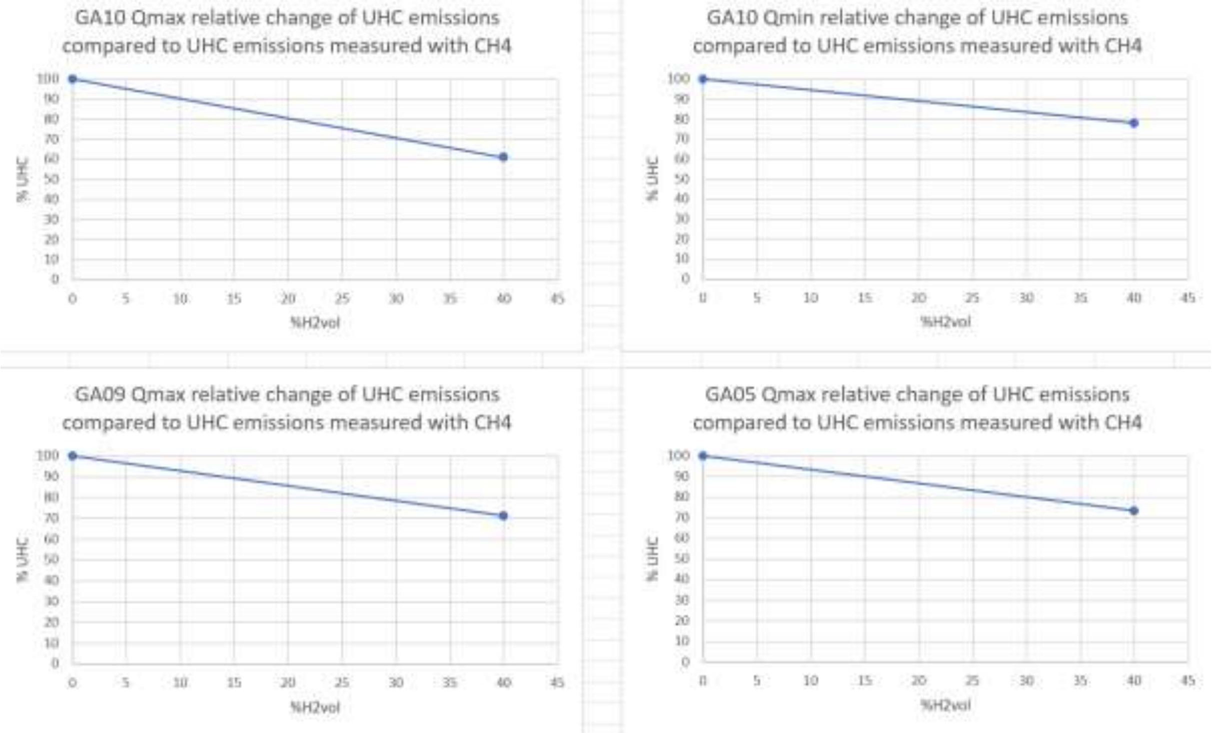


Figure 142: Segm 200 - UHC emissions.

For water heaters boilers the addition of H2 seems to lower UHC emissions in the same manner as for premix boilers.

300 Domestic cooker hobs and ovens

For the tested appliances, the addition of H2 results in a reduction of CH4 emissions at Qmin and generally an increasing emission at Qmax. This may be caused by a higher flame instability.
Note that absolute value of CH4 decreases as Qmin is lower than the proportion of CH4 in the gas.

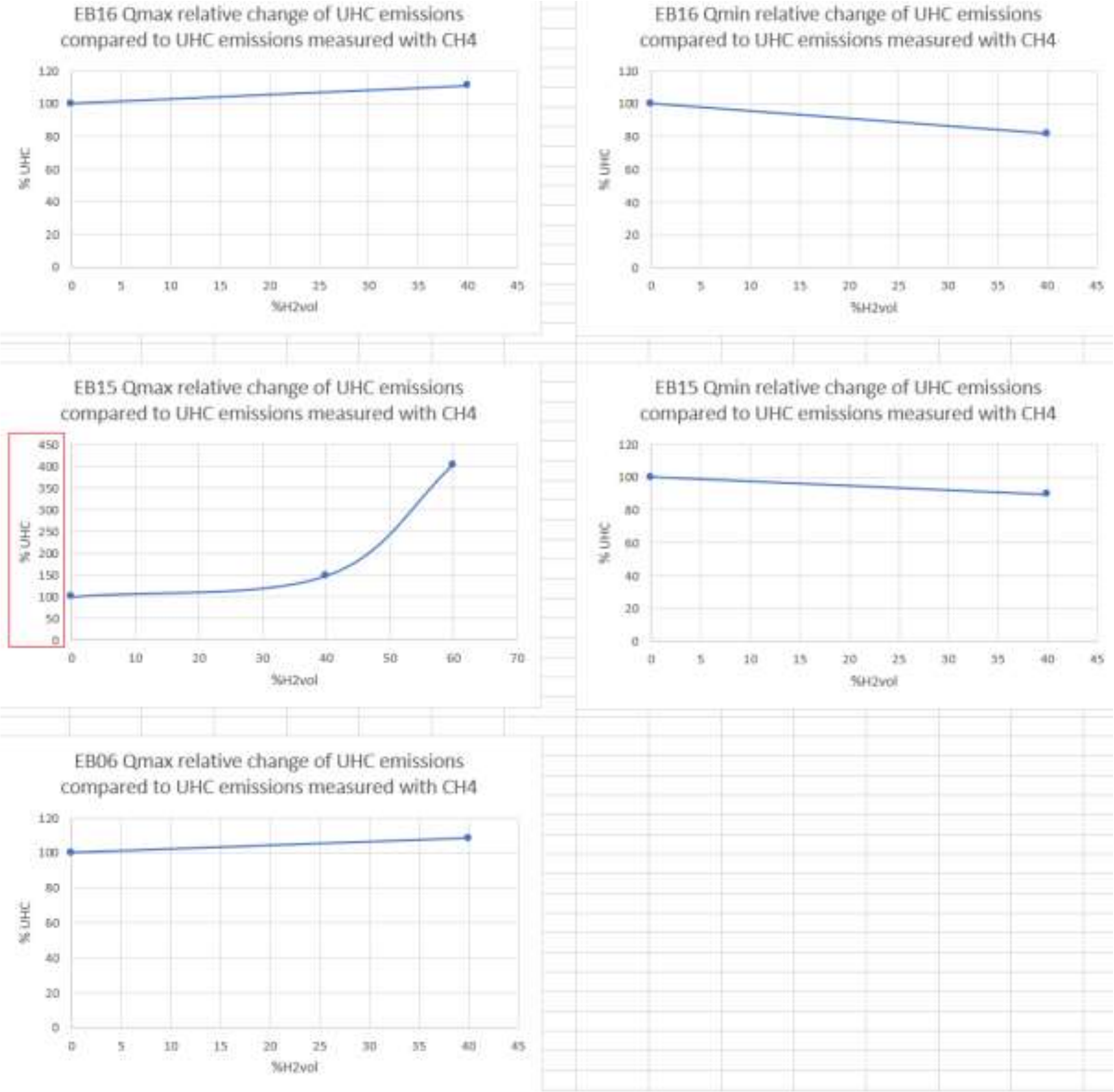


Figure 143: Segm 300 - UHC emissions.

Note that the Y axis on figures above is in red when we the scale chosen deviates from the scale used for the other figures.

400a Catering premix

There is a general drop in absolute UHC emissions for premix catering but no clear tendency, especially if correcting from the proportion of CH4 in the test gas.

We observe a general trend in decrease of CO and NOx emissions with H2 increasing.

Note: There are quite high values of CH4 emissions in continuous operation for EB06.

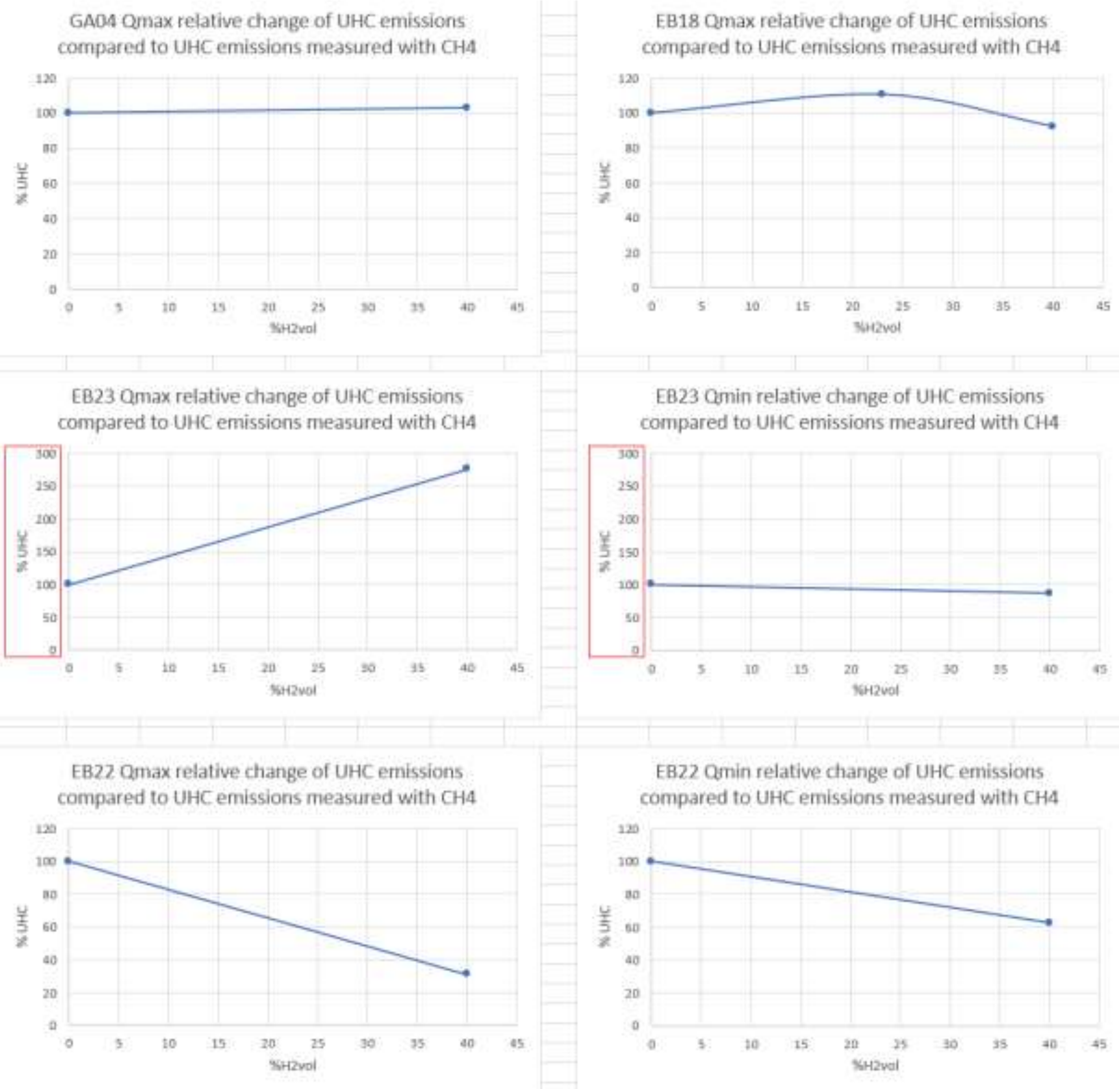


Figure 144: Segm 400a - UHC emissions part 1.

Note that the Y axis on figures above is in red when we the scale chosen deviates from the scale used for the other figures.

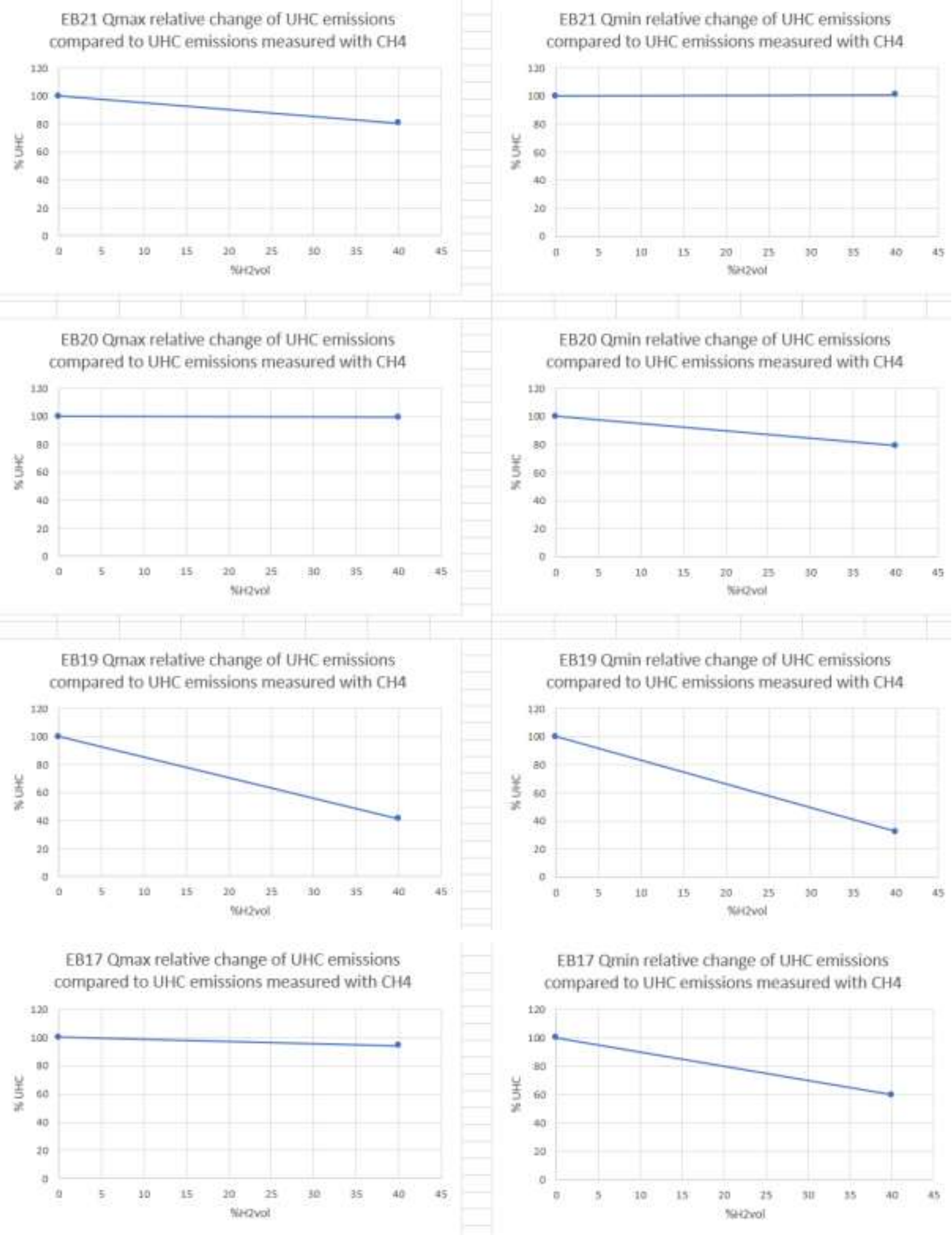


Figure 145: Segm 400a - UHC emissions part 2.

400b Catering not premix

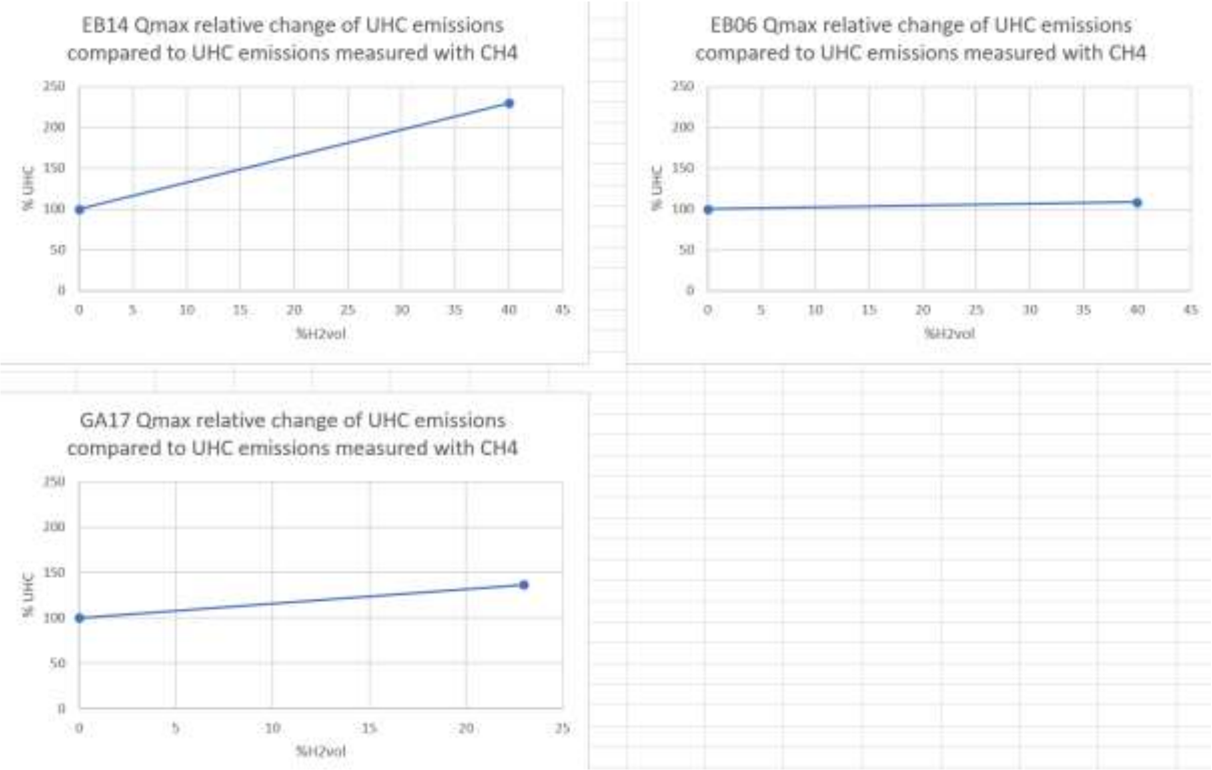


Figure 146: Segm 400b - UHC emissions.

There seems to be in most of the cases an increase in UHC emissions for non-premix catering.

500 Space heaters

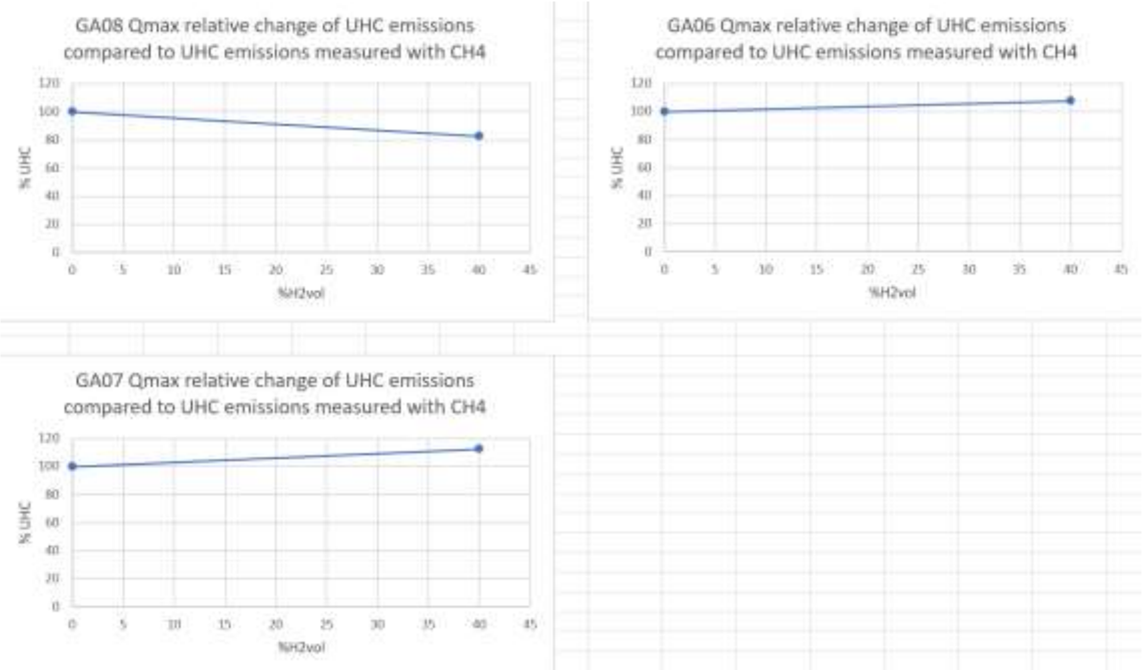


Figure 147: Segm 500 - UHC emissions.

800 Other appliances (here a radiant heater)

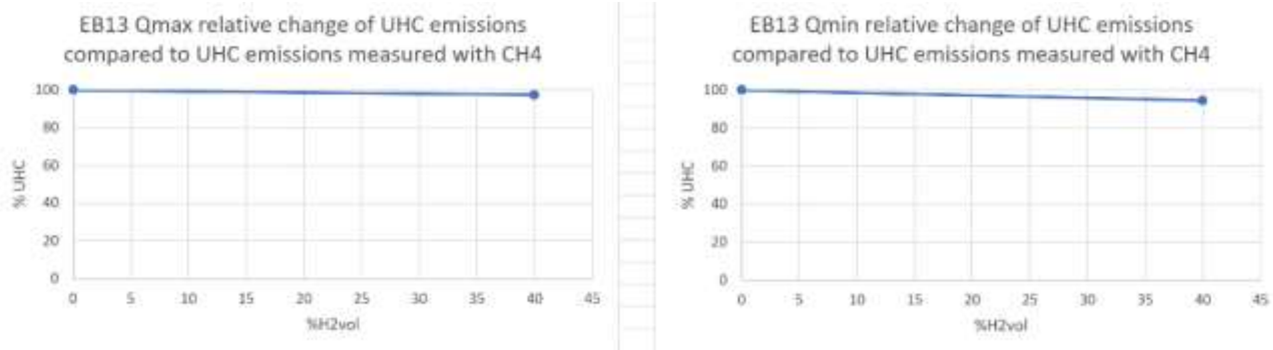


Figure 148: Segm 800 - UHC emissions.

There is very little impact on UHC emissions (but only one appliance tested).

Conclusion for UHC emissions

The results are showing both increase and decrease of CH4 emissions with the addition of H2. To get a correct view of the actual impact of H2 on CH4 emission one should take into account the change in the flue gas composition (see in section 4)

3.5.2 H2 emissions

For unburned H2 we have expressed the measurement in ppm (dry air free). Test have been performed on D5 (premix boiler) GA 16 (not-premix boiler) and GA10 (water heater).

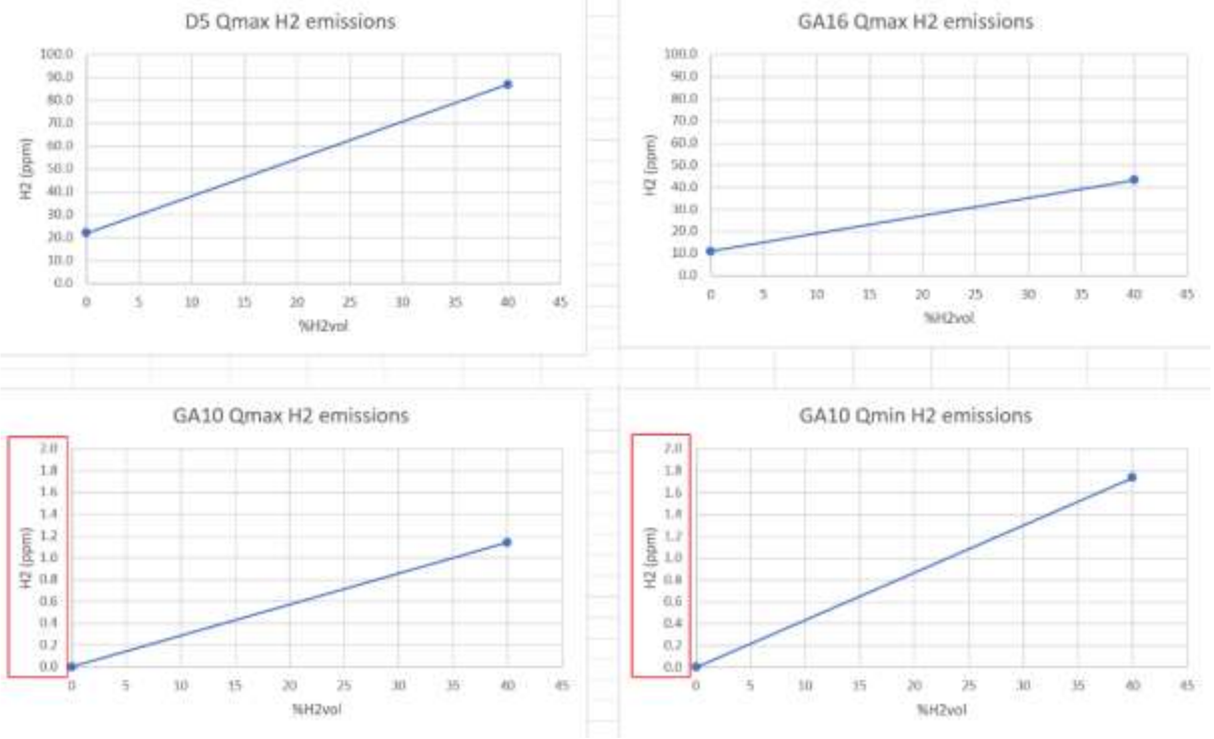


Figure 149: H2 emissions different appliances.

Note that the Y axis on figures above is in red when we the scale chosen deviates from the scale used for the other figures.

We see an expected increase of H2 emissions with H2 injection. Note also that H2 is sometimes also present in the combustion products of pure CH4.

H2 emissions all go up, but sometimes in negligible quantities. There is an overall lack of data for H2 to properly conclude, the reason being the lack of measurement hardware (at laboratories) to measure directly hydrogen in the flue gas with the correct sensitivity.

4 Overall test results and analysis

4.1 Summary of result of safety by Segment type

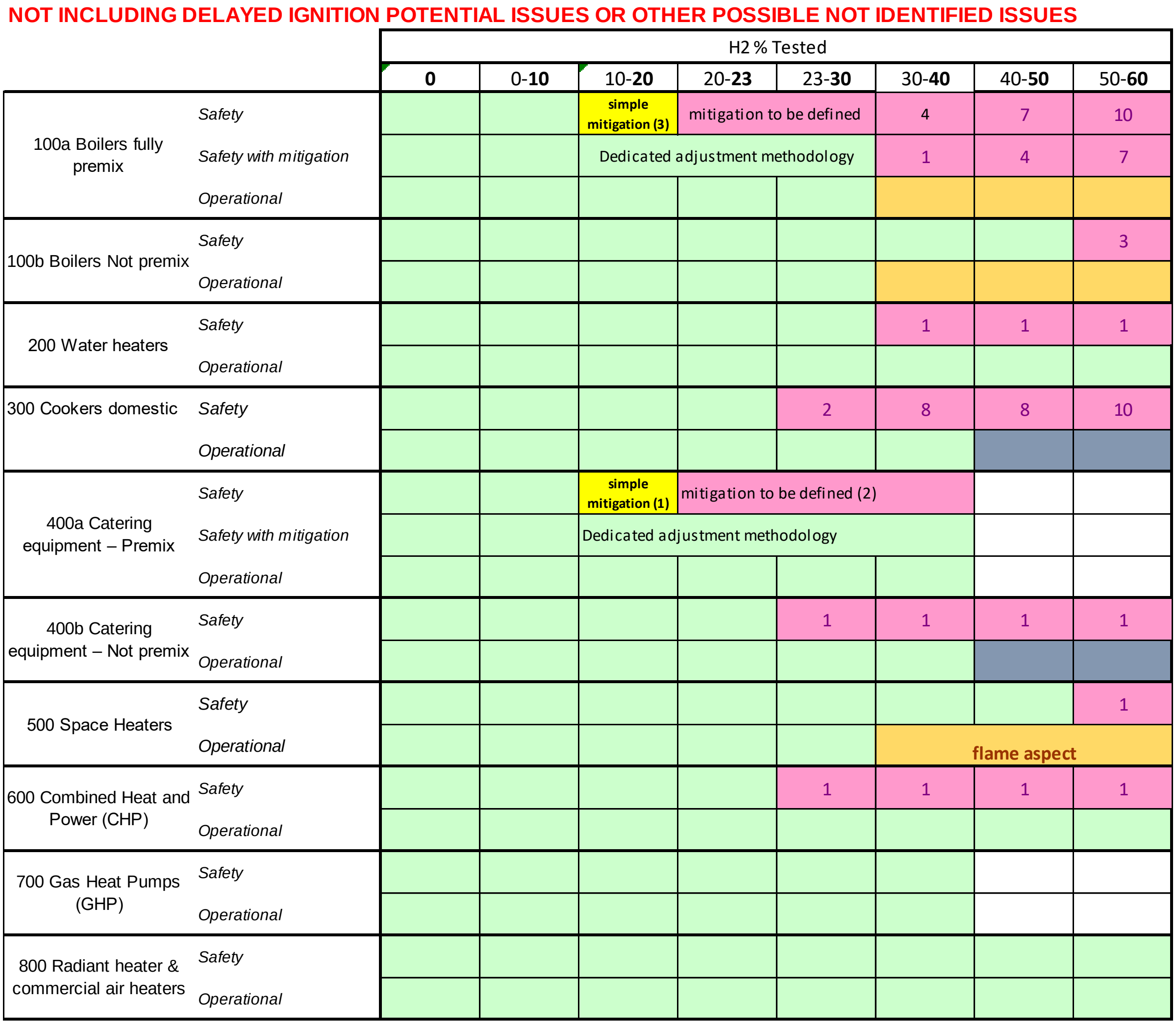
In this chapter, we combine all conclusions of the single segment groups using the impact card figure already given as for example this one:

Table 51: Impact card: Example of synthetic result for segment 100a

		H2 % Tested							
		0	0-10	10-20	20-25	25-30	30-40	40-50	50-60
100a Boilers fully premix	Safety	🟩	🟩	simple mitigation (3)	mitigation to be defined		4	7	10
	Safety with mitigation	🟩	🟩	Dedicated adjustment methodology			1	4	7
	Operational	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧

As a result, the overall picture is as follows **(without taking into account the delayed ignition test):**

Table 52: Synthetic result for all segments tested in the THyGA test campaign.



NOT INCLUDING DELAYED IGNITION POTENTIAL ISSUES OR OTHER POSSIBLE NOT IDENTIFIED ISSUES

		H2 % Tested							
		0	0-**10**	10-**20**	20-**23**	23-**30**	30-**40**	40-**50**	50-**60**
100a Boilers fully premix	*Safety*	🟩	🟩	**simple mitigation (3)**	mitigation to be defined		4	7	10
	Safety with mitigation	🟩	🟩	Dedicated adjustment methodology			1	4	7
	Operational	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
100b Boilers Not premix	*Safety*	🟩	🟩	🟩	🟩	🟩	🟩	🟩	3
	Operational	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧
200 Water heaters	*Safety*	🟩	🟩	🟩	🟩	🟩	1	1	1
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
300 Cookers domestic	*Safety*	🟩	🟩	🟩	🟩	2	8	8	10
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	⬛	⬛
400a Catering equipment – Premix	*Safety*	🟩	🟩	**simple mitigation (1)**	mitigation to be defined (2)				
	Safety with mitigation	🟩	🟩	Dedicated adjustment methodology					
	Operational	🟩	🟩	🟩	🟩	🟩	🟩		
400b Catering equipment – Not premix	*Safety*	🟩	🟩	🟩	🟩	1	1	1	1
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	⬛	⬛
500 Space Heaters	*Safety*	🟩	🟩	🟩	🟩	🟩	🟩	🟩	1
	Operational	🟩	🟩	🟩	🟩	🟩	**flame aspect**		
600 Combined Heat and Power (CHP)	*Safety*	🟩	🟩	🟩	🟩	1	1	1	1
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
700 Gas Heat Pumps (GHP)	*Safety*	🟩	🟩	🟩	🟩	🟩	🟩		
	Operational	🟩	🟩	🟩	🟩	🟩	🟩		
800 Radiant heater & commercial air heaters	*Safety*	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Operational	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

For the last results obtained on delayed ignition, we have created new groups to isolate those segments having issues, compared to those having no issue.

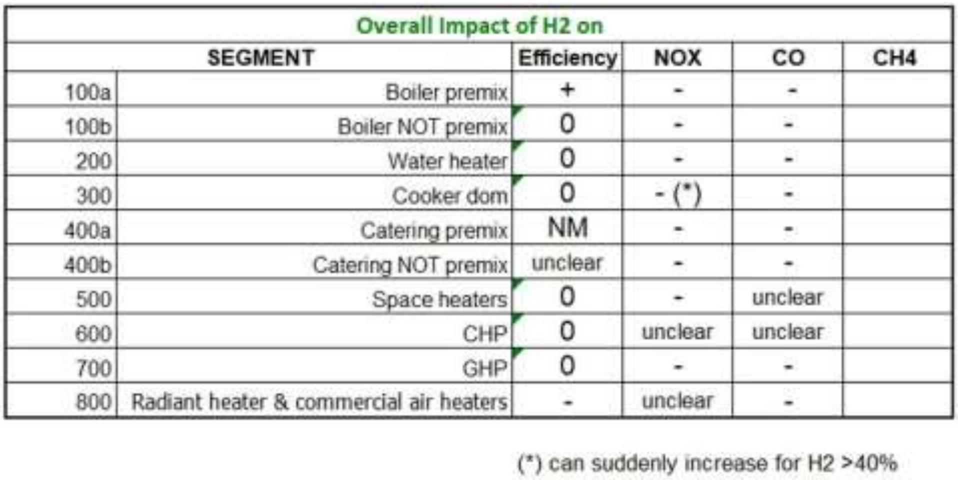
Therefore, we have for non-premix boilers and water heaters the following differentiations (see section on delayed ignition).

- *Sensitive to delayed ignition*
- *Not sensitive to delayed ignition*

These segments are used to fine-tune the population at risk according to %H2, more details is given in THyGA deliverable D3.10 "Compiling of results from all tasks and development of further statistics at EU and country level".

4.2 Summary of result for emissions and performances by Segment type

Table 53: Synthesis of results for emissions and operational aspects



		Overall Impact of H2 on			
SEGMENT		Efficiency	NOX	CO	CH4
100a	Boiler premix	+	-	-	
100b	Boiler NOT premix	0	-	-	
200	Water heater	0	-	-	
300	Cooker dom	0	- (*)	-	
400a	Catering premix	NM	-	-	
400b	Catering NOT premix	unclear	-	-	
500	Space heaters	0	-	unclear	
600	CHP	0	unclear	unclear	
700	GHP	0	-	-	
800	Radiant heater & commercial air heaters	-	unclear	-	

(*) can suddenly increase for H2 >40%

H2 has no or only small impact on efficiency, but for boilers where we see a slight increase of efficiency on Hi due among others to higher heat recuperation on condensation with the testing conditions used.

Heat output decreases with H2 injection, which could prove to bring comfort issues for appliances such as domestic hot water or cooking appliances.

NOx is decreasing with H2.

CO is generally decreasing with H2, but not always (see for example fuel cells).

CH4 emissions are decreasing when looking at the measurements done, but a more detailed analysis is needed to take into account the decrease of the CH4 in the fuel and the increase of H2 emissions.

4.3 Overall conclusions

About 100 appliances have been tested extensively with up to 60% H2 to determine how hydrogen mixed in natural gas will impact their safety, emissions and performances.

Those appliances are representing more than 200 million domestic and commercial appliances installed in the EU, and the tests done are designed in a way to mirror what would happen to them if hydrogen was injected in the natural grid, with different proportions of H2.

The main observations and analyses from the literature (Tasks 2.2 and 2.3) and intermediate report on WP3 testing are confirmed, and new findings are also made.

Safety and operational

When looking at the overall results table and when ranking the issues as a function of an increasing rate of admissible hydrogen %, we can observe that:

- The first issue observed is a limited number of appliances whose design makes them sensitive to delayed ignition. This will happen from 15% H2 and maybe already at 10% H2 for some segments. There is probably no better solution but replacing those appliances or changing some components (retrofit). Adjustment of appliances could worsen the delayed ignition issue.

- The second issue that may happen starting from 20% or maybe below, is high CO production with premix appliances that can be adjusted on-site. The most critical case is when they are adjusted at a time when there is H2 in the blend and used with a rich gas without H2 later. Luckily, this issue or at least part of it can easily be solved with adjusting with O2 instead of CO2 or through other proposals listed in THyGA deliverable D5.2.
- The third issue is Flashback. It generally occurs for 30% H2 or more, appearing first on partially premix appliances when increasing the H2 %.
- There are specific issues that are linked to specific technologies, like CO emissions for the fuel cells but only one test was done so it is difficult to conclude.

Apart from the specific case of adjustment, if the appliances are used as delivered (adjusted in factory on G20) and untouched after installation even when the gas is changing, CO is generally not an issue.

In general CO is decreasing with H2, but this is not the case for all appliances.

Ionisation systems used for the **flame surveillance** are working well even with high % of H2 (tested with up to 60% H2).

Issues with operation ("fit for purpose") where hydrogen may impact the operation of appliances, so they become unsuitable for the purpose they were intended for, are mostly observed for higher % of H2. For example, decorative heaters may not give the same flame aspect that the customer is used to have with natural gas. For cookers, heating time will be longer due to the reduction of maximum heat delivered when adding H2 to NG. Finally, for Instantaneous water heaters the power may decrease in such a way that it would impact the comfort of the user. However, safety issues will generally appear before these operational issues.

Performances & emissions

The impact on NOx emissions is positive for the vast majority of the tested appliances (decrease of measured emissions). Note that this conclusion only applies to the test done under conditions simulating a real domestic or commercial installation, where no changes are made on appliances when the gas quality changes.

The-CH4 emissions **(unburnt hydrocarbon, during start and stop mainly)** are reduced when H2% is increasing, but since there is less CH4 in the fuel, this could be expected**. The counterpart** of H2NG blends is that unburnt H2 emissions would appear. H2 emissions have not been tested on many appliances (test is not as simple as for NOx), and therefore it is difficult to conclude.

The impact on appliance efficiency is generally very modest and can be either positive or negative (several competing phenomena, decrease of Wobbe Index, of heat input, more condensation in some cases…).

Discussion on the limitations of our conclusions

As any study, the conclusion made on the work done will have natural limitations and uncertainties.

A first factor of uncertainty is the correct evaluation of the safety by the different laboratories. Although we believe this should not be a problem for this project, it is a factor worth mentioning: It can play a role in some cases where a conclusion shall be based on an observation that is not "black or white" or on a phenomenon that is not necessarily visible for all appliances due to their construction (e.g. Flashback). Also, laboratories have experience with testing with natural gas, but testing with hydrogen is a new activity and there are no standards yet describing how to test or observe some results. The project was based on our own testing protocol including also uncertainties related to the methods adopted.

One of the other important limitations is the number of appliances tested: 100 appliances were tested when more than 200M are installed. Even is the number is high and allows for many conclusions, such a testing campaign will never be exhaustive enough to cover all technologies or design specificities, especially for older appliances still in use.

- The set of tested appliances was chosen with regard to their representativity of the market and their availability. We have used a weighting method (deliverable D2.5) for focusing testing on the more representative appliances (larger share of installed appliances in boilers and domestic, cookers).
- We also assumed a homogeneous behaviour within each segment of each type described in deliverable D2.1 (and Appendix 1). However, variations of technical features for a single segment of installed appliances are important and a project testing “only” 100 appliances cannot really guarantee that the conclusions and observation made will fully apply to the other appliances in the same segment.
- Moreover, it can happen that two appliances of the same model will not behave exactly the same way due to some aspects in the production line, tolerance rules, etc.
- Also, it shall be noted that for some segments we have only tested one single appliance (for example GHP, PEMFC, SOFC, etc.) which impedes general conclusions.

Therefore, to take into account the listed limitations, the worst-case approach was chosen to conclude segment by segment. This means that if only one appliance does not perform safely for a given operation condition and H2%, the whole segment will be considered as not performing safely with this H2% (event if the other tested appliances did perform well).

Aging is another source of uncertainty. Most of the appliances tested were new (provided willingly by manufacturers). We presumed that a used appliance cannot work better than a comparable new one. This includes the fact that new appliances are generally set by the manufacturers to work under optimal conditions before leaving the factory. The impact of the maintenance (or no maintenance) on installed appliances was not studied either.

There are also several factors that were not explored sufficiently to conclude, due to the difficulties of testing and budget limitations. Delayed ignition is probably the most important of those.

All in all, we can say that we have some natural limitation to the conclusion made for the reasons explained above, but we have tried to compensate for those with our “worst-case” approach.

Recommendations for future testing

The test done for the project to evaluate the impact of H2 has enabled us to be conclusive on many aspects. For some other aspects it would be highly recommended to have more extensive testing to be more conclusive.

Among those:

- The delayed ignition and understanding of how it can impact different technologies differently (e.g. absence of ventilator).
- The hydrogen emissions.
- Impact of aging and maintenance on existing appliances.

References

REF /1/ Project ECOTEST Deliverable D03 "ECOTEST Final report" D03 ECO_WP0_FInal reportV17d.docx. Jean Schweitzer DGC + WP leaders- 2019. Not public

REF /2/ THyGA Deliverable D2.2: Impact of hydrogen admixture on combustion processes – Part I: Theory

REF /3/ D3.5 Intermediate segment of technologies by segment report on the impact of the different H2 concentrations on safety, efficiency, emissions and correct operation

REF /4/ THyGA report D2.1 « Market segmentation of domestic and commercial natural gas appliances »

REF /5/ D3.7. Testing done on components (new and taken from existing installation) from different countries (at least FR, GE, DK and BE) including statistics on results obtained for the leakage testing

REF /6/ D2.5 THYGA "Testing programme for hydrogen tolerance tests of domestic and commercial natural gas appliances").

REF /7/ Gasqual D6.1 Standardization in the field of gas qualities. Mandate CE M400. Phase I. Final report. CEN/BT/WG 197

REF /8/ CEN Hydrogen -H2H2NG Initiative – WP8: End use appliances. GERG 2021

REF /9/ REF x Joerg Leicher – GWI presentation at IFRF 2022/

REF /10/ D3.10 Compiling of results from all tasks and development of further statistics at EU and country level

REF /11/ CEN- CR1404 Determination of emissions from appliances burning gaseous fuels during type-testing

Table of illustrations

Table of figures

ANNEX 1: Examples of appliances ID cards

THyGA Appliance ID card for	GA11_SEGM_108							
Appliance	B							
Burner	premix							
Origin	Already used in another project							
Segment	108							
Max. power input (net) [kW]	18							
Min. power input (net) [kW]	6							
SAFETY ASSESMENT. H2 % tested	0	10	20	23	30	40	50	60
1.1 SAFETY- with CH4	X			X		X		
1.2 SAFETY- with EULOW	X							
1.3 SAFETY- with G23	X							
1.4 Cold start.	X			X		X		
1.5 Hot start.	X			X		X		
1.6 Low air temperature (- 10 C)								
1.7 Flue gas pipe length								
1.8 ROC (PLUGG FLOW)	X					X		
1.9 Impact of H2 on flame detection.	X			X		X		
1.10 Flash back analyse.						X		
3.1 ADJUSTMENT A	X	X			X	X		
3.2 ADJUSTMENT B	X	X			X	X		
3.3 ADJUSTMENT H	X	X			X	X		
3.4 ADJUSTMENT G	X	X	X		X	X		
4.1 Delayed ignition test.								
4.2 Soundness	X							
4.3 Quick variation Qmin-Qmax Shut-off						X		
4.4 Overheat. Meas. of temp.								
4.5 Cooker hob test with 4 burners on	NA	NA	NA	NA	NA	NA	NA	NA
4.6 Influence of wind								
4.7 Long tem (limited time)						X		
4.8 Fluctuation of the aux. energy						X		
4.9 Fluctuation of pressure						X		
4.x Other test								
OVERALL	In its basic G20-20mbar setting, the unit can handle mixtures up to and 40%H2 without any problem. However the adjustment with 20% H2 at EU low will bring very high CO at EU high. Already adjusting at EU low + 10% will bring the CO below 1000 ppm at EU high. Note also the issue with the valve closing time & resulting emissions.							

THyGA Appliance ID card for	EB08_SEGM_303							
Appliance	C							
Burner	Atmospheric multi ring burner (dual wok burner)							
Origin	Spain							
Segment	303							
Max. power input (net) [kW]	5							
Min. power input (net) [kW]	0							
SAFETY ASSESMENT. H2 % tested	0	10	20	23	30	40	50	60
1.1 SAFETY- with CH4	X			X		X		
1.2 SAFETY- with EULOW	X				X			
1.3 SAFETY- with G23								
1.4 Cold start.						X		
1.5 Hot start.				X		X		
1.6 Low air temperature (- 10 C)								
1.7 Flue gas pipe length	NA	NA	NA	NA	NA	NA	NA	NA
1.8 ROC (PLUGG FLOW)						X		
1.9 Impact of H2 on flame detection.								
1.10 Flash back analyse.						X		
3.1 ADJUSTMENT A	NA	NA	NA	NA	NA	NA	NA	NA
3.2 ADJUSTMENT B	NA	NA	NA	NA	NA	NA	NA	NA
3.3 ADJUSTMENT H	NA	NA	NA	NA	NA	NA	NA	NA
3.4 ADJUSTMENT G	NA	NA	NA	NA	NA	NA	NA	NA
4.1 Delayed ignition test.								
4.2 Soundness								
4.3 Quick variation Qmin-Qmax Shut-off					X			
4.4 Overheat. Meas. of temp.								
4.5 Cooker hob test with 4 burners on						X		
4.6 Influence of wind								
4.7 Long tem (limited time)						X		
4.8 Fluctuation of the aux. energy								
4.9 Fluctuation of pressure						X		
4.x Other test								
OVERALL	In general, the dual wok burner does not have flashback but had flame instability with 40% H2 which might cause to flashback. The flame instability extended from inner ring to outer ring over hours.							

THyGA Appliance ID card for	GW14_SEGM_202							
Appliance	WH							
Burner	atmospheric							
Origin	New							
Segment	202							
Max. power input (net) [kW]	23							
Min. power input (net) [kW]	9							
SAFETY ASSESMENT. H2 % tested	0	10	20	23	30	40	50	60
1.1 SAFETY- with CH4	X	X		X	X	X	X	X
1.2 SAFETY- with EULOW								
1.3 SAFETY- with G23					X			
1.4 Cold start.						X		
1.5 Hot start.						X		
1.6 Low air temperature (- 10 C)								
1.7 Flue gas pipe length								
1.8 RDC (PLUGG FLOW)	X					X		
1.9 Impact of H2 on flame detection.	X	X		X	X	X	X	X
1.10 Flash back analyse.								
3.1 ADJUSTMENT A	NA	NA	NA	NA	NA	NA	NA	NA
3.2 ADJUSTMENT B	NA	NA	NA	NA	NA	NA	NA	NA
3.3 ADJUSTMENT H	NA	NA	NA	NA	NA	NA	NA	NA
3.4 ADJUSTMENT G	NA	NA	NA	NA	NA	NA	NA	NA
4.1 Delayed ignition test.								
4.2 Soundness								
4.3 Quick variation Qmin-Qmax Shut-off								
4.4 Overheat. Meas. of temp.								
4.5 Cooker hob test with 4 burners on	NA	NA	NA	NA	NA	NA	NA	NA
4.6 Influence of wind								
4.7 Long tem (limited time)								
4.8 Fluctuation of the aux. energy								
4.9 Fluctuation of pressure						X		
4.x Other test								
OVERALL	The system was tested with 60% hydrogen and no issues were observed at any time. No flashback							

ANNEX 2: Segment list from WP2 (from D2.1)

THyGA Segment	Type of appliance	Category	Burner type	Standard	Estimation of Total EU Appliance Population 2020 (x 1,000)
101	BOILERS	open flued (former EN 297)	partial pre-mix/conv. (atmos. & fan-assisted)	EN 15502	13,588
102			low NO_x		2,012
103			full pre-mix		152
104		room-sealed (former EN 483)	partial pre-mix/conv. (atmos. & fanned)		25,333
105			low NO_x		1,972
106			full pre-mix		1,781
107		condensing boiler (former EN 677)	partial pre-mix fan-assisted		2,920
108			full pre-mix (including CCB)		56,492
109		Forced-draught burners / jet burners (former EN 303-3)	Forced-draught / jet		1,129
201	WATER HEATERS	instantaneous open flued	partial pre-mix/atmos.	EN 26	14,945
202		instantaneous room sealed	partial pre-mix/fanned		
203		storage, open flued	partial pre-mix/atmos.	EN 89	3,121
204		storage, room-sealed	partial pre-mix/fan-assisted		
301	COOKERS	surface burner (cooktops) with atmospheric burner or "Venturi" burner (vertical venturi burner)	single ring	EN 30-x	32,574
302			single crown		
303			multi ring (mainly double or triple ring)		
304		surface burner (cooktops) with partially pre-mix burner (long horizontal venturi)	single ring		1,352
305			single crown		
306			multi ring (mainly double or triple ring)		
307		cavity burner "tubular" (ovens, freestanding ranges)	atmospheric burner		3,853
308			"venturi" burner		
309			partially pre-mix		27,712
310			atmospheric burner		13,056

THyGA Segment	Type of appliance	Category	Burner type	Standard	Estimation of Total EU Appliance Population 2020 (x 1,000)
311		cavity burner "metal sheet" (ovens, freestanding ranges)	"venturi" burner		
312			partially pre-mix		14,658
401	CATERING	open burners and wok burners	circular burner with vertical slots	EN 203-2-1	unknown
402			circular burner with holes		
403		mixed ovens	draught burners	EN 203-2-2	unknown
404		ovens	tubular or circular burners		
405		boiling pans / pasta cookers	micro-perforated burner	EN 203-2-3 EN 203-2-11	unknown
406		fryers	pre-mix burner	EN 203-2-4	unknown
407		salamanders / rotisseries	ceramic or blue flame burners	EN 203-2-7	unknown
408		brat pans	multi-ramp tubular slot burners	EN 203-2-8	unknown
409		covered burners (griddles, solid tops, pancake cookers)	tubular burner or multi-ramp tubular burner	EN 203-2-9	unknown
410		barbecues	chargrill with burner tubes w/ holes on top	EN 203-2-10	unknown
501	SPACE HEATERS	Independent gas-fired convection heaters type B	heating & decoration	EN 613	4,678
502		Independent gas-fired convection heaters type C	heating & decoration, balanced	EN 613	1,839
503		Decorative fuel-effect gas appliance/burner	heating & decoration	EN 13278 + EN 509	2,529
504		Independent gas-fired flueless space heaters	heating & decoration	EN 14829	98
601	CHP	Stirling engines	heating & electricity production	EN 50465	14.8
602		Internal combustion engine			40.8
603		Micro gas turbine			0.5
604		PEM Fuel Cell			5
605		SO Fuel Cell			2.7

THyGA Segment	Type of appliance	Category	Burner type	Standard	Estimation of Total EU Appliance Population 2020 (x 1,000)
701	GHP	engine HP	Heating	EN 16905	60
702		adsorption		EN 12309	
703		absorption			
801	OTHER	commercial dryers		EN 12752-1 and -2	unknown
802		infrared radiant heaters (former EN 416-1)	non-domestic, tube radiant heaters	EN 416	1,000
803		infrared radiant heaters (former EN 419-1)	non-domestic, luminous radiant heaters	EN 419	
804		infrared radiant heaters (former EN 777-1)	non-domestic, tube radiant heaters	EN 416	
805		air heaters (former EN 1020)	non-domestic, forced convection, fan, <300kW	EN 17082	1,000
806		air heaters (former EN 525)	non-domestic, forced convection, <300kW	EN 17082	
807		air heaters <70kW (former EN778)	Ducted warm air; forced convection air heaters	EN 17082	
808		domestic washing machines		EN 1518	< 10
809		domestic dryers		EN 1518	< 10
sum					**approx. 228,000**

ANNEX 3: Uncertainties of measurement. Repeatability

Statistics used and calculation made

Definitions (ISO) of repeatability, reproducibility, standard deviation

UNLESS OTHERWISE MENTIONNED the definitions proposed in this section are from:

- ISO 5725: (Precision of test methods - Determination of repeatability and reproducibility by inter-laboratory tests). *Note that the above has been used by LABNET/LABTQ since 1990.*
- Guide to the expression of uncertainty in measurement (ISO guide 98-3, known as 'GUM')
- ISO 3534: (Statistics - Vocabulary and symbols)
- CEN/CENELEC ECO-CG doc N 195 ‘Adopted recommendations for establishing verification tolerance considering measurement uncertainty’ is also used.

Reproducibility (ISO 5725)

The reproducibility (R) is the value, below which the absolute difference between two single test results obtained with the same method on identical test material, under different conditions (different operators, different apparatus, different laboratories, and different time) may be expected to lie within a specified probability of 95%.

The reproducibility is a value indicating how measurements obtained by several laboratories can be compared, for example when repeating the same efficiency test on the same boiler. The notion of outliers is used to detect measurements, for which large mistakes have been made during tests (e.g. test carried out with wrong heat input or wrong load).

*Note that the **reproducibility** is an amplitude. It is not expressed as ± **a** value as are the uncertainties.*

ISO 5725 suggest that the reproducibility shall be calculated by simply multiplying the standard deviation by a factor (2.83).

Reproducibility standard deviation (SR)

The reproducibility standard deviation is the Standard deviation of test results or measurement results obtained under reproducibility conditions.

NOTE 1: It is a measurement of the distribution of test or measurement results under reproducibility conditions.

NOTE 2: Similarly, “reproducibility variance” and “reproducibility coefficient of variation” can be defined and used as measurement of the distribution of test or measurement results under reproducibility conditions.

[ISO 3534-2, 3.3.12 mod.]

Outliers and Stragglers (Extreme values)

Extreme values are defined as observations in a sample, so far separated in value from the remainder as to suggest that they may be from a different population, or the result of an error in measurement (ISO 3534-1993).

Extreme values can be subdivided into stragglers, extreme values detected between the 95% and 99% confidence levels and outliers, extreme values at > 99% confidence level.

Outliers and Stragglers do not properly belong to the experiment and is corrected or discarded in keeping with the explanation obtained after investigations.

Outlier and straggler *values can be investigated by using the Dixon tests, Grubb, Mandel's test (used in our project here) or other tests described in standards.*

There can be different reasons for extreme values:

- The value is a mistake.
- The distribution is not Gaussian. Grubbs' test depends on that assumption. For distribution having a heavy tail, and it is easy to mistake extreme values as outliers.
- The value may be the tail of a Gaussian distribution.

Repeatability (ISO 5725)

The repeatability (r) is the value, below which the absolute difference between two single test results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory, and short interval of time) may be expected to lie within a probability of 95%.

The repeatability is a value indicating how one single laboratory can reproduce the same measurement, for example when repeating the same efficiency test (e.g. in the morning and in the afternoon).

Note that the repeatability is an amplitude. It is not expressed as ± value as are the uncertainties.

Experimental standard deviation

Experimental standard deviation (s): For a series of n measurements of the same measurand, the parameters characterising the dispersion of the results is given by the formula:

X: average of Xi

$$s = \sqrt{\frac{1}{n-1} \bullet \sum_{i=1}^{n} (Xi - X)^2}$$

The standard deviation used is always an experimental standard deviation unless otherwise specified. Note that the "traditional" standard deviation is using a dividing factor of (n) instead of (n-1).

Uncertainty

Uncertainty: Parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand.

Standard uncertainty: Uncertainty of the result of a measurement expressed as a standard deviation. The standard uncertainty is calculated from the experimental standard deviation (s).

Expanded uncertainty: Quantity defining an interval around the result of a measurement that may be expected to encompass a large fraction of distribution of values that could reasonably be attributed to the measurand.

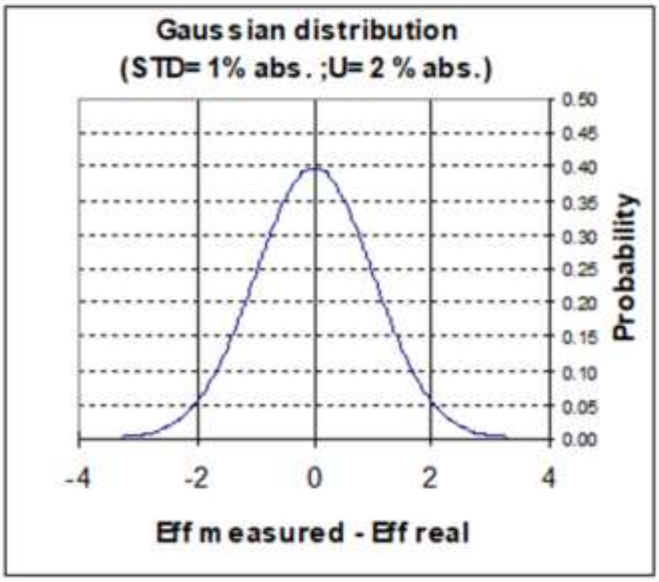
Uncertainty given with a confidence level.

Unless otherwise indicated, one may assume that a normal distribution is used to calculate the quoted uncertainty, and if the confidence level is not given, we assume it is about 95% (see definition further below).

U(95%) = 1,96.s

Very often the following rounding is used: U(95%) = 2.s

Normal distribution

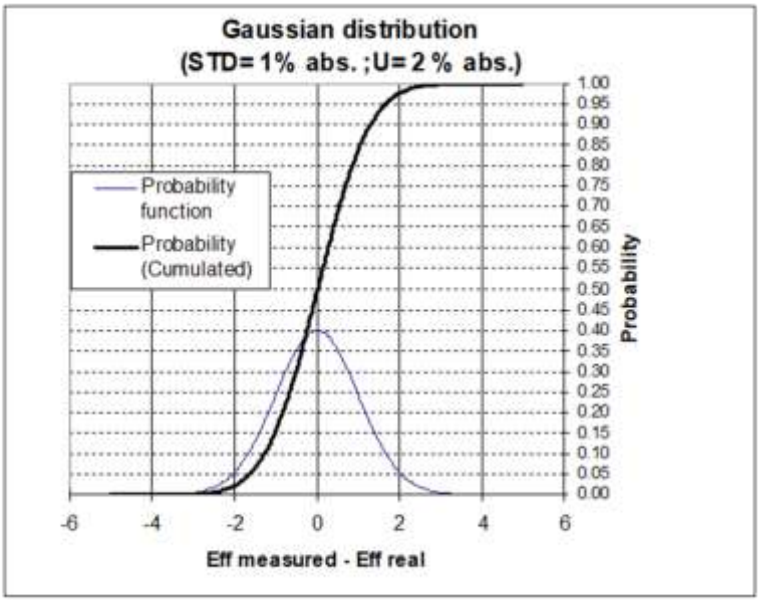


Normal distribution

Calculations are generally based on a hypothesis of a normal or approximately normal distribution of the results. However, when another distribution is known, the appropriate formulas are to be used. Unless otherwise indicated, one may assume that a normal distribution was used to calculate the quoted uncertainty.

The confidence level (comment)

The uncertainty and the reproducibility are always given with a certain level of confidence. In general, most of the laboratories are using a level of 95% of confidence (calculated as about twice the standard deviation). This means that when the uncertainty given is ±2%, there is a probability (5%) that the result is outside of the range of uncertainty. On the figure, it can be seen that the cumulated probability of having the result below -2% is 2.5% and the same probability applies for having the result over 2%.



Normal distribution and confidence level

Allowed variations of test conditions

Allowed variations of test condition parameters during the test may also be called “tolerance”, but the term “tolerance" may need to be reserved to verification tolerances. This parameter gives the allowed range of variation of a parameter (ambient temperature, water temperatures, etc.) during the testing.

Verification tolerance

The verification tolerance is the permitted range of variation that the value of a parameter measured by market surveillance authorities during a product compliance verification procedure may have.

NOTE: The verification tolerance is the value that is given in Ecodesign implementing measure and/or the energy labelling delegated act. The verification tolerance is compared to the declared value or the defined Ecodesign limit.

NOTE: The verification tolerances for market surveillance authorities do not only cover tolerances related to measurement but also production tolerances, etc.

It is not expressed as “± a”, but a value above or below which the value measured of the surveyed parameter shall not deviate with respect to the declared value

Ex: NO_x emissions shall not be more than 20% of the declared value.

Application. Practical determination of uncertainties from laboratories.

The general principles in this section are from the “Guide to assess measurement uncertainties for products under eco-design” /7/

Bottom-up uncertainty calculation

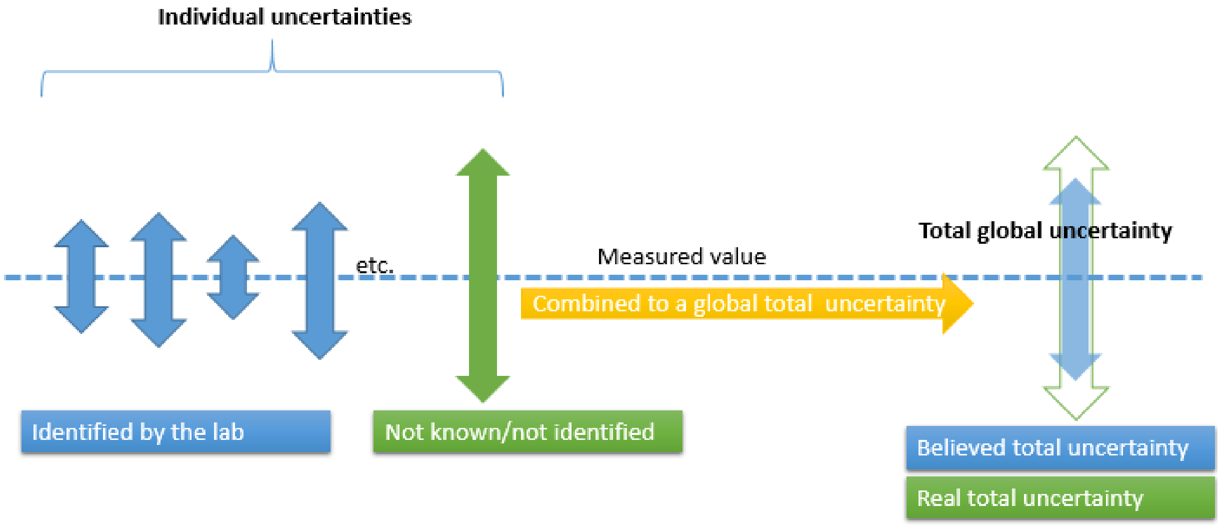
The difference seen during RRTS is partly explained by the laboratory uncertainties.

For a given metering (e.g. temperature), the uncertainty is the combination of different sources **of individual uncertainties** including such as

- Drift between calibration
- Random drift
- Resolution
- Influence of various parameters (temperature, humidity, pressure)
- Linearity of the meter
- Hysteresis
- Instruments
- Method and procedure to use the instruments
- Hardware
- Sampling-position of the probe
- etc.

Combining those is leading to a **global uncertainty** for the given metering (e.g. temperature, flow, etc.).

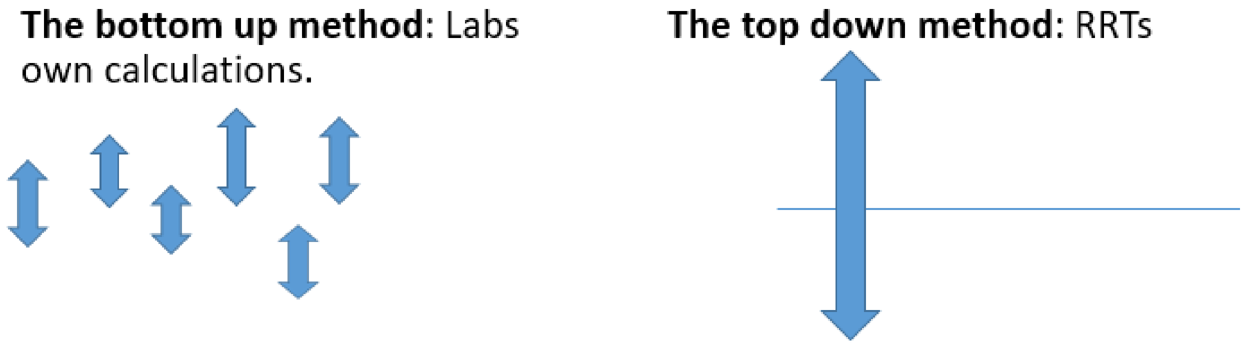
The bottom-up method requires that the laboratory investigates in detail the uncertainties on the whole measurement chain.



Combination of uncertainties

Some of individual uncertainties not known (or uncertainties not taken into account) leads to a possible underestimation of the uncertainty given by labs. Therefore, we can speak about **believed uncertainty** and **real uncertainty**.

The reason why we introduce this definition is simply because often comparing the uncertainty of labs evaluated with the bottom up does not explain the results of RRTs **(Round Robin Tests)**: there are holes between labs declared uncertainty range. In principle there should be overlap of all ranges so there is a common range where the true value is (see figure below, the illustration on left is showing "holes" between uncertainty ranges of labs).



Top down and bottom-up method

Top-down method

The top-down method is simply based on the statistics of a RRT.

In general for a normal distribution,

U = +/ - 2sigma (confidence level 95%) is used.

The value obtained is not nominative by lab, but it is an aggregated results that reflects both the individual uncertainties of the labs & methods.

Selection of parameters and definitions for the statistical analysis

1. Median value **(med)**
   The values are ranked from the smallest to the highest or from the highest to the lowest. Then the value just in the middle is the median value (if the number is odd) and arithmetic average of n/2 and (n/2+1) if n is even.
2. Deviation from median value **(Delta_med)**
   Difference between any value and the median value.
3. Arithmetic mean value (average value) **(Xm)**
   Arithmetic mean of all values (sum of all values divided by the number of values).
4. Deviations from arithmetic mean value **(Delta_a)**
   Differences between laboratory individual values and the arithmetic mean value.
5. Repeatability standard deviation **(s_r)**
6. The standard deviation of the values measured by each lab (in the column of each lab) and the standard deviation of all the values (in the column "total of all the labs).
7. Reproducibility standard deviation **(s_R)**
   The standard deviation of the arithmetic values (if several tests are performed in the lab) or single value measured.

8. Difference between max and min arithmetic mean values **(M-m)**
The difference between the maximum arithmetic average value and the minimum arithmetic average value (if repeatability test are done) or just the difference between the maximum value and minimum value of the declared values.

Within lab repeatability standard deviation in case several values declared

$$s_r = \sqrt{\frac{1}{P}\sum_{i=1}^{P}(s_{L,i})^2}$$

With $S_{L,i}$ = repeatability standard deviation for each laboratory calculated by:

$$s_{L,i} = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}(X_{L,i} - \bar{X})^2}$$

$\bar{X}$: average value for each laboratory calculated by:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_{L,i}$$

n = number of test results for each laboratory (same for all laboratories)
P = number of laboratories

Inter laboratory reproducibility standard deviation SR

$$S_R = \sqrt{\frac{1}{P-1}\sum_{i=1}^{P}(\bar{X}_i - X_m)^2 + \frac{n-1}{n}s_r^2}$$

Xm = arithmetic mean value of the arithmetic mean values $\bar{X}_i$ of the P participating laboratories

$$X_m = \frac{1}{P}\sum_{i=1}^{p}\bar{X}_i$$

If no repeatabilty testes (n=1) then s_R is not adressed and S_R is equal

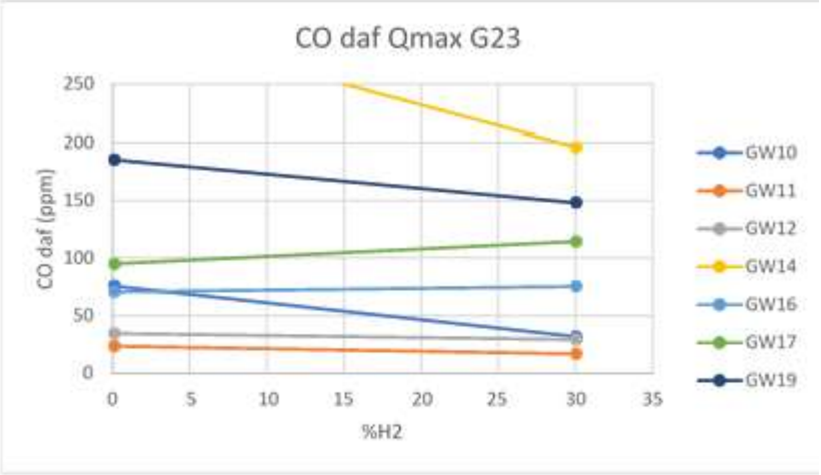
$$S_R = \sqrt{\frac{1}{P-1}\sum_{i=1}^{P}(\bar{X}_i - X_m)^2}$$

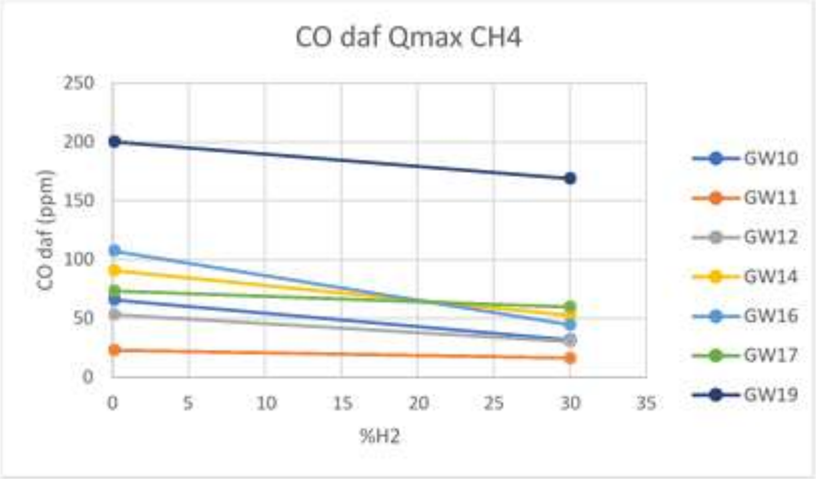
The data above are used to express the “variability” of test results between the laboratories. Several parameters are used (Max-Min, Reproducibility) and those are discussed further in the section 4.5.

ANNEX 4: Detail of test obtained with G23

Comparative CO emissions at Qmax with G23 and CH4 (measurement set2)

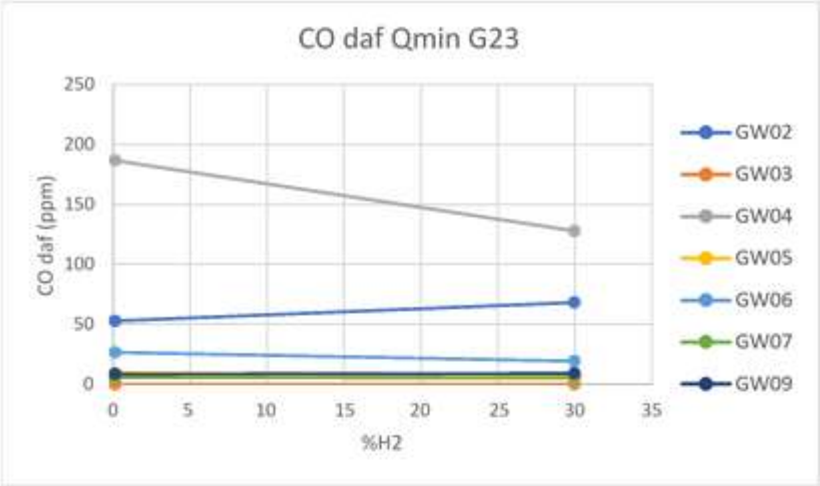
With G23, CO level is generally higher (as expected), but the trend of adding hydrogen is the same, the emissions globally diminish or stay the same.

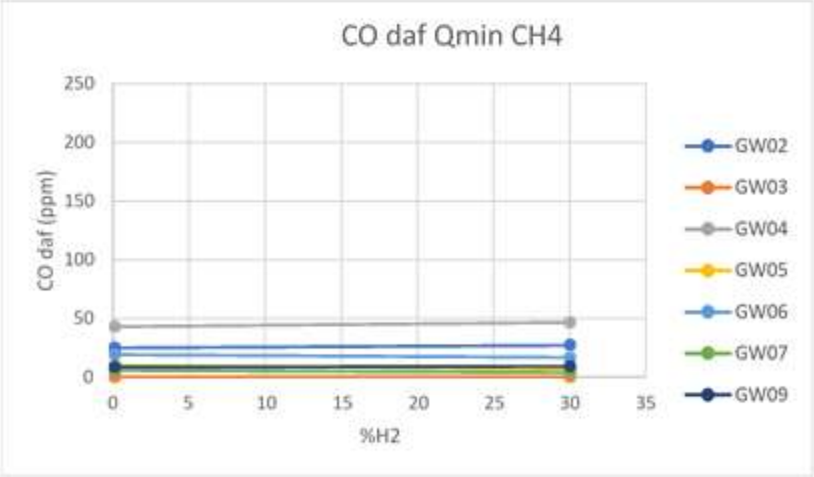




Comparative CO emissions at Qmix with G23 and CH4 (measurement set1)

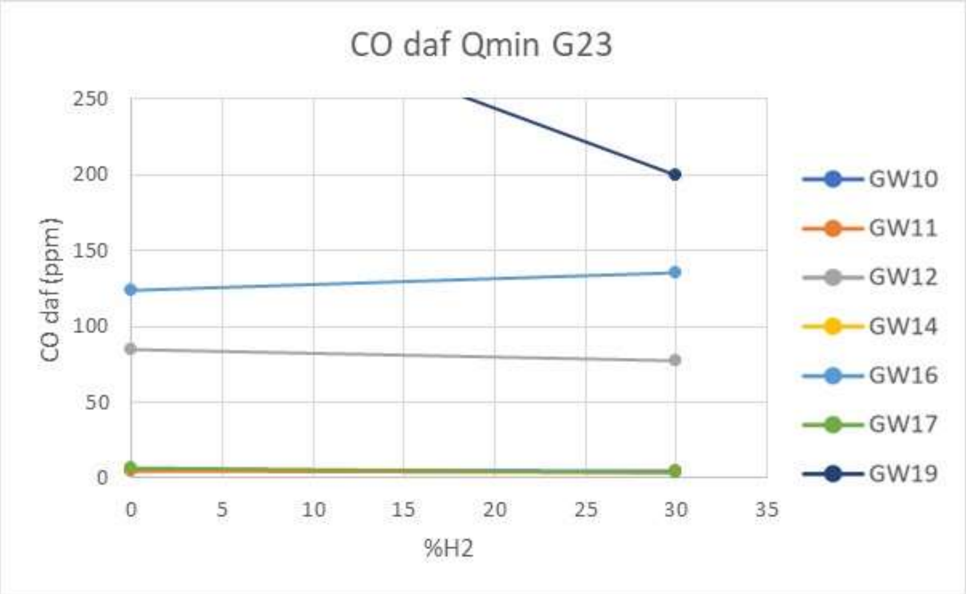
With G23, CO level is generally higher (as expected), but the trend of adding hydrogen is the same, the emissions globally diminish or stay the same.

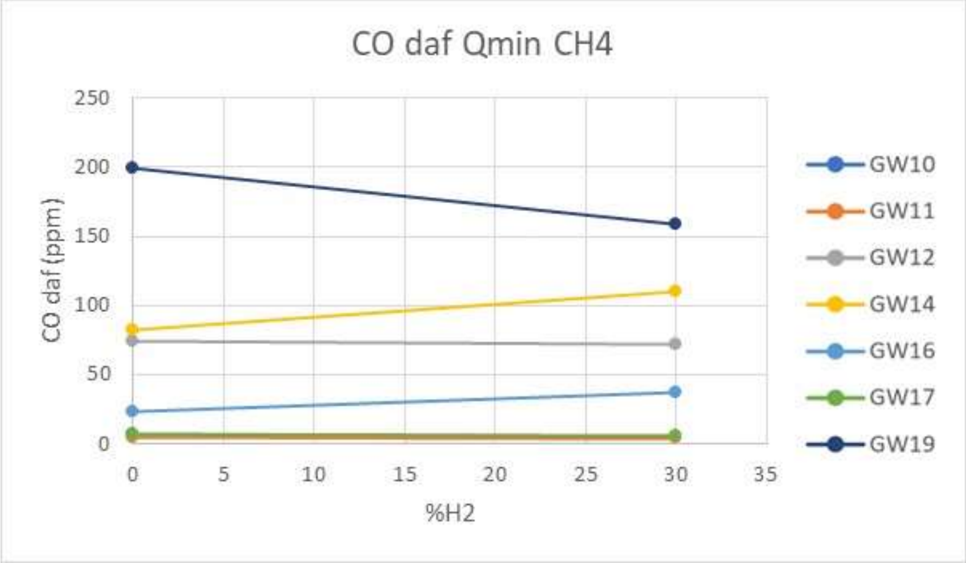




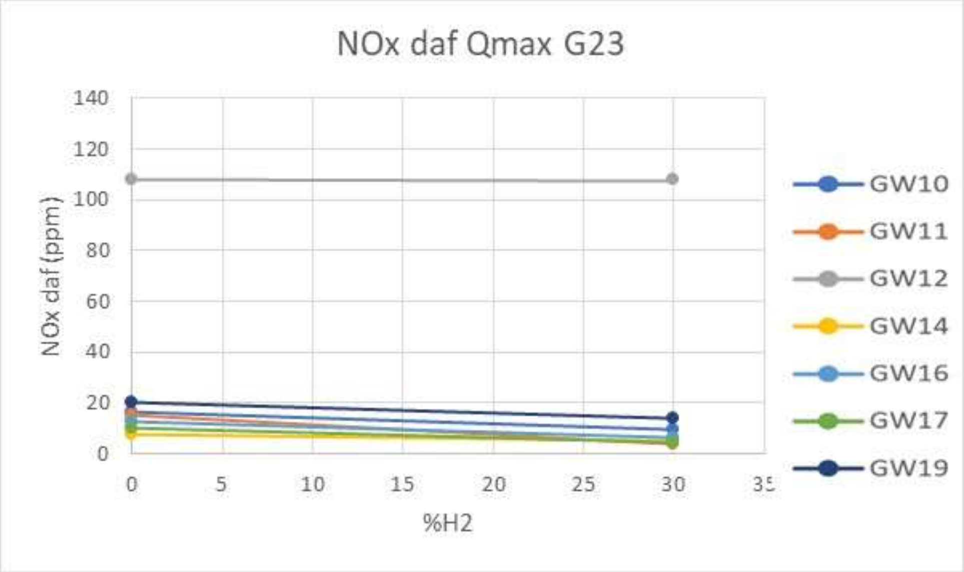
Comparative CO emissions at Qmin with G23 and CH4 (measurement set2)

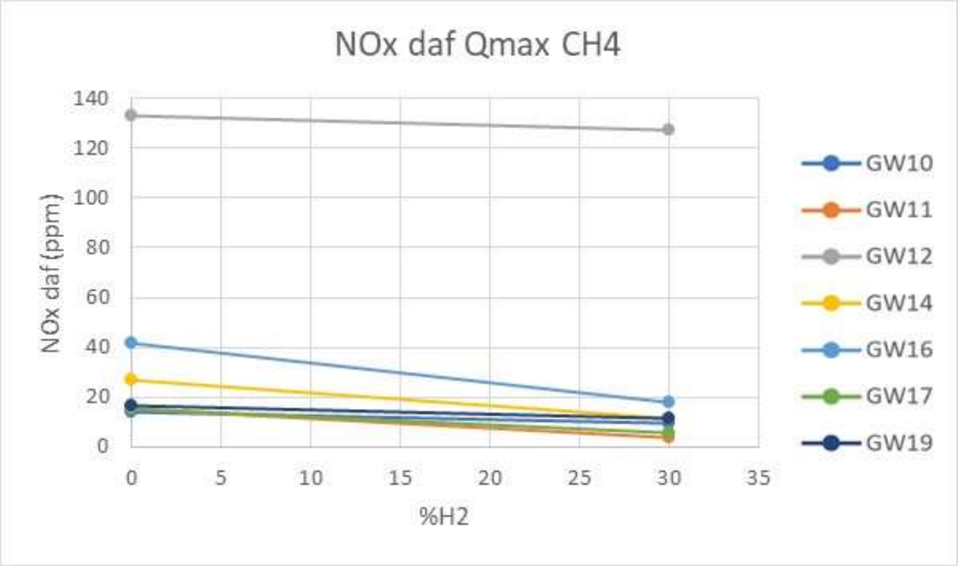
With G23, CO level is generally higher (as expected), but the trend of adding hydrogen is the same, the emissions globally diminish or stay the same.



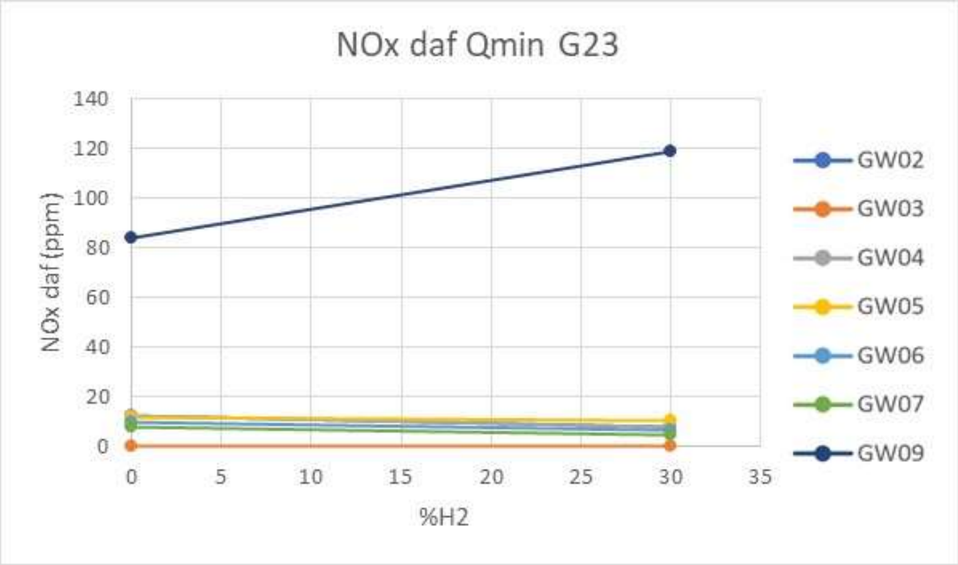


Comparative NO_x emissions at Qmax with G23 and CH4 (measurement set1)

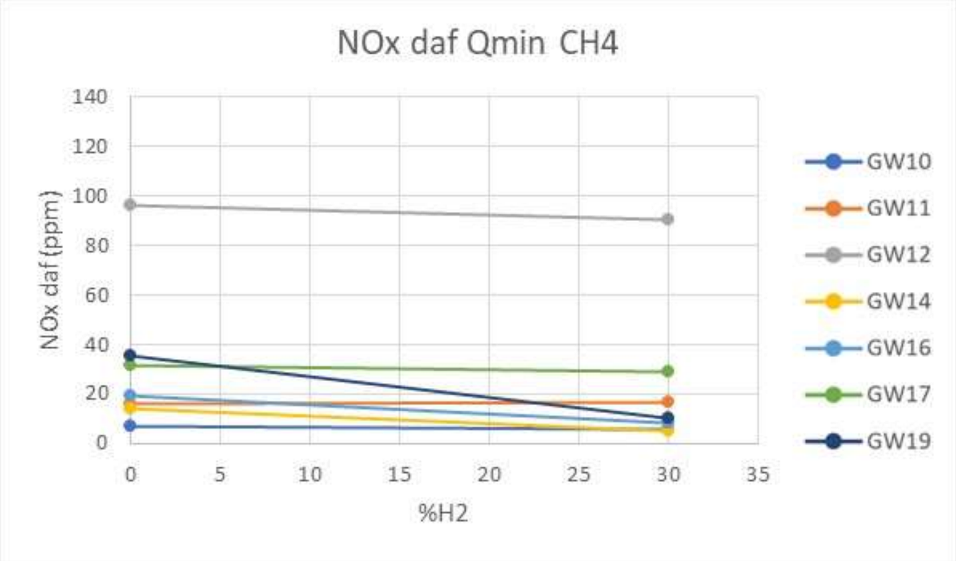




Comparative NO_x emissions at Qmin with G23 and CH4 (measurement set1)



Comparative NO$_x$ emissions at Qmin with G23 and CH4 (measurement set2)



ANNEX 5: Change of gas composition impact on laminar flame speed, Wobbe index and density

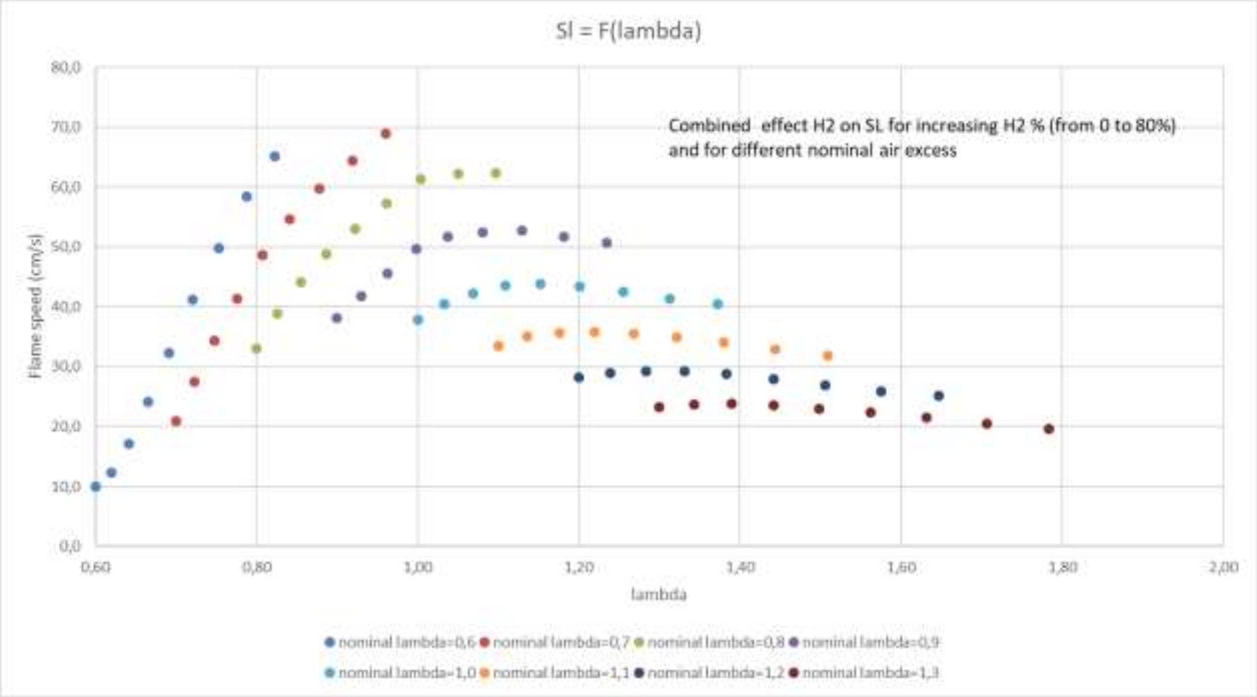
From “THY_WP3_007_Test gasesV01- DGC febr 2020”, rough calculations in view of helping the choice of test gases for THyGA.

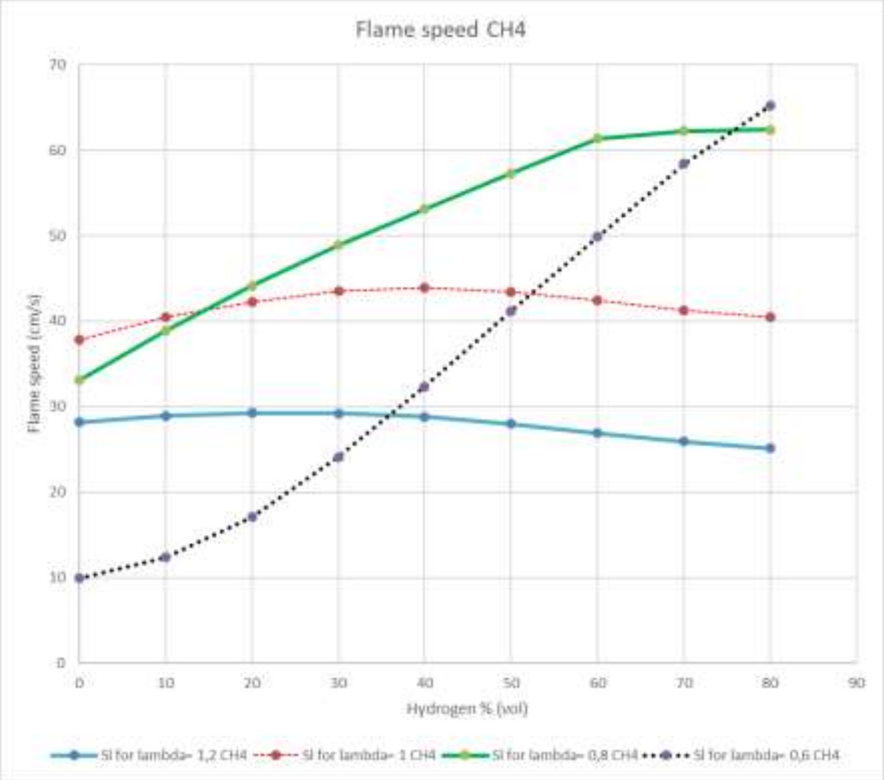
Conditions:

- Tool used: simple model DGC based on a Dutch model
- constant air flow
- no adjustment of gas flow
- lambda given in this note is the initial air excess without H2
- EU high and EU low, see slides WP3 Kick off meeting

1) FLAME SPEED

Observation 1: The flame speed is very much depending on the initial air excess (lambda) in the front flame

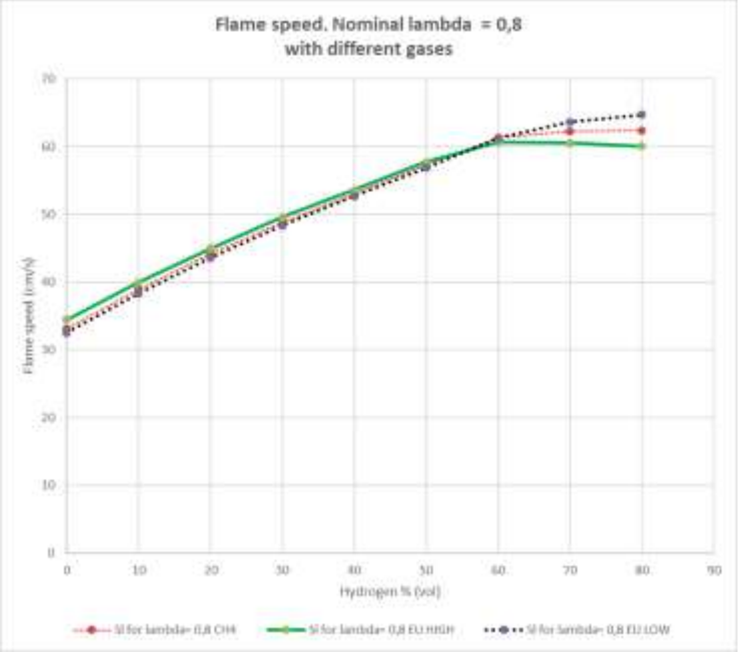


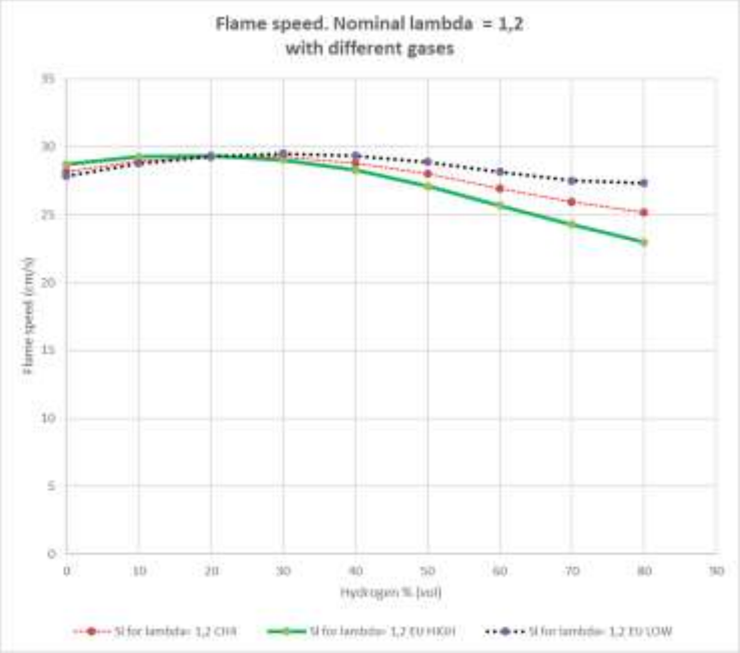


- While premix appliances (e.g. Lambda = 1,2) are not very much impacted by the H2, for atmospheric burners the flame speed increases very fast with the H2 %.
- Depending on the burner type the flame speed may increase when injecting H2 AND decrease after a certain % (e.g. for lambda = 1 the flame speed is reducing when H2 > 40%.

Observation 2

The flame speed is only impacted by the gas used for H2 > 40 to 60%. The impact remains much lower than the initial air excess. Poor gases (e.g. EU low) are more impacted.



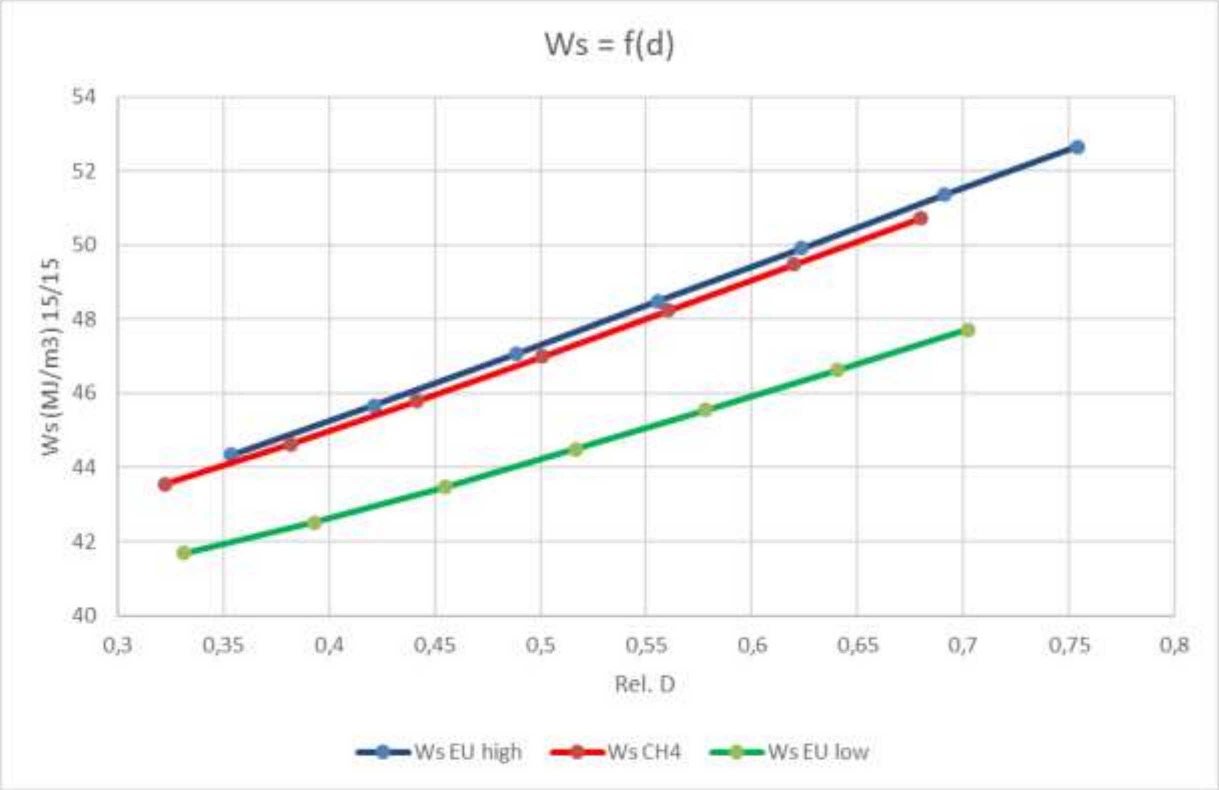


2) Wobbe and Density

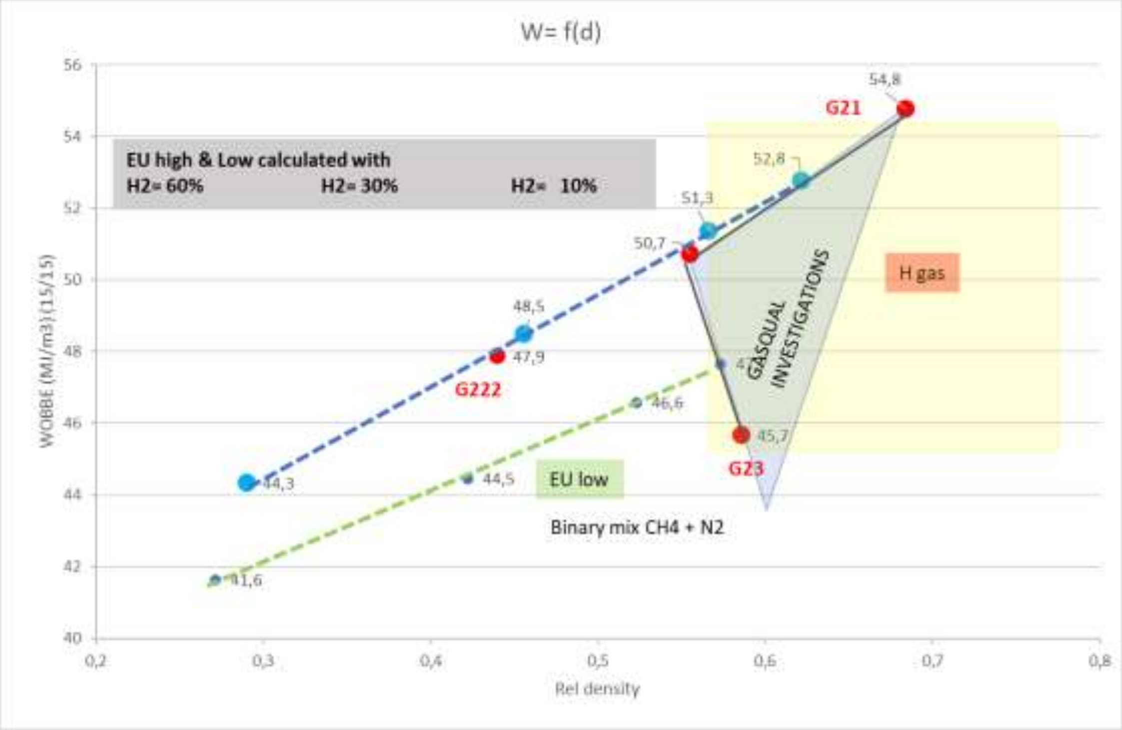
The Wobbe and the density are strongly impacted by the H2. CH_4 Wobbe is between EU high and EU low, but CH_4 density is lower that EU low.

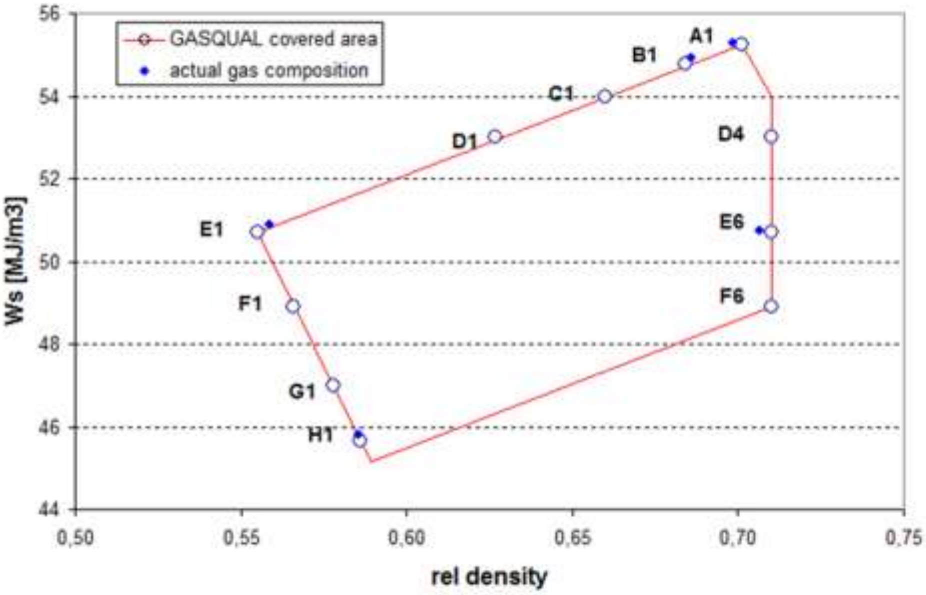
The following figure shows how the Wobbe and density are impacted by H2 injection. Injecting H2 to EU high will generate W,d line close to the G20 line (Shifted) (see lines red & blue). However, starting with G20 will be more challenging, as both Ws and d will be ending at lower values with 60% H2 mix!

Therefore, for the investigation of (W,d) alone, it make sense to test with G20.



Ws = f(d) for EU high, EU low and CH4 (from 0 to 60% with 10% increment).





CONCLUSIONS FOR TEST GASES

The initial gas composition is important for the Wobbe and the density, it is less important for the flame speed (Slight impact and only H2 > 40%.)

ANNEX 6: Colour code used for the evaluation (reminder)

🟩	No issues
🟥	Safety issues
🟨	Potential issue
🟧	Operational issue
▨	Not tested extensively
⬜	Not tested