Self-regulated gas boilers able to cope with gas quality variation
State of the art and performances

Report, October 2018.

Stéphane Carpentier,	Engie Lab Crigen
Patrick Milin	Engie Lab Crigen
Nourreddine Mostefaoui,	CETIAT
Petra Nitschke-Kowsky,	E.ON
Jean Schweitzer,	DGC
Negar Sadegh,	DGC
Olivier Thibaut,	Gas.be

Sponsors:
Gasunie Transport
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A GERG Project

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1 Management Summary

The technology of combustion controlled condensing boilers was first introduced in the market in 2001 and meanwhile highly developed and offered by 11 European manufactures in a wide range of load and application in 24 European countries. Reliable market data is hard to get, but data from Germany reveal an already high and growing share in sales since few years already. Up to now more than half a million combustion controlled boilers are installed in Germany. The technology mainly relies on the technology of ionization signal in combination with a smart control including also the fail-safe function. In contrast to the apparently established market introduction, the knowledge in the technical public (grid operators, installers, members of standardization committees, etc.) and from independent lab- and field investigation seems to be poor. A project initiated in GERG was organized in two phases. Phase I was to execute a literature study technology of combustion controlled condensing boilers. Phase II of the project was to bring light on the actual performances by laboratory testing.

Project goal and approach

With the developing gas markets in Europe – e.g. market liberalization, integration of renewables, European standardization - gas application technologies providing a high flexibility to gases from different natural sources and from renewable production like bio methane and hydrogen become more and more important. Against this background - within GERG five project partners (CETIAT; DGC; ENGIE, EON, GAS.BE) decided to conduct a project on the technology of combustion controlled condensing boilers (CCCB), a technology already introduced in some European markets but still in technical and market development. The first phase of the project was executed as desk research from February to September 2017 and provides results on the technology of CCCB, standardization, market and existing literature about any other aspect. Additionally a proposal of appliance tests protocol was elaborated and those tests should be conducted in a second phase of the project. The project costs of the partners are borne by the single partners themselves. Project organization and the compilation of the common report are supported by the project sponsors Gasunie Transport Services B.V. (NL) and CADENT, UK. Sponsors are having full information of the project.

Results of Phase I

Technical background

Although strong efforts have been done to standardize gas qualities in Europe, the Wobbe range is still defined nationally and differs from member country to member country. UK for example specifies a narrower band from 47.2 MJ/m³ to 51.4 MJ/m³, whereas Belgium allows a range from 46.6 MJ/m³ to 53.9 MJ/m³ (ref.:15°C/15°C).

Effective gas qualities and its fluctuation at single exit points are rarely documented in Europe. Published measurements from France and Germany document a maximum local variation of the Wobbe number in ranges from 3.4 MJ/m³ to even 6 MJ/m³. As supply in the future might be more diversified and injection of renewable gases will increase, gas quality will probably fluctuate even more.

Standard condensing boilers

Standard condensing boilers are designed to cope either to the group H (45.7 MJ/m³ to 54.7 MJ/m³) or E (40.9 MJ/m³ to 54.7 MJ/m³) respectively or the group L (39.1 MJ/m³ to 44.8 MJ/m³) defined in EN437. Within the gas group they should operate with the defined range of gas quality safely, reliable and environmentally friendly. Comprehensive lab investigation within the GasQual project on new condensing boilers revealed the following:

- New condensing boilers adjusted to the nominal value of the gas group H cope with the whole bandwidth of gas quality within the group H
- Emissions of CO and NO_x as well as efficiency depend partially strongly on the Wobbe number of the supply gas even within group H.
- Once the nominal adjustment of condensing boiler is changed (which may occur in the field, when gas quality is fluctuating) the appliance does not cope any more to the whole Wobbe range required.
- Few experiences are documented for older, long-time installed combustion controlled condensing boilers.

The new developed technology of combustion-controlled appliances may overcome these difficulties, as they adjust steadily to the nominal operation point avoiding an increase of emissions and false adjustments due to varying local gas qualities.

Technology of Combustion Controlled Condensing Boilers
Intensive desk research on this technology comprising literature research, technology analysis and market investigation has been conducted by the project partners.
Information on different gas quality sensors on the market is compiled, including direct and indirect measuring methods as well as sensors measuring before, within and after the combustion zone. The easiest method applicable for fully premixed burners used in condensing boilers is the measurement of the ionization current within the combustion zone. The signal responds quickly on gas quality change, so that a fast control is realizable. The form of the ionization curve depends strongly on the air factor, which itself depends on the gas quality. However the absolute value of the ionization signal may depend on the age of the probe and the boiler etc. This problem is solved by smart control software including a recalibration mechanism. Different systems basing on patents from Kromschröder, Siemens and others are realized in different boilers.
Condensing boilers of one single manufacturer type are equipped with a CO-probe to control air factor and gas quality. According the first information this manufacturer will switch to ionization controlled boilers too.
The construction and assembly of the actuator elements, fan and gas valve in the combustion controlled condensing boilers are very similar: The fan with an electronic speed control is the leading element. Gas is introduced in a venturi tube sitting in the inlet of the fan so that the air flow rate determines the pressure on the outlet side of the gas valve. The simple gas valve controls inlet pressure and an orifice often regulated by a step motor. The fail-safe function is given by the smart control.
Within the standard EN437 CCCB are approved due to the category I2N comprising all gas groups within family 2, i.e. (39.1 MJ/m³ to 54.7 MJ/m³).

Market investigation Combustion Controlled Condensing Boilers
First CCCB entered in 2001 the market on a boiler with a maximum load of 15 kW. Up to now 12 manufacturers offer this technology with in a wide load range from 12kW up to even 150 kW. Not only single family houses, but also multi-family houses and light to medium commercial buildings boilers may be equipped with this technology. The technology is offered on the wide panel of models. The technology is offered in at least 25 European countries. It is interesting to mention, that the technology is even offered in countries, where the respective category due to EN437, I2N, is not yet accepted, for example UK. In these countries CCCB are approved due to I2HLL or I2ELL and their technical advantage may not be aware for installers, customers and grid operators.
Very few reliable data of the market penetration of this technology are available. An inquiry of the Federation of German Heating Industry for DVGW revealed that nearly one third of the

sold heating appliances in 2014 were combustion controlled condensing boilers. Information about the share of installed appliances may be deduced from the inquiry during the L/H-conversion projects in Germany. It seems to depend very much on the region and on the local preferred manufacturers. Share of up to one quarter of all installed condensing boilers have been documented.

Technical Investigation documented

Literature research revealed an immense amount of publication on different sensor technology, gas quality studies and very specific details, but a lack of independent lab tests and field test of CCCB technology. Some few older publications document lab measurements of functionality, emissions and real life behavior. Praxis behavior of CCCB is documented but not published in one project. Against the background of gas quality standardization in Europe and the intent of some countries to enlarge their legal Wobbe range it is of great interest to make a new effort to measure and evaluate the technology of combustion controlled condensing boilers with lab tests.

Results of Phase II

Evaluation in the lab of existing boilers equipped with combustion control

The goal of the lab tests is to investigate –within the limited time and budget – six selected CCCB under conditions relevant for the current and future practices. As gases we defined the whole range of test gases due to EN437 with a slight extension at the lower end due to the German group LL (34,3 MJ/m³ - 54,7 MJ/m³) including a bio methane and mixtures up to 30% Hydrogen. Tests have been conducted in stationary and unsteady conditions.

Main results of phase II

The testing of 6 different boilers all equipped with combustion controls shows the following results:

Result 1, Combustion controls and boiler installation and maintenance:

All six boilers are compact, quick and easy to install. Because of the combustion control no on site adjustment is necessary. This means that the operations of commissioning and maintenance or repair should be faster and easier. This will result in cost savings.

Result 2, Air factor:

The combustion control system of all boilers keeps the air factor (e.g. O_2 and CO_2) quiet constant over the whole range of Natural Gases with Ws from 34.3 MJ/m³ to 54.7 MJ/m³.

Result 3, Emissions:

Because of the constant air factor emissions of CO and NO_x stay at their low level over the whole range of Wobbe number.

Result 4, Gases with hydrogen:

The boilers operate safely and with low emission with gases containing up to 30% hydrogen. Emissions of CO and NO_x are even reduced. However, the combustion control system does not work as exactly as for gases without hydrogen admixture.

Result 5, Efficiency:

The efficiency (maximum load) stays quite constant within the measurement accuracy of < ∓ca. 2% for four of the boiler.

Result 6, Operation under rapid change:

All boilers are able to cope with instantaneous jumps of gas quality from minimum to maximum and vice versa without any interruption of operation. The time to return to nominal operation (stabilization time) is less than 2 to 3 minutes.

Result 7, Stable heat input and heat production:

Boilers with ionization controls are, for most of them, able to maintain the heat input of the appliances.

Result 8, Abnormal operation situations:

Test has shown that control based on ionization can compensate variations of voltage, gas pressure and blockage (air inlet and flue gas).

The results of test obtained were also compared with existing tests results of boilers not equipped with combustion controls. The conclusion are that boilers with combustion controls:

- Can accept gases over the combined range of L and H gas without needing any adjustment
- Improve the safety of the end-user by maintaining CO emissions more or less constant all over the ranges of L and H gases.
- Reduces the NOx emissions by maintaining those more or less constant over the whole ranges of L and H gases
- Keep the heat delivered to the user constant
- Keep the efficiency constant

Considering the low investment cost of the control system (in a mass production of boilers), it would be very much advisable that the use of this technology should be extended to all boilers sold on the market.

2 Introduction

More than 200 million of domestic appliances are using natural gas [1]. Most of the customers are using gas for room heating, hot water production and cooking for the reasons that gas is reliable, economic and ecologic energy source. In the commercial sector (restaurant, schools, hospitals), the same technologies are used at a larger scale. The different players in the European gas industry, TSO, DSO, retailers and appliances manufacturers in cooperation with their respective technical associations and market partners are working continuously to further develop the high standard and to respond the customer request under the changing market organization and liberalization.

Diversification of sources and integration of renewables are two important aspects of the market development. Europe imports more than 80% of gas from different countries by pipelines and in the form of LNG with more or less variable qualities according to the production gas fields. These gases mix in the networks according to preferential flows and to consumption (climatic variations and industrial requests). The integration of renewable energy e.g. bio methane and renewable hydrogen from power to gas is of the increasing importance in view of the rising need to intensify the efforts of climate protection.

In this context gas quality and the definition of acceptable ranges of variation is in intensive discussion and a central goal of European standardization work.

Realizing the future challenge a growing number of manufacturers has developed and brought to market integrated self-regulating components for appliances and especially for condensing boilers.

Gas boilers represent a very significant part of the gas market with 80 million units installed in the EU. Therefore it is highly relevant to investigate the performances of this fairly young combustion control technology especially under the aspect of changing gas quality. Will the use of combustion controls help the appliances to accept a wider gas quality range? What would be the costs, and are there any “side effects” on efficiency or emissions? Are combustion controls reliable in the practice? Is this technology able to cope with the whole range of gas qualities?

And what is the relevance of the technology in the current market of installed appliances and in the sales market?

The answer to these questions will bring important information not only to end user customers, installers and manufacturer but also for the discussions within the standardization process of gas quality in Europe.

3 Project Goal, Scope and Approach

The text below is extracted from the proposal
The project has been initiated within GERG (European gas research association) by a consortium of 5 partners (CETIAT; DGC; ENGIE, EON, GAS.BE). The objective of this common study is to make during the **first phase** (desk study), a technical review (state of the art normative situation, etc.) on the technology developed, available products, standardization and literature.
The ability of these combustion controlled appliances to cope with gas quality variations should be assessed, as well as the influence on safety, emissions and efficiency as far as possible from the desk study
In a **second phase,** 5 boilers from different manufacturers will be tested under several agreed test conditions of gas supply to check the performances of the control devices integrated in these boilers. All results will be compared to the results of appliances that are not equipped with those systems to elaborate the advantages.
This will bring an extensive knowledge about the performances of the combustion control system, knowledge that will be shared with the partners and sponsors of this project.
One of the final goals is also to summarizing the main results in a publication that will be prepared in a suitable way for public dissemination about the advantages of the technology. Further development chances of such controls will also be discussed.

3.1 Working packages and timeline

1. Phase: Desktop investigations (month 1 to 6) that will include points such as

    a. Technology description
    Description of the currently used technology
    (Sensor, gas valve, fan, control unit)
    Future systems for control, new sensors, new actors, new burners
    Sensibility to different gases including bio methane and Hydrogen

    b. Market share
    Appliances with combustion control, (on the market or in development)
    List of manufacturer offering boiler with combustion control
    List of appliances in development (if available)
    Market share
    Costs

    c. Literature research
    Existing test results in regard of sensibility to different gases including bio methane and Hydrogen

    d. Summarizing and evaluation of results from literature and conclusions on the following questions:
        - Wobbe range of safe and reliable operation?
        - Influence of gas components? Hydrogen in particular?
        - Effect on efficiency?
        - Effect on emissions?
        - Reliability of the control over time

- Correction of ambient weather influences (combustion air temperatures, pressure in flue gases)
- Further benefits?
- Comparison to boilers operating with a wide range of Wobbe number without control

e. Conclusion and decision about Phase 2 (Testing)

2. Phase 2: Testing (month 7 to 12)
At least five (we tested six) of the most interesting appliances are tested in the laboratory of the project partners to check their performances and ability to cope with the whole range of gas quality, the impact on emissions, efficiency, reliability and safety. Results will be compared to measurements on standard condensing boilers (not equipped with combustion controls).

A detailed measuring program is agreed between the project partners before testing, including at least

- Test gases
- Way of switching the gases
- Measured variables
- Load (Full Load, minimum load, …)
- Ambient condition range (Combustion air temperature, flue pressure)

Reference of Wobbe number and calorif value is 15°C/15°C in this report.

3.2 Project Organization

The project is executed by five project partners:

Danish Gas technology Center (DGC), Dr. Neergaards Vej 5B - 2970 Horsholm, DENMARK,
CETIAT, 25 Avenue des Arts (LA DOUA), BP 52042 Villeurbanne 69603 – Cedex France
GAS.BE, 15 Place Masui, 1000 Bruxelles, Belgium
E.ON Metering GmbH, E.ON Metering GmbH, Gladbeckerstr. 404, 45326 Essen, Germany
CRIGEN, 361 avenue Wilson, 93210 La Plaine Saint Denis, with the financial support of
GRDF, 6 rue Condorcet – 75009 Paris - France

Project partners work closely together in phase 1 to elaborate and exchange the information and compile the phase 1 report.
In phase 2 each of the partners test one selected combustion controlled condensing boiler in his own laboratory under agreed conditions. Results are exchanged, discussed and evaluated commonly.

The project is partly supported by two sponsors:

Cadent (previously National Grid)
Gasunie Transport Services B.V.

Project sponsors are invited to the main project meetings and they get the full project information confidentially.

3.3 Project Funding

A detailed project costs in the respective working packages are listed in appendix 1. The total costs are Euro 190.000.
Partners have decided to organize the work in an equal way and pay their own costs for both phases. Sponsors participates with a fee of 8000 Euro that is used to cover the coordination and reporting costs of the project. The partners/sponsors will be mentioned and referred to in

all publications (see deliverables list) showing their involvement in the harmonization process.

4 Technical Background

4.1 Legal Gas qualities ranges in Europe

The quality i. e. the composition of natural gas depends on the different sources within Europe and in the supply countries, like Russia, Norway, North Sea, Libya, Algeria and worldwide taking LNG in to account. The main component with more than 80% is methane but different gases like nitrogen, carbon dioxide and higher hydrocarbons may be part of natural gases. The Wobbe Number (calorific value divided by the square root of the relative density) is the main characteristic number describing the combustion behavior of the gas, besides calorific value itself and the air requirement.

All the European countries using natural gas in distribution grids defined a range of Wobbe Number for the supply gases in their grids and requirements for appliances.

The European legal Wobbe ranges are collected and compiled within the project GasQual, see Figure 1. Note that values from the Netherlands are not on the figure below, but the Netherland has the widest range (Max – Min = 8,7MJ/m3)

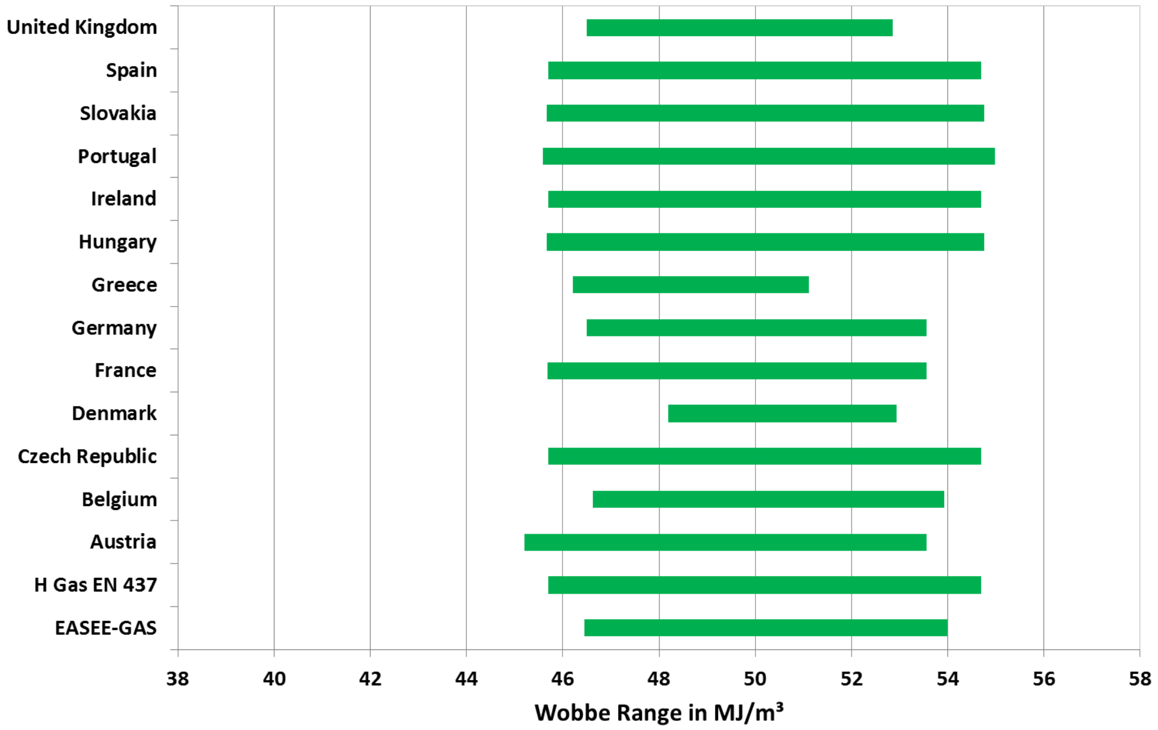


Figure 1: Some exemplary legal Wobbe ranges of the European Countries

Since 2005 the members of EASEE Gas agreed a common business practice with a Wobbe range of 13.6 – 15.8 kWh/m³ (25°C/0°C) or 46,5 MJ/m³ to 54,0 MJ/m³ (15°C/15°C) for cross border trading. Unfortunately this range is not legally binding and has not really been applied. A harmonized European legal range of Wobbe Number to be implemented in the European Standard of gas Quality H for cross border trading is central part of the work of CEN SFGas WG “Pre-normative Study of H-Gas Quality Parameter”.

4.2 Short History of gas quality harmonization and standardization and corresponding project GasQual

Harmonization - First phase (<2015)

The process of harmonization has a long history behind it. It started in 2002 with EASEE gas specifications covering not only the Wobbe but also other parameters.

EASEE-gas

The Gas Quality Harmonisation
Common Business Practice

Approved parameters, values and ranges

Parameter	Unit	Min	Max	Recommended implementation date
WI	kWh/m^3	[13.60]	15.81	1/10/2010
d	m^3/m^3	0.555	0.700	1/10/2010
Total S	mg/m^3	-	30	1/10/2006
H_2S + COS (as S)	mg/m^3	-	5	1/10/2006
RSH (as S)	mg/m^3	-	6	1/10/2006
O_2	mol %	-	[0.01]*	1/10/2010
CO_2	mol %	-	2.5	1/10/2006
H_2O DP	°C at 70 bar (a)	-	- 8	See note **
HC DP	°C at 1 – 70 bar (a)	-	- 2	1/10/2006

* EASEE-gas has organised an oxygen measurement survey, which by end of 2005 will examine the maximum feasible limit equal to or at an alternative specified value below 0.01 mol %.

** At certain cross border points, less stringent values are used than defined in this CBP. For these cross border points, these values can be maintained and the relevant producers, shippers and transporters should examine together how the CBP value can be met in the long run. At all other cross border points, this value can be adopted by 1 October 2006.

Figure 2: EASEE gas specifications

In 2008, CEN received a mandate (mandate M 400) from the EU to make a new harmonized gas H standard.

The work was organized in two phases:

a) Investigations to determine the impact of gas quality variations on the actual population of domestic and commercial appliances under the project GasQual [1]

b) A cost-benefit analysis of different scenarios

c) Standardization

100 appliances were subject to extended tests in the project GasQual [1] bringing conclusions on 27 segments of appliances. For condensing boilers one of the main conclusions from GasQual project was the importance of possible adjustments of the appliances. This was confirmed by results from real life in Denmark after experiencing gas quality changes on the market.

Despite the investigations, the new standard EN16726 Gas Infrastructure - Quality of Natural Gas - Group H [2] was published without Wobbe specifications due to disagreement between experts and uncertainties about the future of the standard: would it be legally binding or not.

In 2013, the European Commission welcomed a Marcogaz / EASEEGas initiative on regional harmonization. The idea was to gather a few countries (Belgium, Germany, Denmark, France, and Spain) with the idea to make a desk-exercise to study the consequences of harmonization in the five countries involved. The exercise called **Pilot Study I -** was however carried out without the involvement of manufacturers and the project failed.

A gas standard without Wobbe range specifications is unacceptable for the EU and many other stakeholders. Many stakeholders advocated for a wide gathering of all EU expertise in order to establish an uncontroversial view on Wobbe impact.

Harmonization – second phase (> 2015)

A "Pilot2" (**Prenormative H gas Quality Study**) initiative (sometimes called **Pilot Study II**) was established in 2016 on the basis of a request from the Commission. The new forum was under the CEN with the mission of updating EN16726 / 2 with a Wobbe range.
The work is organized in several groups, as shown in Figure 3.

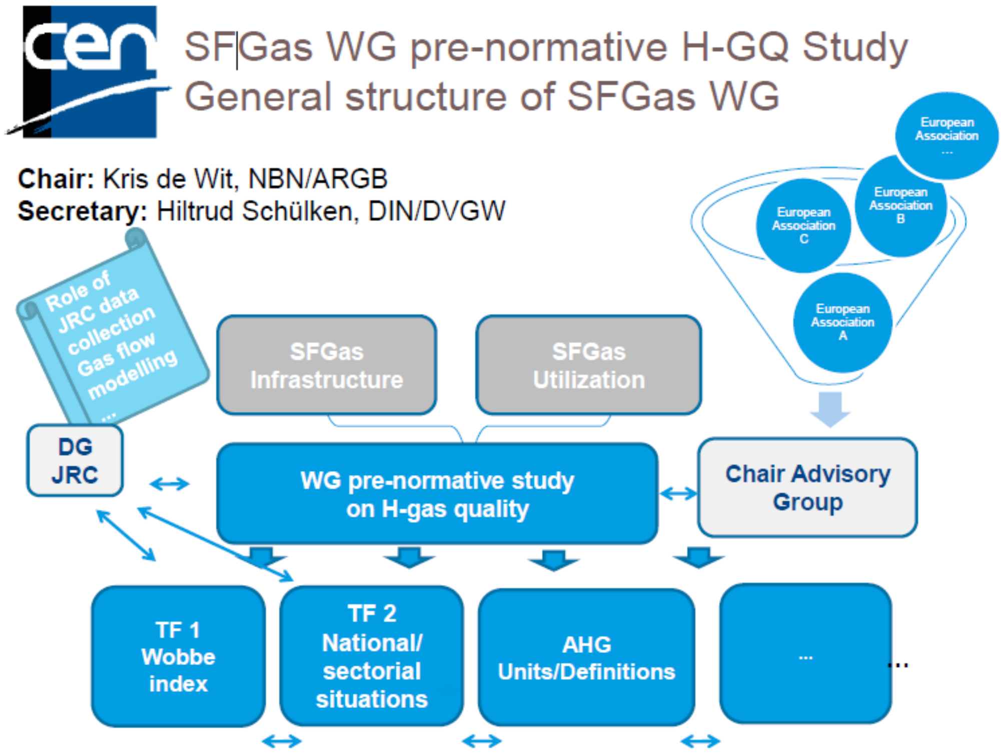


Figure 3: Organization of the prenormative H gas Quality Study

The JRC (Joint Research Center), which is the EU's research force, participates with dedicated technical tasks.

The work is scheduled for 5 years, the first 3 being based on the 3 TF Task Forces. The last 2 years are dedicated to the revision of EN16726.

4.3 Practical Gas quality ranges and variation in Europe

The legal specification of Wobbe number is the maximum range and variation which is permitted in a certain country. Appliances have to be designed by the manufacturer to operate safely and reliable with this range of Wobbe Index. Within the European standard EN437 test gases, test pressure and appliance categories are agreed corresponding to the respective Wobbe ranges.
The actual Wobbe range that installed appliances experience depends very much on the region, the local construction and operation of the grid, the time and the traded gases.

As the European market changes it is expected that gas quality may fluctuate heavier and quicker in the future.
To understand gas quality conditions appliances are already operating with in Europe, it is very interesting to analyze gas quality behavior in local distribution grids or at exit points respectively.
Within the GasQual project existing Wobbe ranges in the European countries are compiled and are shown in Figure 1 too.
Appliances and most gas application may be adjusted to different Wobbe numbers. The challenge is to operate with wide range of Wobbe number without any adjustment. So the local variation or fluctuation of gas quality is important from point of view of the appliance.

Natural gas for Europe is imported from different sources like Russia, North Sea, Middle East and Africa by pipeline or by LNG tankers, see Figure 4. The European gas transmission networks are highly interconnected for a better operability and a high security of supply.

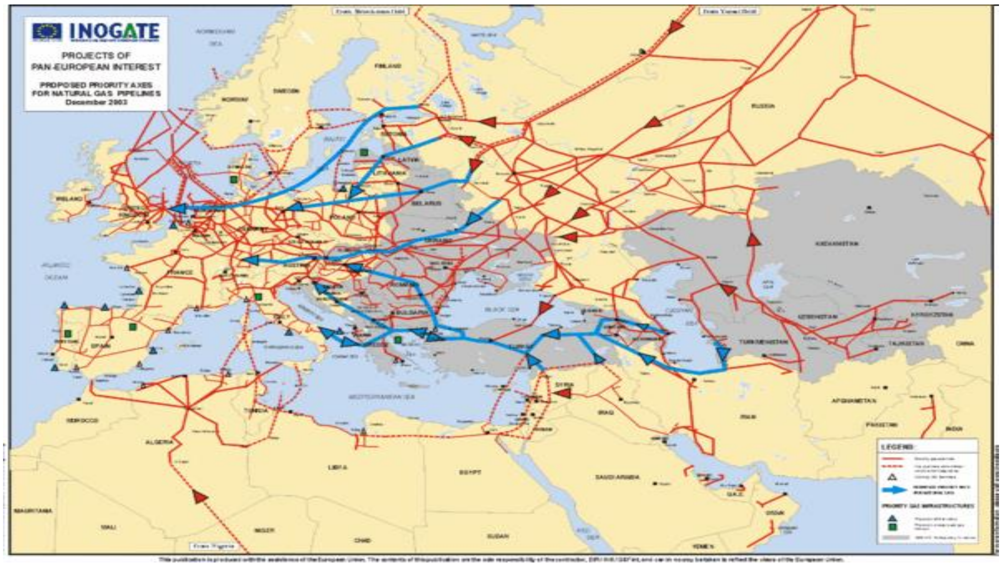


Figure 4: The European gas transmission networks

As gas is a natural product which characteristics depend on the origin. Additionally within the transport and distribution grids the different flow streams may mix and vary due to climate, demand and trading. The fluctuation of the gas quality may be very important when the transport network is supplied by different sources.

4.3.1 France

The transport network in France beeing subject to large gas quality fluctuations is a good example. The French transport network with the different injection points is shown in the Figure 5. Pipeline natural gas is injected from the east (Russia, North sea, Switzerland and Netherlands), the west (Algeria gas from Spain) as well as LNG from 3 injection points which are Fos (south), Montoir in the west and Dunkerque in the North.

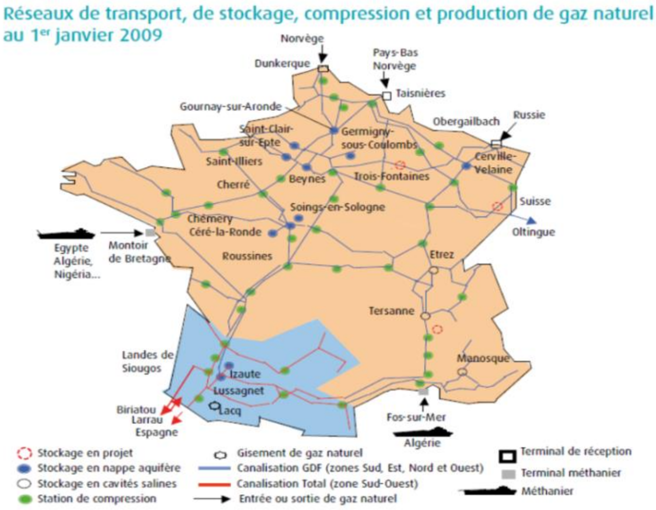


Figure 5: The transport grid, storages, compressor sites and production of natural gas in France (1.1.2009)

The specifications of the natural gas to be transported are fixed by contracts between the producers and the transportation companies. However the imported gases have different compositions and characteristics. The gases injected into the transport network are analyzed at the point of injection by chromatography and metered for billing purposes.
The Figure 6 shows the Wobbe index measured at 2 LNG injection points (Montoir and Fos), 3 gas pipeline injection points (Obergaibach – Dunkerque – Taisnières) as well as the H gas and Pilot Study I upper and lower limits.

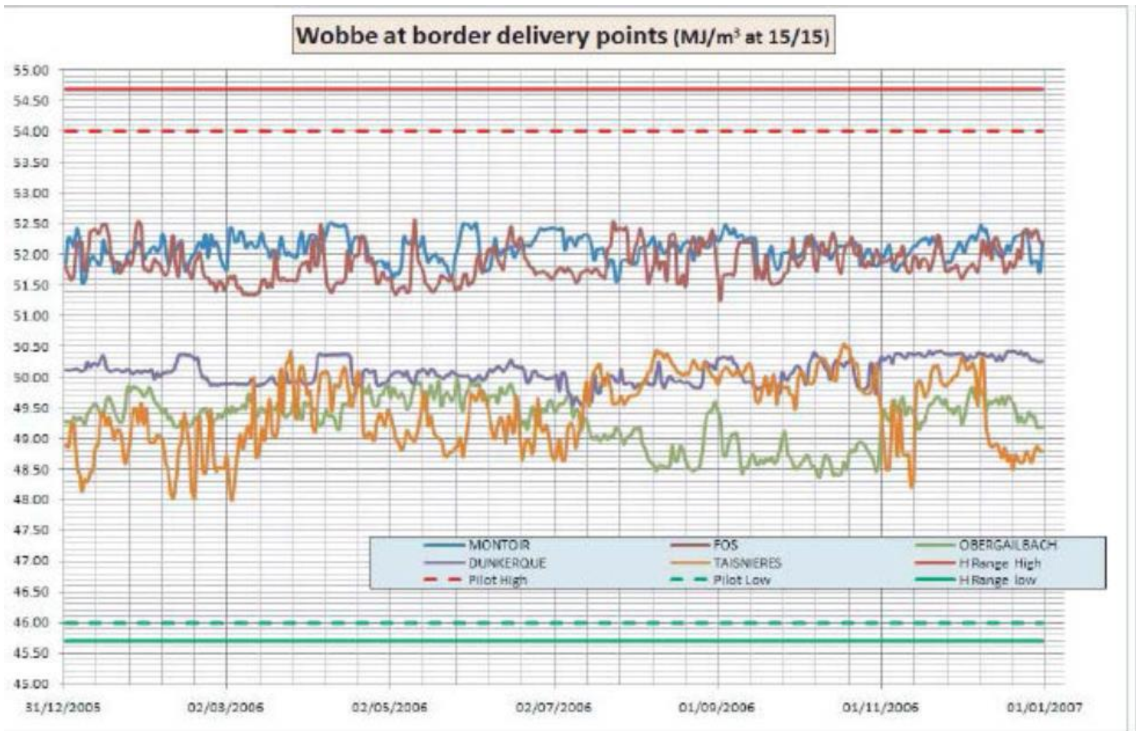


Figure 6: Wobbe Index measured at two LNG injection points, 3 gas pipeline injection points. The limits for H Gas in France as well as the discussed limits in the Pilot Study I are introduced as well.

Obviously the LNG (51.5 to 52.5 MJ/nm^3) is richer than pipeline gas (48 to 50.5 MJ/nm^3) and the gas transported in France covers middle range (48 to 52.5 MJ/nm^3) of H gas.

Gas quality fluctuation may be wider in some regions where both pipeline gas and LNG are imported. Depending on the availability of LNG, the gas WI (Wobbe Index)may fluctuate more in the regions supplied mainly by LNG as shown in Figure 7 where measured WI is in the south of France is plotted in continuous black line.
The doted lines represent the WI of LNG and pipeline gas of the different injection points. We can see that this control and metering point is alternatively supplied by pipeline natural gas and by LNG.
The maximum fluctuation happens in the summer period and can reach 3.5 MJ/nm^3.
The speed of change can also be very high as shown below (green arrows) where a decrease or an increase of Wobbe index can happen very fast.

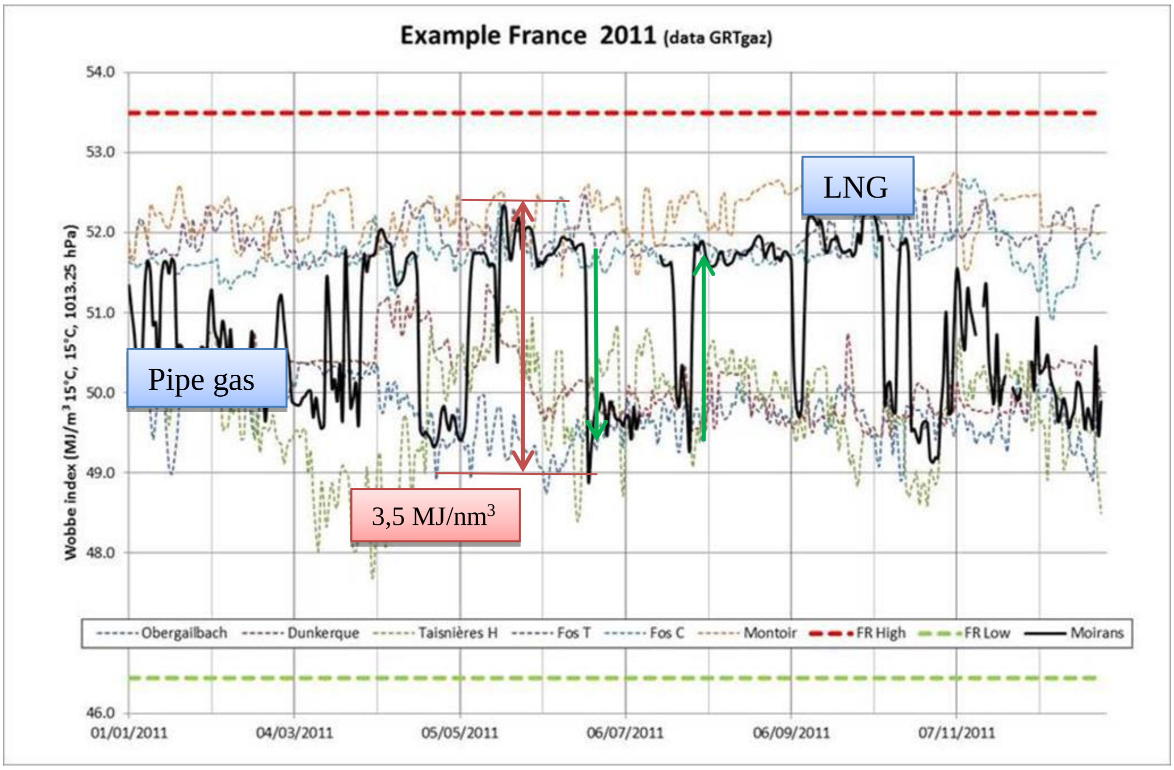


Figure 7: Wobbe index measured in the south of France as continuous black line. The dotted lines represent Wobbe index of LNG and pipeline gas respectively.

4.3.2 Germany

Germany lying in the center of Europe is a considerable import and export country for gases from different sources serving also as a transit country for the neighboring countries. Bio methane is already a well-developed technology in Germany and more than 144 bio methane sites are injecting into the transport or distribution grid respectively. Even some Power-to-Gas sites are injecting hydrogen up to 2%. This situation leading to a high security of supply and a growing integration of renewables implies, on the other hand, a fluctuating gas quality within the legal limits.
As one of the largest German distribution grid operators E.ON investigated systematically the fluctuation of gas quality at more than 50 exist points of their distribution grids over Germany over a period of 3.5 years, see [3]. Depending on the single exit point the fluctuation may be quite different. An example for an exit point with high fluctuation is shown in Figure 8. An overview over all 50 exit points is given in Figure 9 including also the legal limits in Germany defined in DVGW G260 [4].

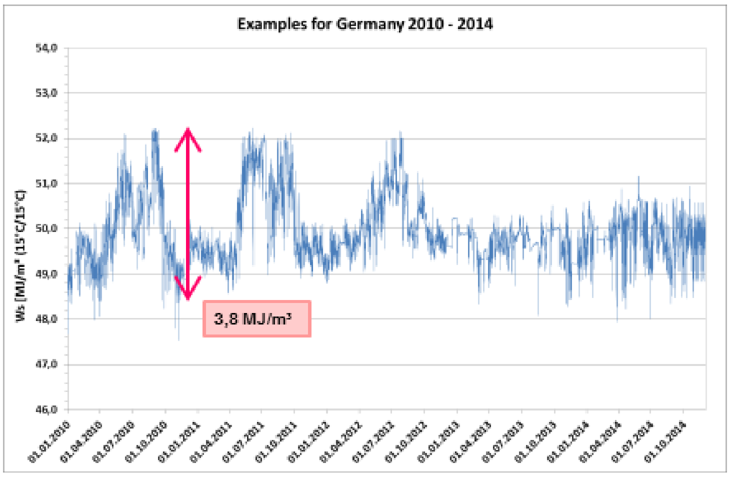


Figure 8: **Wobbe Index measured in Germany**

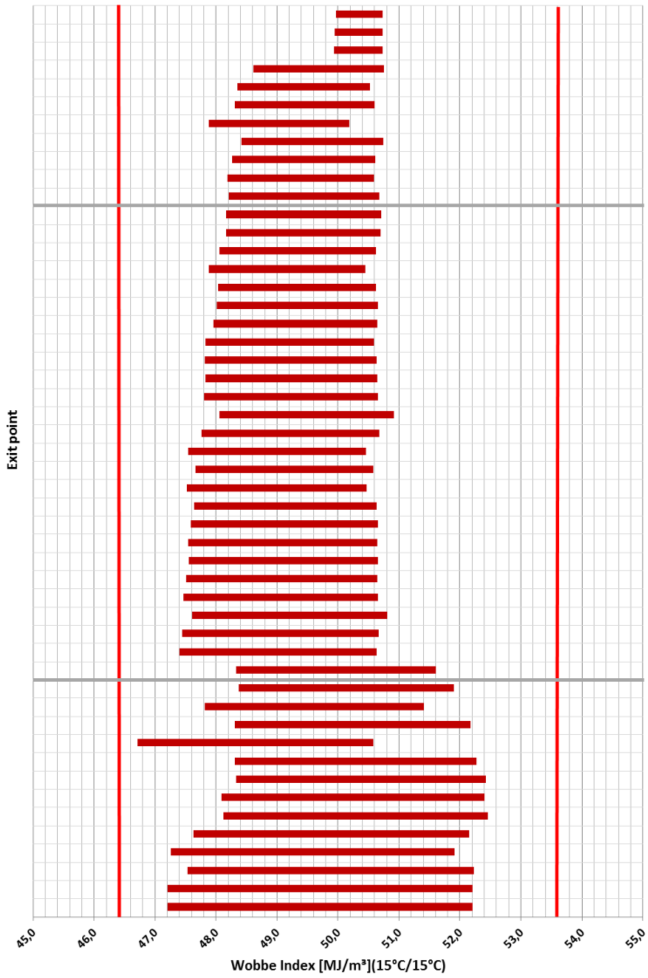


Figure 9: Fluctuation rate of Wobbe number on 50 exit points of E.ON distribution grids in Germany over 3.5 years, see [3]

Obviously fluctuation ranges of 3 to 4 MJ/m³ are observed at several different exit points thus implying that installed appliances in this region are exposed to this range of Wobbe Index over the time.
Similar results are worked out and published by a DVGW project called "Hauptstudie" [5].

4.3.3 Europe

In the frame of the European project CEN SFGas WG pre-normative H-GQ Study for the preparation of the revision of the gas quality standard EN16726 gas quality data from all over Europe are collected from ENTSOG and from the JRC in order of the project. Analysis per exit point is still in work, but in first results presented in workshops. It is already obvious that gases in the range from around 48 MJ/m³ to around 53 MJ/m³ are frequently transported, and even Gases at the lower and higher end, like bio methane, locally produced gases and LNG respectively are distributed.

4.4 Conclusion

Legal Wobbe ranges in Europe are not yet standardized in EN16726. National bands in the member states cover ranges lying between around 44 MJ/m³ and 55 MJ/m³ comprising different width between around 4 MJ/m³ and up to around 8 MJ/m³. Within the European project the technical background for the implementation of the Wobbe range in the EN16726 is worked out.
Measuring results of local Wobbe number in time reveal in dependence of the region and exit point an actual fluctuation of up to around 5 MJ/m³, so often less as the allowed range by legal national limits. In the future this actual range may be exceeded, when new gases as bio methane, LNG and hydrogen enter the market. These new gases are highly appreciated, because they increase the security of supply and renewables reduce the climate foot print. Appliance technology should be prepared to a wide Wobbe range including a fluctuation in time.

5 Standardization

The CEN technical committee which can be influenced by the evolution of boilers and have to adapt their standardization work are:

- CEN TC 238: test gases and appliance categories
- CENTC 109: gas boilers
- CEN TC 058: safety and control accessories for burners and boilers.

5.1 EN 437 (CEN TC 238)

The EN 437 specifies the test gases, test pressures and categories of appliances relative to the use of gaseous fuels of the first, second and third families. It also specifies the Wobbe ranges of the different gas families and groups. It serves as a reference document in the specific standards for appliances that fall within the scope of the Council Directive on the approximation of the laws of Member States concerning gas appliances (90/396/EEC). This standard is transposing article 2-2 of the gas appliance directive 90/396/EEC which states that "*Member States shall communicate the types of gas and corresponding supply pressures used on their territory to the other Member States and the Commission before 1 January 1991. They shall also communicate all changes in good time. The Commission shall ensure that this information is published in the Official Journal of the European Communities*."
The standard makes recommendations for the use of the gases and pressures to be applied for the tests. The full procedure will be given in the corresponding appliance standards.
The test gases and the test pressures specified in EN437 are in principle intended to be used with all the appliances in order to establish conformity with the corresponding standards.

History of the versions:
EN 437 ed. 1 : 1994
EN 437/A1 ed. 1 : 1997
EN 437/A2 ed. 1 : 1999

EN 437 ed. 2 : 2003
EN 437/A1 ed. 2 : 2009
EN437:2017 (E) in formal vote. Planned to be published in Nov. 2018.

The technical definition of the gas groups H, L and E within the second family and the definitions of the categories I2H, I2L and I2E and all their limits gases exist since the first version of 1994 and they are still the same without any changing throughout the versions.

The specific I2N category, which is used for combustion controlled appliances, appeared in the second edition of 2003. The definition as given in EN437, § 6.1.2.2. is: "Appliances using only second family gases at the prescribed supply pressure and that automatically adapt to all gases of the second family". The limit gases for the category I2N are the limit gases of the family I2E added by the limit gases of the family I2L, see Table 1.

Reference gas	Incomplete combustion gas	Light back gas	Lift limit gas	Sooting limit gas
G20	G21	G222	G231	G21
G25	G26	G25	G27 G271(DE)	G26

Table 1: Reference and limit gases corresponding to the appliance category I_{2N} due to EN437. Appliances for Germany have to cope with G271 as lift gas at 25mbar pressure, which represents the group LL. see EN437, B6 for DE.

An overview of the groups and limit gases and the respective Wobbe numbers is given in Figure 10.

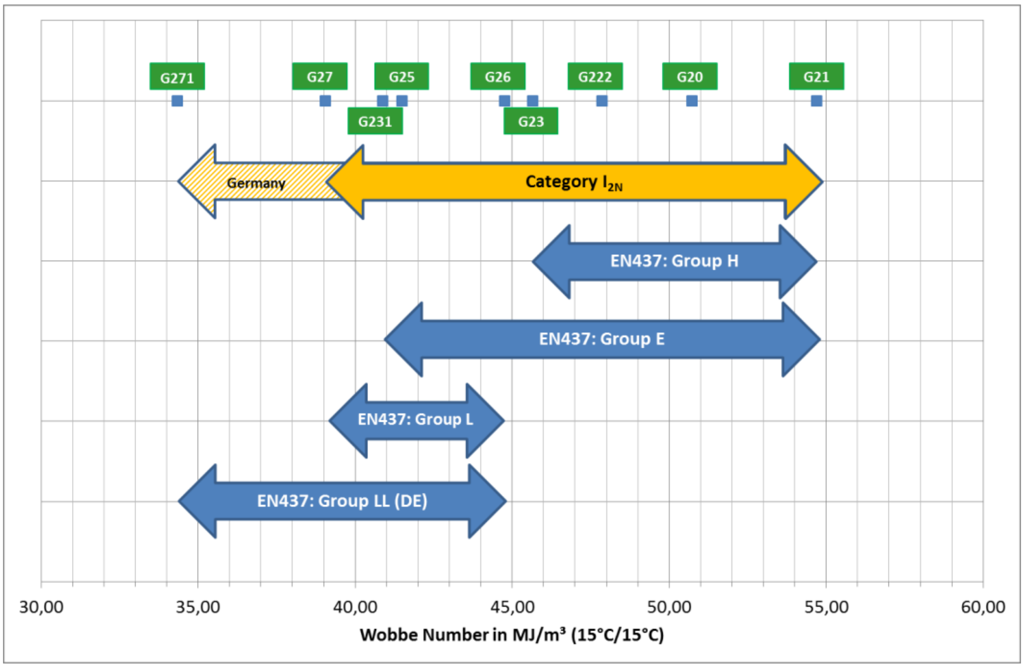


Figure 10: Overview on Wobbe range and values of gas groups, test gases of EN437 including the range of appliance category I_{2N}.

Only 10 of 33 countries participating in the CEN process accept up to now the appliance category I2N in EN437 2017 (E), see Table 2.

Country Code	BE	DE	DK*	ES	FR	GR	NL*	PL	PT	SI
	X	X[a,c]	X[a]	X[a]	X[a]	X[a]	X	X	X[a]	X[a]

Table 2: Countries authorizing the use of category I_{2N} due to EN437.
a) ***Categories applicable only to certain types of appliances, specified in the individual appliance standards***
c) link to B.6 of EN 437 specifying for DE, a test shall be done with the lift limit gas G271 at 25 mbar.
****) These countries authorize the category in the version EN437 2016(E), which is in formal vote currently.***

In fact only Belgium, Netherlands and Poland are using the category I2N without restrictions. Germany requires a supplementary test with lift gas G271 at 25 mbar.
For the remaining countries, I2N is not applicable to all appliances and its use is specified in the corresponding appliance standards.

5.2 EN 15502 (CEN TC 109)

CEN TC 109 is the technical committee which writes standards for gas boilers.
Mainly WG1 of this CEN TC published the following standards.

- EN 15502-1 (generic standard) covering all boilers operating with gaseous fuels
- EN 15502-2-1 (specific standard) covering boilers operating with gaseous fuels of type C and type B configurations using fans for air intake /extractor for flue gases
- EN 15502-2-2 (specific standard) of type B1 using a draft diverter.

The EN 15502-1 specifies the common requirements and test methods concerning, in particular the construction, safety, fitness for purpose, and rational use of energy, as well as the classification, marking and energy labelling" of gas-fired central heating boilers that are fitted with atmospheric burners, fan assisted atmospheric burners or fully premixed burners, and are hereafter referred to as “boilers”. This European Standard is to be used in conjunction with the specific Parts 2 (Part 2-1 – Part 2-2.).
All tests and verifications gases are related to the EN 437.

History of the versions:
EN 15502-1 ed. 1: 2012
EN 15502-1/A1 ed. 1: 2015

The EN 15502-1 replaces partially those previous European standards mainly the common requirements of gas boilers:

- EN 297:1994 Gas-fired central heating boilers - Type B11 and B11BS boilers fitted with atmospheric burners of nominal heat input not exceeding 70 kW
- EN 656:1999 Gas-fired central heating boilers - Type B boilers of nominal heat input exceeding 70 kW but not exceeding 300 kW
- EN 13836:2006 Gas fired central heating boilers - Type B boilers of nominal heat input exceeding 300 kW, but not exceeding 1 000 kW
- EN 483:1999 Gas-fired central heating boilers - Type C boilers of nominal heat input not exceeding 70 kW
- EN 15420 Gas-fired central heating boilers - Type C boilers of nominal heat input exceeding 70 kW, but not exceeding 1 000 kW
- EN 677:1998 Gas-fired central heating boilers - Specific requirements for condensing boilers with a nominal heat input not exceeding 70 kW

- EN15417:2006 Gas-fired central heating boilers - Specific requirements for condensing boilers with a nominal heat input greater than 70 kW but not exceeding 1000 kW
- EN 625:1995 Gas-fired central heating boilers - Specific requirements for the domestic hot water operation of combination boilers of nominal heat input not exceeding 70 kW

The specific standard EN 15502-2-1 was published in 2012, then amended and published in 2017 as EN 15502-2-1+A1.

The self-adaptive boilers should be covered by the generic standard EN15502-1 and the specific part EN 15502-2-1+A1.

Up to now no specific part of the standard for combustion controlled appliances has been elaborated. Within EN 15502-1+A1, 3.1.4.15, at least a definition of a gas/air ratio control, which is a central part of each combustion controlled condensing boiler is given:
“gas/air ratio control: device that automatically adapts the combustion air rate to the gas rate or vice versa”

About the constructional requirements of the EN 15502-1+A1, the gas-air ratio control must comply (§ 5.4.9) with:
- the EN 88-1 for the pneumatic gas/air ratio control
- the EN 12067-2 for the electronic gas/air ratio control

The combustion control boiler must fulfill the same operational requirements like the other kind of boilers.

5.3 CEN TC 58

CEN TC 58 is the technical committee which writes standards for safety equipment and accessories used to control the safety and operation of burners and boilers. If the boiler is equipped with electronic components or systems that perform a safety function, these must meet the requirements of following standards:
- NF EN 88-1 : Pressure regulators and associated safety devices for gas appliances.
- NF EN 125 : Flame monitoring devices for appliances using gaseous fuels.
- NF EN 12 6: Multifunctional valves for appliances using gaseous fuels.
- NF EN 161 : 2011: Automatic shut-off valves for gas burners and gas appliances.
- NF EN 298 : Automatic control and safety systems for burners and appliances with or without fans using gaseous fuels.
- NF EN 12067-2 : Air / gas ratio control devices for gas burners and gas appliances - Part 2: Electronic devices.
- NF EN 13611 : Auxiliary equipment for gas burners and gas appliances - General requirements.
- NF EN 14459 : Control functions for electronic systems for gas burners and gas appliances - Classification and evaluation method.
- EN 16340 : Combustion product sensing devices for gas burners and gas burning appliances;
- EN 1854 : Pressure sensing devices for gas burners and gas burning appliances

5.4 EN 15502-2-1+A1 Integration of Combustion Control

Since there is no CEN TC for drafting a specific standard for self-adaptive boilers, CEN TC 109 and CEN TC58 decided to establish an ad hoc group within WG1 of CEN TC 109 to study this point. This group is composed of experts from the two technical committees.
The goal is to have an interface on common requirements. CEN / TC 58 will specify the requirements of auxiliary equipment and CEN / TC 109 will develop the requirements for the equipment used in the boiler.
The experts of this ad hoc group listed the important points to be revised or to be introduced into the generic standard and its specific parts. In addition, with the new gas quality provisions in relation to the M400 mandate that resulted in the drafting of EN 16276 without a Wobbe index range, the standard EN 15502 series of standards need to be revised to introduce specific requirements for the variation in gas quality. In particular, the following points should be revised or added as decided by the ad hoc group.

- Adaptive devices for combustion control.
- The use of the overheating limit gas (G24 already defined in the NF EN 437 standard) for premix burners.
- The effect of the injection of hydrogen into the gas distribution networks.
- The effect of ambient conditions (temperature and humidity) on the operation of the device.
- On the safety auxiliary side, it is necessary to introduce requirements in relation to the new provisions of standards EN 13611 of 2016 and NF EN 14459 and possibly those of standard EN 12076-2. An important point under discussion is how to check the effect of the Wobbe Index fluctuation and what is the maximum rate of change (MJ/m^3) per unit time. This value is not defined and the work under the Pilot Study II for gas quality is also looking for a value corresponding to this fluctuation.
-

The generic standard EN 13611 "Auxiliary equipment for gas burners and gas appliances will be published at the end of 2018 as a harmonised standard according to gas appliance regulation (426/20196/UE). The CEN TC 58 WG 12 was activated to revise the EN 12067-2 which deals with air/gas ratio control devices for gas burners and gas appliances.
A meeting of the WG 12 was held in September 2018 to launch the revision of this standard. One of the main topics of the revision is the introduction of the requirement of the Intelligent Combustion Control Devices.

5.5 Summary and Conclusion

The Wobbe Index range for combustion controlled appliances, test gases and definition of category I_{2N} is well developed within EN437 and since a long time accepted and currently approved again in the new EN437:2017(E) under preparation for formal vote. This category is accepted without any foot notes by three countries (Belgium, Netherlands and Poland) only. Another seven countries (Germany, Denmark, Spain, France, Greece, Portugal and Slovenia) accept the category with the restriction to “certain types of appliances, specified in the individual appliance standards”. Germany requires a specific test with G271 at 25 mbars. Currently a common group of CEN TC109 and TC58 works intensively on the future development of the standards. This report and the planned measurements might deliver technical results and arguments for this work.

6 Technology of Standard Condensing Boilers

6.1 What is a condensing boiler [6]

A condensing boiler is a boiler designed for low-temperature operation including recovering low-temperature heat and the latent heat from water vapor produced during the combustion of the fuel. The respective heat exchangers are specially constructed to collect the latent heat and to discharge the condensed water without disturbing the combustion.
In general, gas boilers are produced as a series of similar appliances having different capacities. Examples of nominal capacities are 10, 20, 30 and 50 kW. For the **domestic market**, most of the gas boilers (single units) have a nominal heat output of about 20 kW. The 20 kW are needed to cover the sanitary hot water production (especially in the case of boilers without water tank), whereas for heating 10 kW or less would be sufficient for most of insulated houses and apartments. That is why most of the boilers on the present market are "**modulating**" boilers. This feature allows the appliance to deliver reduced heat output without stopping the burner (the gas and air flows to the burner are reduced). Modulating ranges from 4 to 20 kW are typical, and technologies allowing very low minimum range are developed (starting from 1 kW). The modulation feature reduces the too frequent start-stop of the boiler and improves the user's comfort and the lifetime of the appliance.

For apartment blocks and other large buildings, where the heat demand is larger than for single-family houses, larger boilers are used, but also the combination of several domestic appliances connected in so-called "cascade" is a possible solution. In that case, the number of appliances in operation is determined by the heat demand.

6.2 Burners for condensing boilers [7]

Two types of burners are used for condensing boilers:

- Surface burners- normally used for domestic appliances
- Jet burners for larger boilers *(those will not be treated here)*

Just in the very first types of condensing boilers, atmospheric burners have been used. As in condensing boilers a top down combustion is preferred to prevent burners from dropping water usually the design of burner, heat exchanger- and boiler design quickly changed to fan assisted burners.
Surface burners are fan assisted fully premixed burners of quite different design compared to standard atmospheric burners. The burner form may be flat, (half)-cylindrical or even spherical with a surface of perforated plate, woven-fiber of metal or ceramic material. Each hole in the plate (‘burner port’) serves as a flame holder. The geometry of the surface and the holes, together with the flow rate of the fuel combustion air mixture determines the shape and the size of each individual flame.
The development of fully premixed surface burners brought a great progress in NO_x – reduction of domestic appliances. The very even mixture of air and gas avoids temperature peaks producing NO_x. Additionally the short flame reduces the time of flue gas and air being exposed to high temperature thus again reducing the NO_x-production.
Most of the modern burners for condensing boilers may be modulated with a load ration of 1:4 up to 1:10 [8]. The air ratio ist laying between 1,2 to 1,4 and is more or less constant over the whole modulation range for a given gas quality.

Figure 11: Examples of surface burners for condensing boilers:
1. Row: Flat and cylindrical burners, steel and metal fiber surface (source http:// bekaert.com)
2. Row: Compact burners, knitted metal fiber (source http:// bekaert.com)
3. Row: radiation burner, spherical metal mesh (source: Viessmann)
4. Row: Flat ceramic burner

6.3 Fuel /Air control of conventional condensing boilers

Conventional condensing boilers are designed to adapt the load to the heat demand of the flat or house at present. Modulating ranges of 1:3 to even 1:10 are realized. The fan for combustion air and the gas valve are controlled in a way that the relation of the volume flows, i.e. the air factor of combustion stays constant in case the gas quality doesn't change. This might be a pneumatic or an electronic control.

In modern condensing boilers the pneumatic control is realized by a unit of fan and gas valve, see Figure 12 The fan is equipped with a so called venturi inlet. Air and gas are mixed up in this venturi in the fan inlet and transported through the fan to the burner. The pressure inside the venturi is determined by the air flow rate. The gas valve outlet is directly connected to the venturi. The outlet pressure of the gas valve is kept constant, so that the gas flow rate is determined by the air pressure within the venturi thus realizing a constant relation between air and gas flow.

Figure 12: Unit for modern condensing boilers: Fan (motor in black in the front, casing and outlet to the right) venturi (on the back) and gas valve (on the right).

Another type of pneumatic control may be realized with a pressure pipe connecting the air pressure with the control pressure of the gas valve e.g.. Electronic controls measure the air pressure and control the gas valve by electric signal.

All these systems control the relation between air and gas flow rate solely. In case the gas quality changes and gases with another minimum air request are supplied, the air factor of combustion is changing accordingly as well as the load.

6.4 Impact of Gas Quality Variation on Gas Appliances

The influence of gas quality change may be derived from some simple considerations.
The Wobbe number W, one of the most important characteristics of combustion gases, is defined to describe the variation of load $\dot{Q}$ with changing gas quality:

$$\dot{Q}_2 = \dot{Q}_1 \times \frac{W_2}{W_1}$$

So for the Wobbe range defined in EASEE Gas CBP and with G20 as nominal Gas (Ws=50.7 MJ/kWh) maximum variation of load is possible:

$$\Delta\dot{Q}: +6\% \ for\ Ws = 54\frac{kWh}{m^3}$$

$$\Delta\dot{Q}: -9\% \ for\ Ws = 46.4\frac{kWh}{m^3}$$

This load variation is no issue for most of the heating appliances, like condensing boilers as load is modulated due to the actual demand. But reduced load might be an issue for instantaneous water heaters.

For flame stability, efficiency and emissions of CO and NO_x it is much more important, that the air factor is changing with gas quality also. As for natural gases even including biogas or hydrogen the air requirement is proportional to the calorific value, see Figure 13 the air factor changes inversely to the Wobbe Number if the volume flow of combustion air stays constant.

$$\lambda_2 = \lambda_1 \times \frac{W_1}{W_2}$$

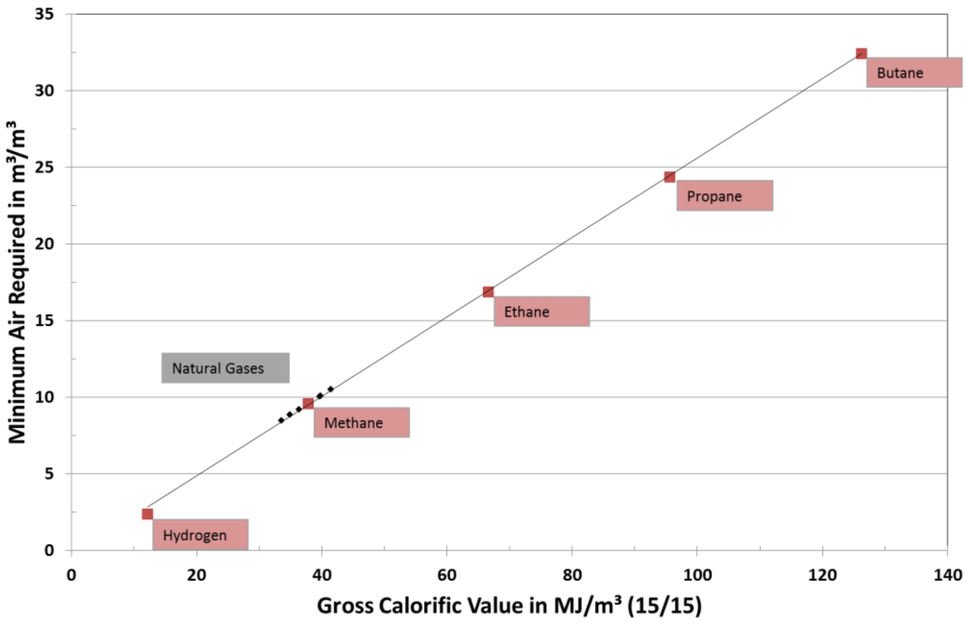


Figure 13: Minimum combustion air requirement of different hydrocarbons, natural gases including biogas and hydrogen admixture over the calorific value of the respective gases.

In practical, in some cases the air factor might have a retroaction on the volume flow of air, so that the relation between W and λ is not so strict. In dependence of the set point of λ, the combustion has to be stable over a more or less wide range of λ for the EASEE Gas-range:

$$\lambda_{setpoint} = 1.2: \quad 1.13 < \lambda < 1.31$$
$$\lambda_{setpoint} = 1.3: \quad 1.23 < \lambda < 1.42$$

Test gases in EN437 for gas appliances comprise this Wobbe range, so appliances are tested in general over the whole range of load and air factor, see chapter 5.1. Efficiency and emissions are defined for the nominal gas G20.

As a result of the shift in air factor, emissions of CO- and NO_x will show large variations, flames might blow off, thermo-acoustic resonance could occur and efficiencies may be influenced. These effects depend on the construction of burner, heat exchanger and flue gas conduit. Even the weather and operation conditions may have an influence.

The above doesn't apply to combustion controlled condensing boilers, see 7.3. The Wobbe number variations are, in principle, not impacting load and the air factor and by that not affecting the efficiency and emissions of appliances equipped with an intelligent combustion control system.

6.5 Existing Experiences on Standard Condensing Boilers

6.5.1 Lab Measurements of the project partners

The five project partners have a lot of different experiences in their labs on the investigation of standard condensing boilers under different conditions and with different test gases for various applications. One exemplary measurement on a conventional condensing boiler is shown in Figure 14. In this case, no changes have been done on the test conditions, but only the different test gases are supplied to the boiler.

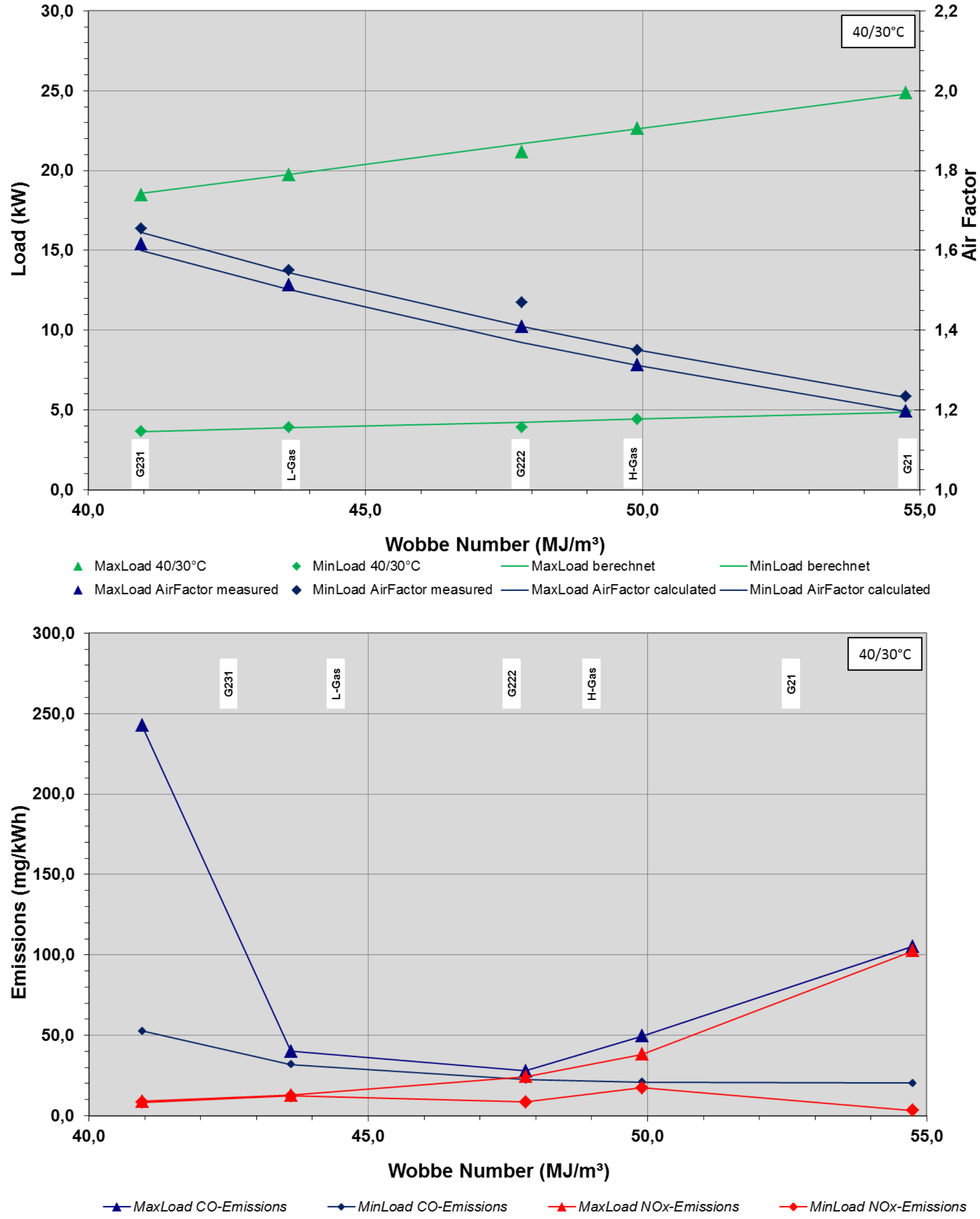


Figure 14: Exemplary measuring result on a typical conventional condensing boiler with test gases for natural gases group E due to EN437

On the top of Figure 14 the measured load and air factor are plotted as points and the curves are calculated due to the equations given in chapter 6.4. proving a good match. This typical boiler adjusted to 22 kW with natural gas H (close to G20) varies the load between 18 kW at the lower end of Wobbe number and 25 kW at the upper end of the Wobbe number. As domestic boilers modulate and adapt to the actual heat demand most of the time a variation in load is not affecting the convenience of the customer. Much more important is the considerable change in air factor, as this influences the flame stability, emissions and possibly the operational behavior like cold start or acoustic behavior of the boilers. In the present example the adjusted air factor of 1.3 in operation with Natural gas H (close to G20) changes to 1.6 with G231 and 1.2 with G21. The development of emissions is shown on the bottom side of Figure 14. The CO-emissions show the typical lift at both ends of Wobbe number (or air factor respectively). The strong lift at the lower end is a sign for a strong tendency to flame lift. Some additional effects i.e. temperature or weather, might cause a shut-off of the appliance. The NO_x emissions increase with increasing Wobbe number (or air factor respectively).

6.5.2 Experiences of the GasQual Project

An extensive and systematic investigation had been done under the mandate M 400 by the project GasQual. As the CO-emissions give a reliable signal for flame instability in the frame of the GasQual project extensive test have been carried out to evaluate the variation of CO with the Wobbe for about 100 gas appliances including 11 condensing boilers. The results are showing large differences between appliances. During the investigations the boilers were supplied with different test gases being adjusted to nominal conditions at different Wobbe numbers. For the development of load, air factor and by that emissions the actual difference between Wobbe number of supplied gas and Wobbe number of adjustment gas is important. So for comparison of all experiences the “delta Wobbe” defined as difference between the Wobbe number of adjustment gas and the Wobbe number of supply gas serves as x-axis.

Figure 15 shows an example of one boiler CO data measured for various gases. The results only shows the data measured **at nominal pressure and nominal voltage.**
Typically the CO-emissions increase at both ends of Wobbe number and air factor respectively. Figure 16 gives the CO results on a second boiler with various gases, adjustments and additionally varied gas pressure and boiler voltage. Obviously the influence of pressure and voltage leads to a higher scattering of the measuring points and the simple U-curve now may serve as an envelope, than a best fit curve.

NO_x-emissions from fully premixed burners as used in condensing boilers usually increase with increasing Wobbe number, see example shown in Figure 17. Although emission variations with Wobbe number are similar for fully premixed burners, there might be significant differences depending on specificities in burner and boiler construction. In phase II of the project an overview of results from the standard condensing boilers will be given for comparison with the results of the combustion controlled condensing boilers.

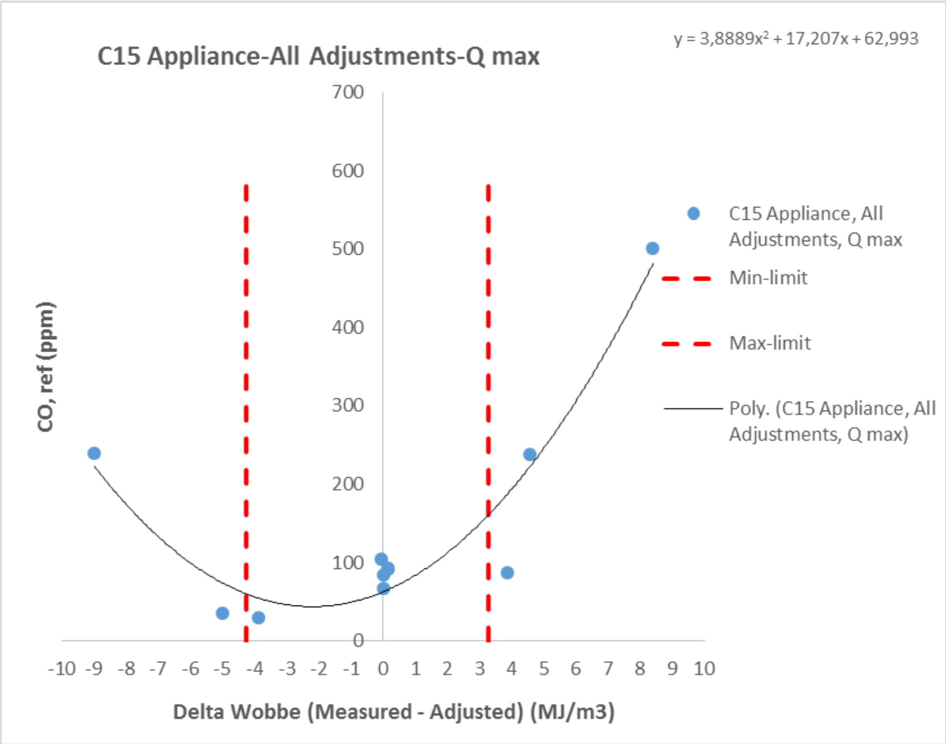


Figure 15: CO-emissions of a condensing boiler with changing gas quality (Wobbe number) and different adjustment. The X-axis gives the difference between adjusted Wobbe number and Wobbe number of supply gas. The curve shows the typical U-form with CO-lift at both ends. Example of measuring results achieved in the project GasQual.

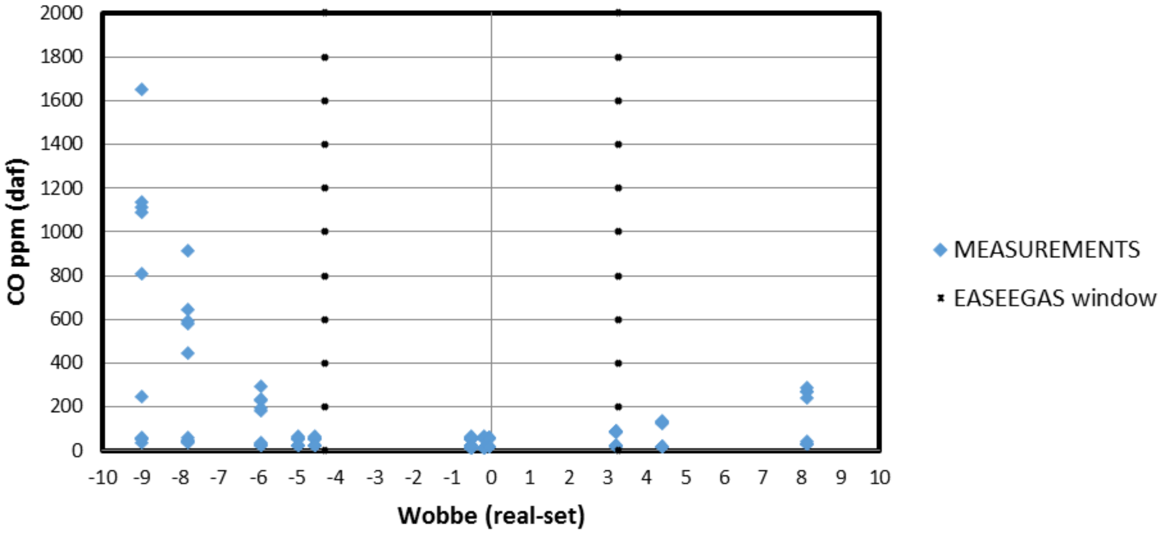


Figure 16: CO-emissions of the condensing boilerE2 with changing gas quality (Wobbe number) and different adjustment. Additionally gas pressure and supply voltage are varied. The X-axis gives the difference between adjusted Wobbe number and Wobbe number of supply gas. The curve shows the typical U-form with CO-lift at both ends and additional influence of changing gas pressure and voltage. Example of measuring results achieved in the project GasQual.

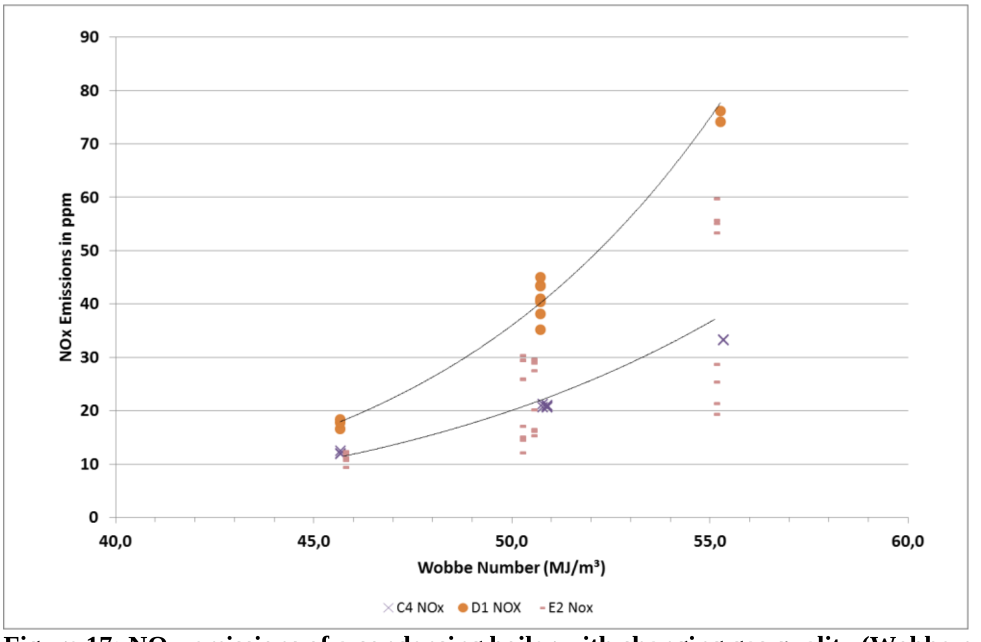


Figure 17: NO_x -emissions of a condensing boiler with changing gas quality (Wobbe number). Typically the emissions increase with increasing Wobbe number. Example of measuring results achieved in the project GasQual.

GasQual has also been investigating the impact on efficiency and emissions on the 11 boilers tested

The relative variations of Efficiency and NO_x over the range investigated (45-56 MJ/m^3) are as follow:

Efficiency

- Average change over the Wobbe range = 0,23% (abs) (increase with Wobbe)
- Maximum change over the Wobbe range = 1,5% (abs)
  (note that for many boilers no changes was measured as the difference was in the range of test repeatability)

NOx at Pmax

- Average change over the Wobbe range = 68 ppm (increase with Wobbe)
- Maximum change over the Wobbe range = 100 ppm)

NOx at Pmin

- Average change over the Wobbe range = 19 ppm (increase with Wobbe)
- Maximum change the Wobbe range = 50 ppm)

So Efficiency is slightly increasing with the Wobbe. However the increase is in general below the testing repeatability range of laboratories. This means a very low impact of gas quality on efficiency.

NOx emissions are increasing with the Wobbe. The value of increase can be important and may depend on the initial adjustment air-gas. The increase is more important at maximum load (compared to minimum load).

6.5.3 Proposal of a Method to determine the Tolerance of Burners against Gas Quality Change

For comparison of the results on standard and combustion controlled appliances, the development of a method to determine the quantitative tolerance of condensing boilers against gas quality changes is proposed.

We are working on a methodology - based on the “U” shape model (see Figure 15): the typical measured CO-curves are the basis of this method, which are in a first step approximated by simple functions. The Figure 18 shows a model for CO-curves for 11 boilers. Note that the Figure 18 is based on test data from GasQual only including test results obtained under **NOMINAL conditions for the pressure and voltage**. This means that they are not including (at this stage), the impact of worsening parameters used in GasQual.

In the second step, for each boiler (curve) and a chosen CO-level the Wobbe variation is set. Supposing the CO emissions should be below a certain level (eg. 300 ppm), what would be the Wobbe variations that are possible keeping the emissions below the value chosen?

In the example of the Figure 19, for the boiler E2 keeping the limit of about 300 ppm, the Wobbe number may change between -6 MJ/m³ and + 8 MJ/m³. This is a total tolerance of 14 MJ/m3 (15/15). Using this method for all boilers and different levels of CO, can be used to produces a dWobbe-Tolerance curve and can be used to compare quantitatively boilers sensitivity to Wobbe variations. This method will be used to compare results of combustion controlled appliances in phase II of the project.

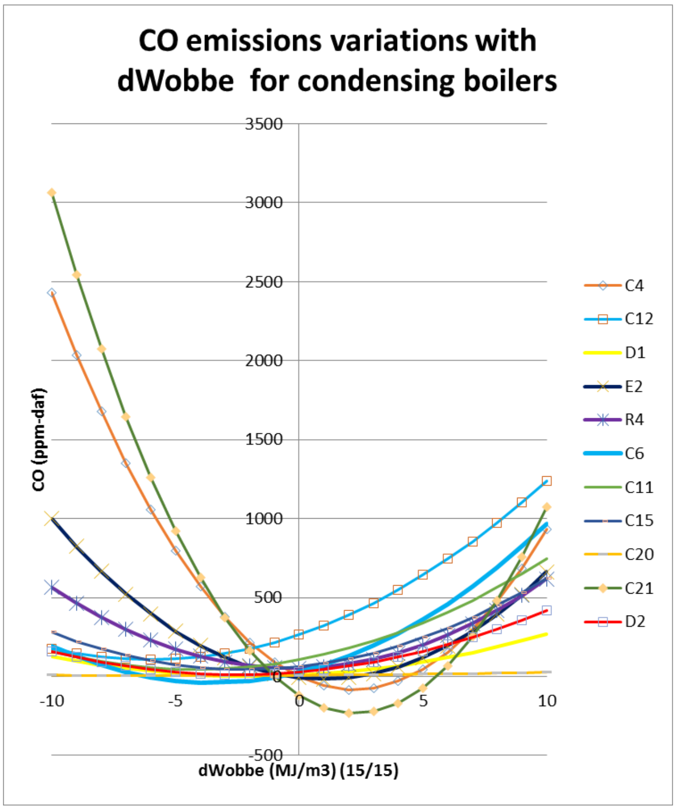


Figure 18: Model based on measurement for CO emissions variations with Wobbe index for condensing boilers. Data for those curves are from measurements under nominal pressure and voltage only.

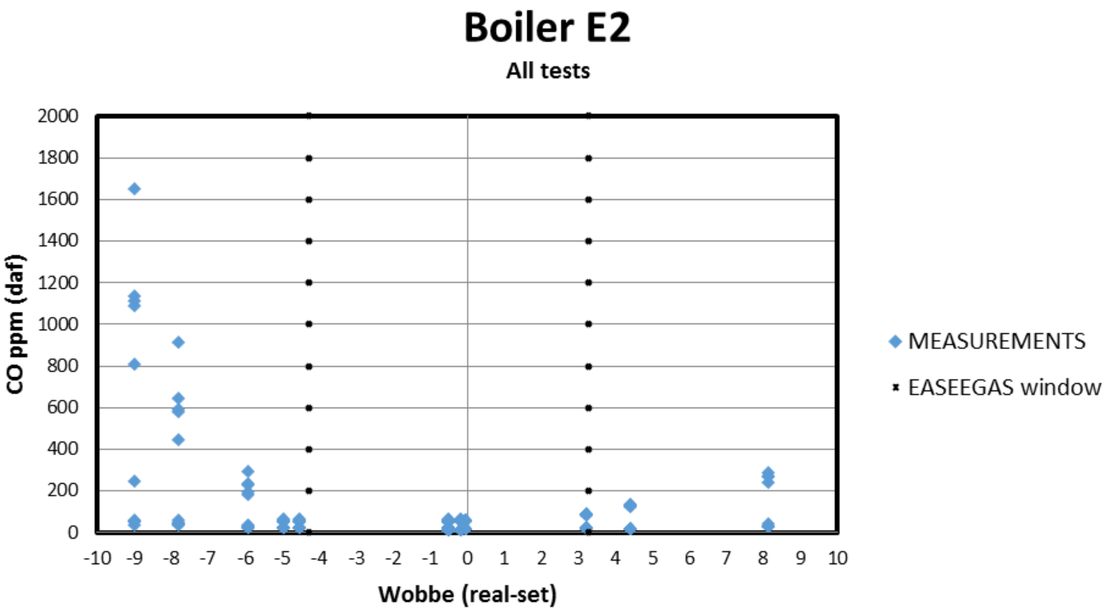


Figure 19: Example of tolerance to Wobbe index variations for a boiler tested in GasQual

This current proposed method is based on result under nominal conditions only. As mentioned before and shown in Figure 16, measuring points are much more scattering when variation of pressure and voltage are included.

The Figure 16 shows it is difficult to find a model that would match all the points:

- For the same dWobbe, the CO emission will also depend on the load and the conditions of the tests (gas pressure, boiler voltage, etc.).
- The U shape is not symmetrical: going from 45 to 55 MJ/m^3 (dWobbe = +10) will not impact the boiler the same way as going from 55 to 45 MJ/m^3 (dWobbe =-10) (with identical CO2 as start condition)

This may require refining a bit the models used and develop a double model:

- One for the increasing Wobbe (on the right side of Figure 20: doted black line)
- One for the decreasing Wobbe (on the left side of Figure 20: red dots)

On basis of the above ideas we will work further with GasQual data for inclusion in the final report with testing results.

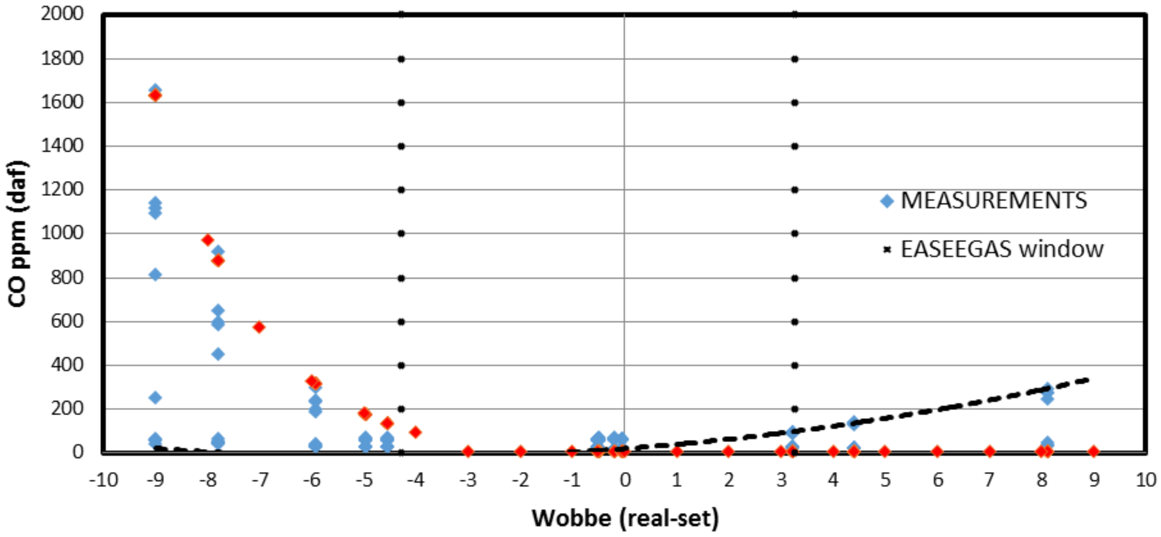


Figure 20: Model for the increasing Wobbe (doted black line) and decreasing Wobbe (red dots)

6.6 Summary

Data from the project partners labs and on a far more systematic evaluated way the GasQual data gives us a detailed picture on how gas boilers are impacted by gas quality changes.
The main influence of Wobbe is on CO- and NO_x –emissions, good-operation and safety, while the impact on efficiency is in general small.
Especially for appliances that are adjusted in the field to an unknown gas and for conditions that are different from nominal ones the impact may be significant.
Data available from the GasQual project on 11 boilers will give a significant number of results that can be compared to the results obtained with appliances equipped with combustion control.
In this section we have developed a method to quantify the tolerance to gas quality variations and the same method will be used for the boiler with CC (combustion control) so to have a solid basis for comparison. Note that the method developed has been only applied to CO emissions under nominal conditions and the work will be extended to show also the impact of gas quality variations under harsher testing conditions (low/ high pressure & voltage). The model should be completed during phase II of the project.
The testing of boilers with combustion controls will tell if the technologies used for control can counterbalance the effects of gas quality variations on safety and NOx emissions.

7 Technology of Combustion Controlled Condensing Boilers

7.1 Components

7.1.1 Gas Quality Sensors and Probes for Gas Quality detection

The Control and monitoring devices are classified in three categories: Upstream, within and downstream of the combustion zone.

7.1.1.1 Devices upstream of the combustion zone

The objective of the measurement upstream of the combustion is to identify or know the characteristics of the fuel supplied to the burner in order to determine the optimum air-gas ratio for the combustion. The composition of the gas also makes it possible to know its energy content. The control and monitoring would be done in an open loop.
The most promising possibility is the indirect measurement of the heating value or the Wobbe Index of the gas.

7.1.1.1.1 Direct measurement of the Wobbe index

A - Gas Chromatography

The chromatograph makes it possible to obtain the calorific value and the Wobbe index of the gas from a complete knowledge of the gas composition.
Chromatograph is accurate, but requires a long response time and maintenance.
It is therefore not suitable for continuous monitoring of the combustion.

B - Mass Spectrometry

A mass spectrometer is based on the mass / charge ratio of ionized species. The mass spectrum is generated by ionizing the gas mixture and by accelerating it with an electric field. The ions are separated by their momentum. The concentration of the compounds is determined as a function of the intensity peaks, the ionic current being converted into electric current. The response times are very short.

C- Infrared Spectrograph

Infrared (IR) spectrographs use the properties of natural gas components to absorb light at a given wavelength of the infrared spectrum. Oxygen, nitrogen and hydrogen do not absorb in the IR. This makes it possible to identify the other components of the natural gas hydrocarbons (CxHy), CO and CO_2, which absorb in other areas of the IR spectrum.
Using the absorption band of methane and that of other hydrocarbons, the measurement of the absorption makes it possible to determine the calorific value of the gas.
In addition to hydrogen, components greater than C_4H_8 do not absorb IR radiation, so they are not taken into account in the calorific value measured from the absorption of the gas.

7.1.1.1.2 Indirect methods

Indirect methods involve measuring the physical properties of the gas and using correlations that could be established between the physical properties and the calorific value and the Wobbe number. This chapter describes the methods or devices that have been published and some of which are used in the field.

A - Wobbelis

The Wobbelis was developed at Gaz de France R&D center (now known as ENGIE Lab-CRIGEN). It is based on the measurement of the absolute temperature and pressure upstream of a sonic orifice and the measurement of the mass flow upstream of a calibrated orifice. The Wobbe index is determined in 2 phases:

- A calibration phase with a gas with a known composition (pure methane)
- A phase with a gas of unknown composition.

The comparison between the mass flows obtained between these two phases of more than 125 different natural gases allowed a correlation to be established between the ratio of the two measured mass flows rates Xm and the Wobbe index for each gas.

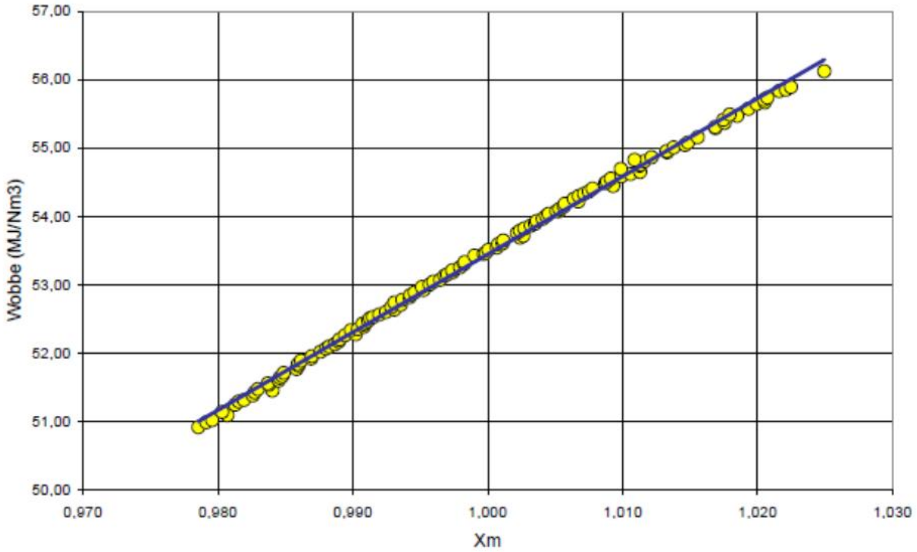


Figure 21: Wobbelis gives a strong correlation between Xm (ratio between flow rate of investigated natural gas and flow rate of pure methane) and the Wobbe number of the investigated natural gas. [9]

B - Method developed by "Ecole des Mines of Nantes (France)" (patented)

The calorific value of a gas can be determined as a function of the thermal conductivity of the gas at 2 different temperatures. It is then possible to translate variations in composition by variations in thermal conductivity.

To do this, natural gas is considered as a ternary mixture of 3 groups of its most important components (CH_4, C_2H_6, C_3H_8 and N_2)

- Group 1 consisting of methane (CH_4) which is the main component of natural gas,
- Group 2 consisting of all other hydrocarbons ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10})
- Group 3 consisting of inert gases nitrogen (N_2) and (CO_2) carbon dioxide.

The hypothesis is made that if two physical properties allow to describe a ternary gas, then the combustion properties of this ternary gas will also be those of a real gas having the same physical properties. It will then be possible to determine the composition of the real gas and then to calculate its calorific value and/or the Wobbe index.

The sensor measures the thermal conductivity at 30 ° C. and 80 ° C. by means of two electrical resistors placed in a cell containing the gas to be analyzed. The output signal of the sensor, as a function of the conductivity, is then used for the resolution of the preceding system in order to obtain the proportions of the ternary mixture.

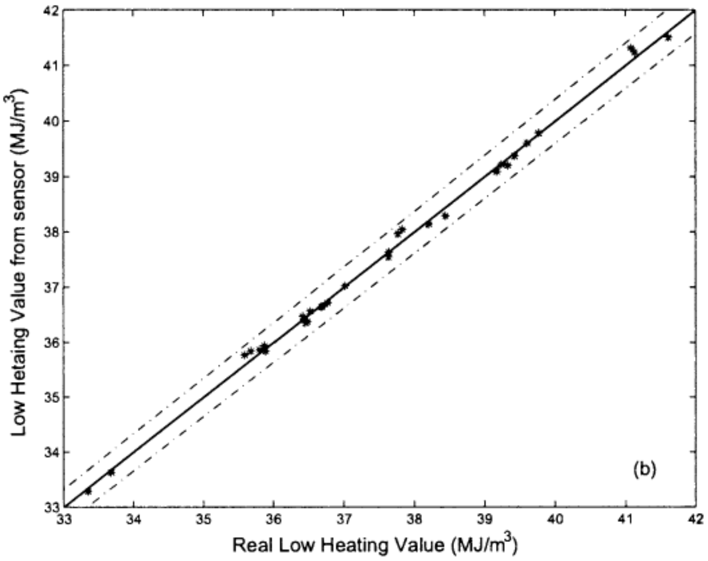


Figure 22: Comparison of real LHV measured and LHV of the ternary gas mixture

This composition finally makes it possible to calculate the low calorific value of the ternary gas and therefore by hypothesis that of the real gas which would have the same physical properties, in this case the conductivity at 30 and 80 ° C.
The calorific value of the gas can be determined at +/- 1% .
It is also possible to the following properties 2 by 2.

- Viscosity and thermal conductivity at a fixed temperature
- Thermal conductivity and refractive index
- Speed of sound propagation and refractive index

The density, the dielectric constant or the IR absorbance can also be used, see Figure 22.

C – Micro Wobbe Index meter

Bronkhorst High Tech BV (Netherlands) has developed a very small (5 * 5 * 5 cm3) Wobbe Index meter in collaboration with the University of Twente and using the MEMS principle (Micro Electro Mechanical Systems). This system allows real-time measurement of Wobbe Index for gaseous fuels (natural gas, biogas and hydrogen).

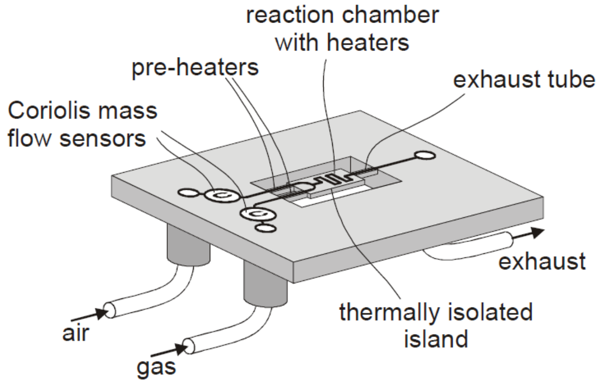


Figure 23: Schematic representation of Bronkhorst/Twente micro Wobbe index meter

At the gas and air inlets, Coriolis mass flowmeters are used to measure the mass flowrate and the density of the air and the gas to be analyzed. The gas and air are heated electrically at 600°C

in separate tubes. The heated gas and air are then mixed and spontaneous combustion takes place. The temperature rise which depends on the thermal conduction through the silicone substrate allows the measurement of the calorific value of the gas. With density and calorific value, the Wobbe index is finally obtained.
This costly system is intended for industrial customers.

D - Others

- The Federal Polytechnical School of Lausanne (CH) developed a portable system for measuring the viscosity of a gas which is correlated to its WI.
- Another system developed by Gasunie (NL) is based on the speed of sound propagation at 2 different pressures which can be correlated to the WI.
- The last principle developed by Honeywell is based on the measurement of the thermal capacity, the thermal conductivity and the viscosity of the gas. The system makes it possible to know the Wobbe Index, the calorific value, and the density. It is intended for industrial processes.
- Advantica presented an apparatus called GASPT in 2001 at the IRGC. The method consists of measuring the propagation speed of the sound and the thermal conductivity at 2 temperatures. A special design has been adopted for the acoustic resonator. This device is designed to measure the IW in industrial processes.
- System Gas-lab Q1, developed by a collaborative project between Ruhrgas AG, Sensors Europe and Flowcomp systemtechnik is based on the use of 3 micro-sensors. The first to measure the thermal conductivity and the two others which are IR to measure the CO2 content and the Hydrocarbons allowing the determination of the density, the calorific value and the Wobbe Index
- The gasQS system was developed by MEMS AG and uses the principle of correlations based on 3 measurement sensors. The system was developed as part of a project between EMPA and WIKA and funded by Swiss Gas Association / Swiss Federal Office of Energy. It is based on the measurement the thermal conductivity and thermal capacity and the mass flow and the density of the gas which can be correlated to the calorific value, the Wobbe Index, the air / gas ratio and the methane index (Figure 24).

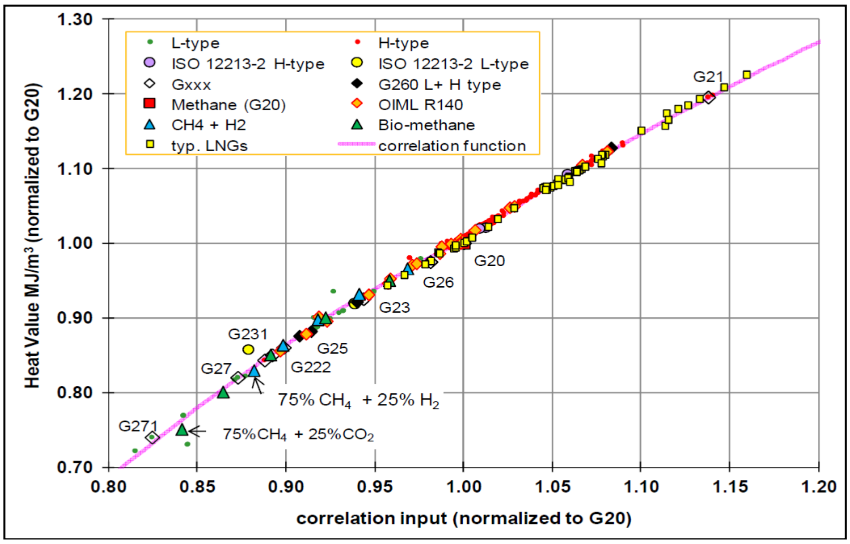


Figure 24: Correlation based on three measurement sensors in relation to the calorific value of different gases from the gasQS system of MEMS

7.1.1.2 Devices within the combustion zone

A - Flame ionization (general)

The combustion of a gas, for example methane (CH_4), takes place in various stages before the formation of the stable end-products of combustion, CO_2, H_2O, N_2, O_2, CO and NO_X (NO and NO_2). These end products are formed from free radicals present in the combustion zone or the flame front as described below. The presence of these positively charged or negatively charged free radicals generates an electrical current called ionization current which can be quantified and used for combustion control.
This principle is generally used in domestic boilers for flame detection (safety device). The cathode is the ionization probe (a simple refractory conductor) placed near the burner. The anode is the burner itself (to the ground).
The ionization current depends mainly on the gas used (which influences the concentration of ions in the combustion zone), the air / gas ratio and the location of the probe with respect to the flame front.
It can be characterized for different operating points or different positions of the probe. The value for optimal operation can be used as a reference.

Figure 25 shows an example of the free radicals and the induced ionization current in the flame front.

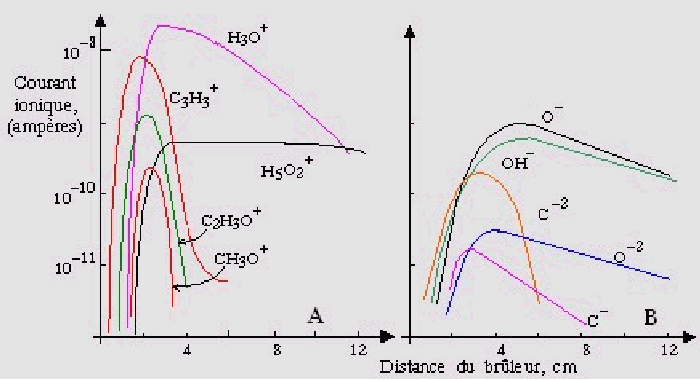


Figure 25: Flame ionization current and free radicals in the flame as function of the distance from the burner tip.

Figure 26 shows an example of the use of an ionization electrode and the measurement of the ionization current for a boiler.

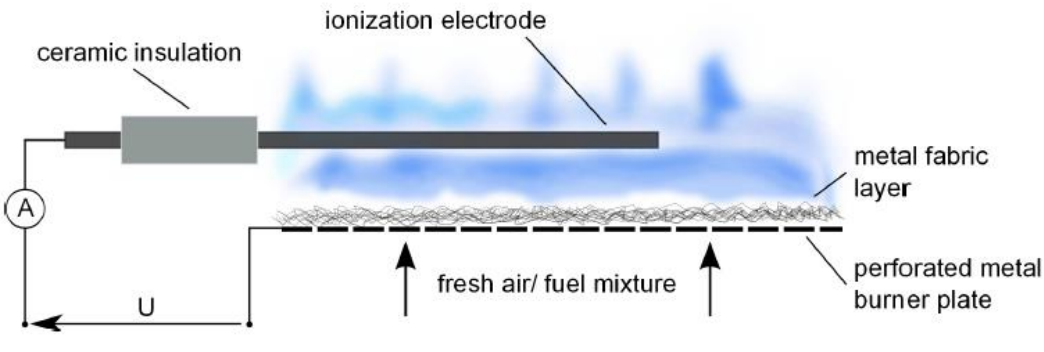


Figure 26: Principle of measuring the ionization current

This ionization current can therefore be used to control the air / gas ratio and maintain an optimum air factor. Since the measurement is instantaneous, the combustion is adjusted in real time.
The ionization current measurement is also sensitive to the position with respect to the flame and the burner, in particular as a function of the power.
Since the probe is placed in an environment subject to oxidation, it is prone to aging and the signal can be altered. All these influences may change the level of ionization current, but the form of the ionization curve with changing air factor stays similar. This fact is used in the practical cases using flame ionization current on boiler and burner combustion control, see chapter 7.2.
This ionization probe is also used for safety purposes (flame monitoring device) and the additional cost is reduced.

B- Flame temperature monitoring

The flame temperature is influenced by the air factor (Lambda). The flame temperature decreases when lambda increases (the maximum theoretical temperature is reached at the stoichiometry (Lambda = 1).
The measurement of the flame temperature (or its consequences) can therefore give an image of the quality of combustion. Moreover, when the lambda decreases to one, the flame approaches the burner surface and increases the surface temperature. It is therefore also possible to link the combustion quality to the temperature of the burner surface. Consideration should be given to the influence of operating conditions on the temperature control mechanism in relation to the operating water temperature.

C- Optical methods: IR emissions

The absolute value of infrared radiation can be used as a measure of temperature while its spectral composition can give information on the ratio of the concentrations of the different radicals.

7.1.1.3 Devices downstream of the combustion zone

O_2 Measurement

The measurement of the residual oxygen content (O_{2mes}) in the products of combustion makes it possible to know the air/ gas ratio (Lambda) by using the following equation.

$$\lambda = 1 + \frac{v_{\min t}}{l_{min}} \frac{21}{(21 - O_{2mes})}$$

It is then possible to keep the lambda measured constant to the optimum value independently of the various used gases.
Several technics are used for oxygen content measurement.

- Paramagnetic sensors
- Zirconium sensors
- Laser diodes

CO / H_2 sensors

Continuous monitoring of the CO / H_2 contents in combustion products is an alternative to the control by monitoring the O_2 content.
This control uses a modified zirconium probe. The CO content in the combustion products is monitored and is the main indicator of the combustion quality.
Poor or incomplete combustion of hydrocarbons (bad mixing, not enough combustion air, overloading of the burner) generates excessive amounts of CO. Even with excess air, CO emissions can also be excessive because of flame instability, blow off.

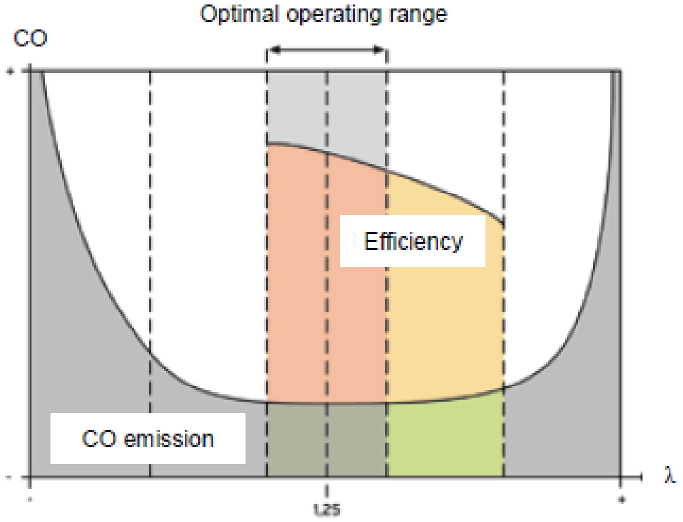


Figure 27: Basic relation between the air factor λ, CO-emissions and efficiency respectively

Vaillant uses a CO sensor developed with Steinel AG on its wall hang boilers.
CO sensors are useful to minimize CO emissions and excess air and thus increase combustion efficiency by adjusting to a safe operating point and taking into account the aging of the burner.

Steinel Sensor

The Steinel sensor developed with Vaillant is a semiconductor based on aluminum oxide (Al_2O_3) with a surface made of gallium oxide (Ga_2O_3) (ceramic) to limit the sensitivity to moisture and allowing stability of the measurement. On a semiconductor, oxidation-reduction reactions at the surface will change the resistivity of the surface material of the sensor.
CO reacts with oxygen to form CO2. The number of Oxygen ions decreases allowing the conductivity to increase and the resistivity to decrease. By monitoring of the resistivity, it is then possible to know the level of CO produced.

Lamtec CarboSen 1000 probe

The CarboSen 1000 probe is a modified zirconium probe to detect the CO, H2 and unburned CxHy to measure the equivalent CO. It uses a selective CO / H2 electrode having low and targeted catalytic activity so that to minimize the catalytic reactions of CO, H2 and other unburned gases.
The operating temperature of the sensor of 630 ° C is produced by a heating element.

7.1.1.4 Summary and Conclusion on Gas Quality Sensors

An increasing need in knowledge of gas quality in different application, e.g. gas distribution, billing, industrial application and the intensive development of various electronic devices

have generated the development of numerous different sensors and technologies. Some of these sensors and technologies came up to a standard to be used in industrial application and for measurement in gas transport and distribution grids. Up to now most of the sensors are still quite expensive for the introduction in relatively low-cost and wide spread domestic and commercial boilers.
For low-cost application ionization- sensors, recently developed mass flow probes in combination with temperature sensors and CO-sensors are applied.

7.1.2 Burners for combustion controlled condensing boilers

In condensing boilers with combustion control fully premixed surface burners in flat, cylindrical or spherical form are used like in standard condensing boilers.

7.1.3 Fuel Air control of combustion controlled condensing boilers

Most of the combustion controlled condensing boilers are using similar fan/venturi/gas valve like standard condensing boilers, see Figure 12. To realize an independent control of air and gas the gas pressure regulator is equipped with an additional controllable orifice controlled by a step motor for example. The electronic control gets the signal from the combustion and sets the gas orifice in the gas valve to have the right relation of gas to combustion air.

7.2 Realized Systems in Combustion Controlled Condensing Boilers

7.2.1 Systems based on the Ionization signal

The first system of a combustion controlled boiler based on the ionization signal has been realized in the late nineties of the last century by the company Hydrotherm owned by Stiebel Eltron. The essential new idea to overcome the problem of aging and exact positioning of the ionization probe was a repeated self-recalibration of the system by using the typical curve form of ionization signal with changing air factor λ and it's fixed maximum close to λ=1, see [10]. A second basics necessity was the acceptance of electronic automatic firing devices including the fail save feature.
Stiebel Eltron patented this new developed system for boilers suitable to give condensing boilers the ability to cope to a wide range of gases. The Ruhrgas AG as a big gas company buying and selling gases from different sources was very interested to spread this technology and therefore bought the patent. Ruhrgas' sub company Kromschröder completed the development and sold the system to different boiler manufacturers under the trade mark SCOT, "**S**afety **Co**mbustion **T**echnology".
The flame ionization electrode is used for flame monitoring and combustion control. The gas valve and the combustion air fan are controlled separately so that the burner always operates at an optimum ionization current defined by the manufacturer.
Kromschroeder declares that this system can adjust the appliance to operate safely with gases with a range of Wobbe index between 34.3 and 54.7 MJ/m³ corresponding respectively to test gases from G271 to G21.

A detailed explanation of the calibration procedure, the control procedure during change of gases is given in the internet, see Figure 28.

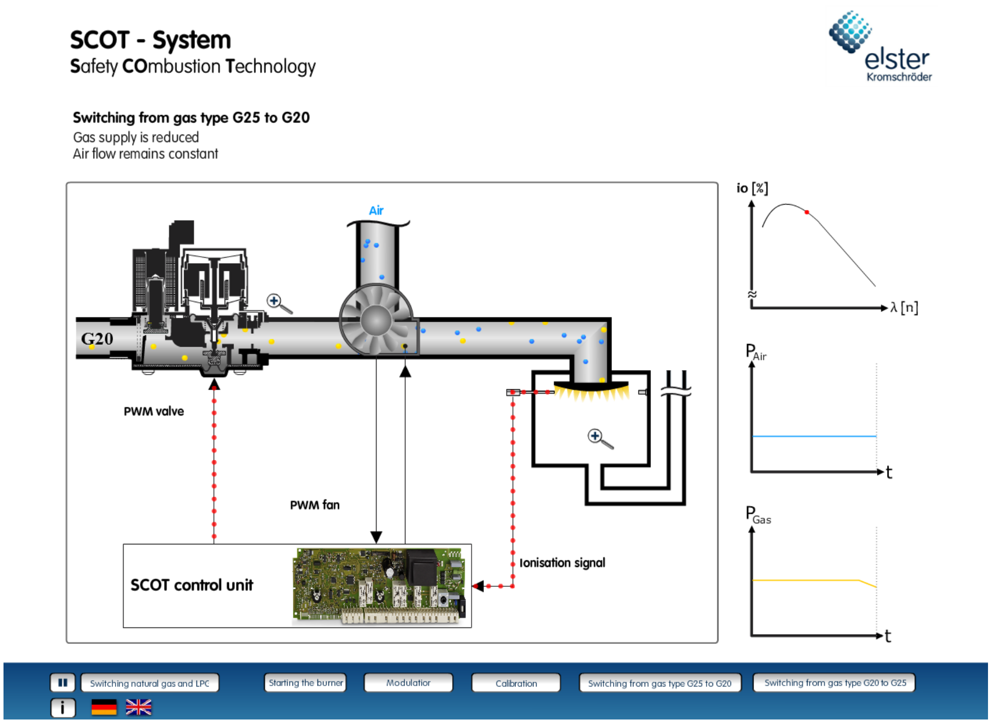


Figure 28: Explanation of the combustion control system SCOT based on the ionization signal, see http://www.kromschroeder.de/fileadmin/kromschroeder/Produkte/scot/scot_22_04_2010_de_web.swf

Over the years new systems based on the ionization signal were developed with new and deviating ideas concerning the specific way of recalibration.

Currently the system of nearly all known combustion controlled appliances is based on ionization signal as this is produced by a cheap and reliable sensor.

7.2.1.1 System LAMBDA PRO of Viessmann

On the basis of the SCOT patent Viessmann developed the system “Lambda Pro”, which is shown in Figure 29, see [11]. This system acts on the gas and the air flow rate to maintain the air factor at an optimum value depending on the gas used. The control system used is similar to that of Kromschroeder.
Viessmann declares that the gas boilers equipped with the lambda Pro control can operate with gases with a lower Wobbe index range of 34.3 to 57.7 MJ/ Nm³ (15°C).

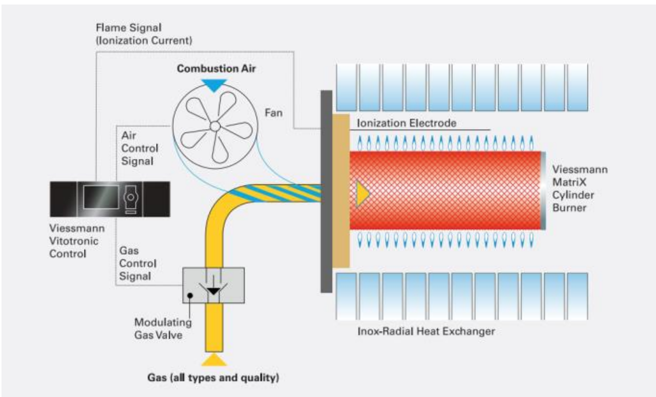


Figure 29: System LAMBDA PRO Viessmann

7.2.1.2 Think system of Baxi / Chappée SA / BDR Thermea

Baxi produces boilers that are equipped with a combustion control device called Think. This device makes it possible to automatically adapt the boiler to the quality of the fuel either natural gas (NG) or liquefied petroleum gases (LPG) without intervention on its hardware. The combustion control system is based on the ionization current. The device acts on the gas valve or the fan speed so that the boiler always operates with an optimum air / gas ratio. The control used is the Siemens model with Sitherm (Pro) which uses a logic similar to that of Kromschroeder.

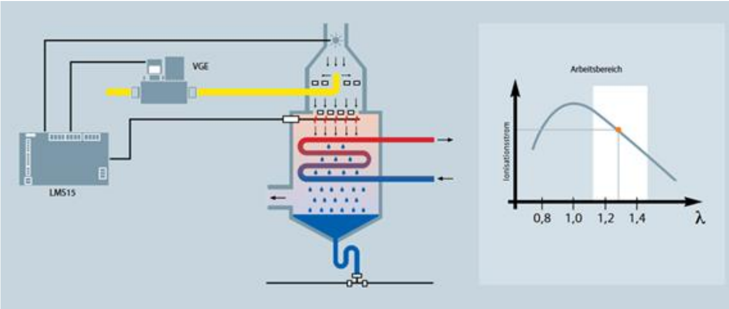


Figure 30: Think System of Baxi

7.2.1.3 Control system of Vesta SIT

The principle of this system is based on measurement the voltage instead of the ionization current. According to the patent, this method avoids the impact of aging of the electrode. The input signal is an AC signal. The air factor is calculated according to a correlation between the input signal and the response which is sampled and then processed using the Discrete Fourier Transform (DFT). The method makes it possible according to the claims to detect the displacement and aging of the electrode. The control curve of ionization voltage - power is adjustable. The control system makes it possible to recognize the gas family.

7.2.2 Systems based on Burner temperature and airflow monitoring

As it is well-known, the flame temperature depends strongly on the air factor of the combustion, but also on the burner load. Compared to these influences the gas quality itself affects the temperature only slightly. This behavior provides the chance to control the combustion by a temperature signal, but additional information on the load is necessary too. The following developments are built on this system.

7.2.2.1 "Lambda Constant" EBM PAPST

Since the flame temperature cannot be measured, the system relies on monitoring the temperature of the flame burner head. The temperature of the burner is always proportional to the combustion air required, and therefore to the air gas ratio (lambda).
By measuring the temperature and knowing the air flow and connecting these two parameters to the optimum value of lambda, the device used acts on the air / gas ratio to maintain an optimum target value.

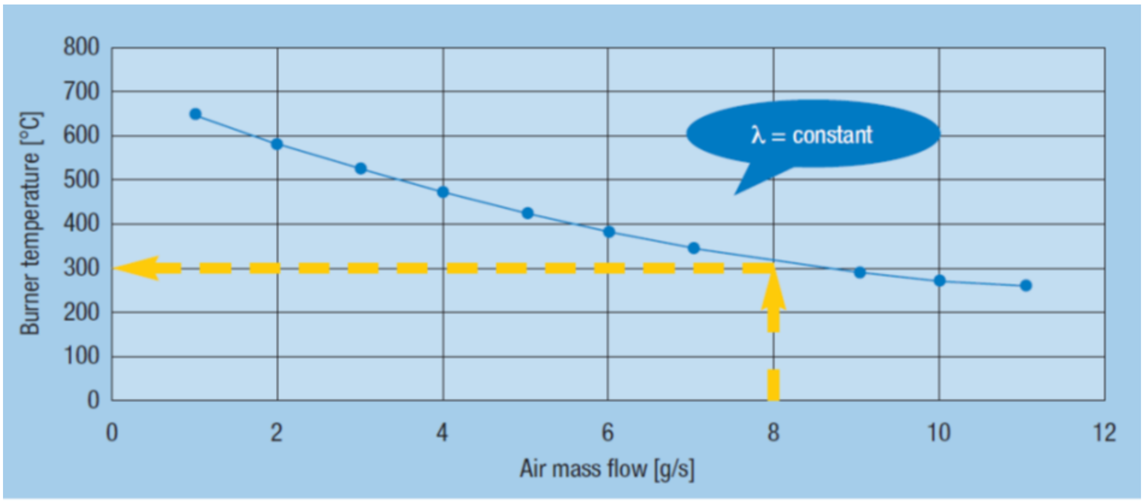


Figure 31: Burner temperature in dependence of the combustion air flow

This mechanism is not very robust, as the burner temperature depends on the ambient air conditions.
Because it has also to be adjusted to family of gas it does not accept large variations of the gas quality. The system is used on the boiler Elite of HTP company USA.
http://www.htproducts.com/eliteft.html.
Due to the newest information from EBM Pabst the system is currently not sold any more, but further development work is going on.

7.2.2.2 System Gas Manager of the Company Polidoro

This device was presented at ISH in 2015. It consists of a temperature measurement at the burner head which according to Polidoro makes it possible to maintain a constant air/gas ratio lambda according to the nature of the gas.
This system has been validated for G20 and G30 and their limit gases. This principle is adaptable on cylindrical burners but not on surface burners.
The Figure 32 shows the principle used.

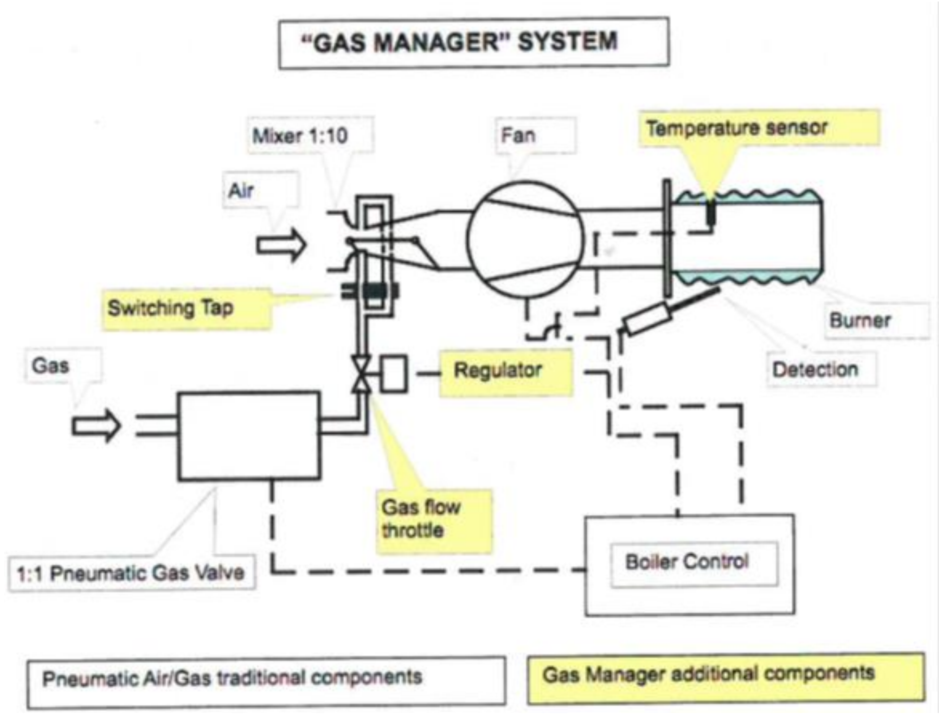


Figure 32: Gas manager system from Polidoro

7.2.2.3 System of the Company Atag

The Dutch company Atag developed a combustion controlled condensing boiler for a project running in the Netherlands distribution grid. The boiler may cope with a huge range of gases from including raw biogas, natural gases and even LPG. This boiler has been presented on the ISH, but it is not offered to the market, but for the project mentioned only. Due to statements of Atag the technology is based on temperature measurement close to the burner surface.

7.2.3 Systems based on CO-Sensors

The Company Vaillant developed a combustion controlled condensing boiler with a system basing on the CO-measurement in the flue gases. As mentioned before, see Figure 15, Figure 16 and Figure 27 CO-emissions of fully premixed surface burners tend to increase at both ends of air factor and by that Wobbe number. This effect is used to find the right operating point for the boiler for the whole range of gases. The calibration process is similar to that of controls based on ionization. The gas flow is increased slightly to that point where CO-emissions are increasing strongly. The operation point is found at a certain distance to the steep increase of CO-emissions. By this way the appliance is always operated in a safe way with an optimum air factor, see [12] and [13].
Due to new information Vaillant is developing together with their sub companies in France a new system basing on the ionization signal too. This new system will probably replace the current CO-based system.

7.3 Existing Experiences

First condensing boilers with combustion control entered the market in the beginning of the millennium; see Chapter 8"Market research", so that increasing experiences in Europe exists since more than 15 years. The technology seems to take the market quietly and inconspicuously as there are few publications on lab tests or field tests. In [14] lab test of four different technologies are investigated and compared to standard condensing boilers being supplied with the whole range of gases approved due to EN437 including the German lower limit. The overall assessment was positive, especially concerning the range of emissions in dependence of the gas quality.

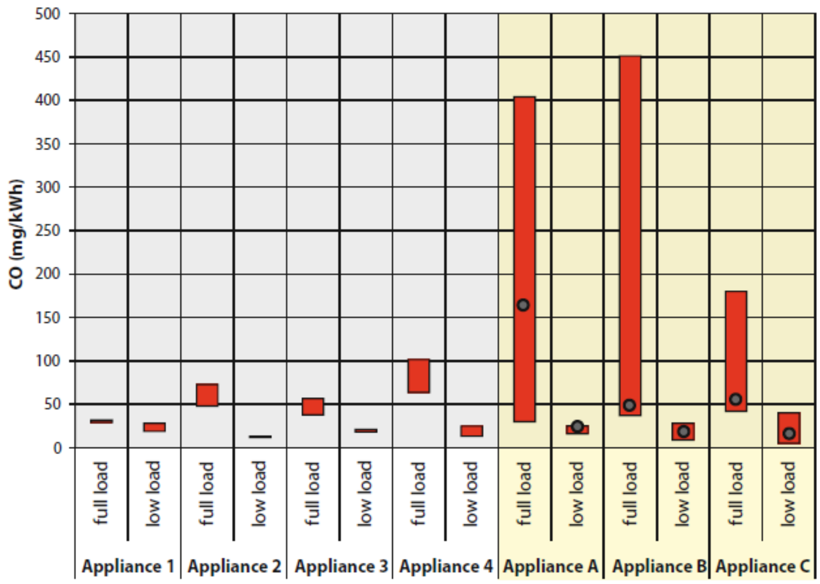


Figure 33: Appliance operation for all of the different gases (Ws = 39,1 MJ/m³ - 54.7 MJ/m³); maximum and minimum CO emissions on four combustion controlled appliances 1-4 and thre conventional condensing boilers A,B,C,○ operated with G20, see [14].

Additional lab test have been done with gases including hydrogen admixture up to 30%, see [15]and [16]. All investigation revealed that the influence of hydrogen is not controlled by the ionization control systems. Appliances are still operating reliable and safe, but the air factor increases with increasing portion of hydrogen introduce into natural gas.
Field tests have been carried out by the Gas- und Wärme-Institute Essen e.V. in 2008 They investigated combustion controlled appliances in the field by reducing the combustion air inlet and/or the flue gas outlet. The internal not published report proved a good functioning and reliability of the test boilers.
Currently first experiences are made during the conversion process from L- to H gas in the first regions in Germany, Belgium and France. No publication of results during this process is known up to now.

7.4 Summary

The construction of combustion controlled condensing boilers is, in the most important parts, very close to that of standard condensing boilers. They use the same types of burners, often a similar combination of fan, venturi for gas inlet and mixture and heat exchanger.
The main difference is lying in the additional sensor giving information about the combustion state, the gas valve, which is controllable independently of the air flow and as a central part the electronic control unit.
Different sensors to determine the gas quality or the combustion state for application before and within the combustion as well as in the flue gases are described in this chapter. For combustion controlled condensing boilers three of them are used. The ionization probe together with a smart control including a regular recalibration process is the most applied technology. One manufacturer uses currently a CO-sensor, but due to informal hints there are developments for a new system relying on ionization too.
Some boiler types with temperature sensors including a second signal as mass flow are in development but not yet widely in application. Using the temperature signal might have the advantage of being sensitive to hydrogen admixture too.
Although combustion controlled condensing boilers are sold since 2001, few lab and field tests are published. Phase II of the project will fill this lack by lab testing several combustion controled condensing boilers.

8 Market research

8.1 Information Acquisition

All five project partners contributed to the acquisition of information about the production, distribution and market share of condensing boilers with combustion technology by means of personal contact to manufacturers, visit of fairs (ISH 2017), former experience of market and lab work, internet research and exchange with experts. A common questionnaire has been prepared for the structuring of discussions with the manufacturer, see appendix A. A self-description of the project for manufacturers has been written to ask for information and support by delivering test appliances, see appendix B.
Finally all received information is compiled and analyzed for detailed information see also appendix C.

8.2 List of Manufacturer

A list of manufacturer offering combustion controlled appliances has been compiled from the information received, see Table 3

Manufacturer	Load range	Year of market entry
Ariston		
Bosch Thermotechnik Buderus	up to 20 kW	2017
Bosch Thermotechnik Junkers	up to 20 kW	2017
Brötje	15 kW-38 kW	2006
Chappee	12 kW	2016
Hansa	up to 36 kW	2018
Interdomo	15 kW-68 kW	2012
Rotex (Daikin)	15 kW – 28 kW	2017
Max Weishaupt	15 kW-60 kW	2001
Vaillant	up to 28 kW	2003
Viessmann	13 kW–150 kW	2005
Wolf	15 kW-30 kW	2013

Table 3: List of manufacturers selling combustion controlled condensing boilers

The list reveals that already in the beginning of the century first combustion controlled appliances appeared on the market. Over the years more manufacturers followed and currently at least 11 different manufactures are selling such types of appliances.
Most of them offer appliances in the typical load range suitable for flats and one to two family house. But also appliances up 150kW or/and for cascade installation are offered, which are suitable for multifamily houses, offices buildings or light commercial buildings like schools, hospitals, etc. In discussions with manufacturers some explained that they are developing combustion controlled condensing boilers for higher load ranges up to 200 to 300 kW. This means that not only domestic applications are possible, but also installation for multifamily houses, office buildings, schools, small hospitals i. e. the whole area of light commercial application may be supplied.

8.3 European Countries provided with Combustion Controlled Condensing Boilers

The manufacturers have different marketing areas in Europe and currently 26 of the European Countries are delivered by at least one manufacturer, see Figure 34.
In important gas using countries like Belgium, Germany, France combustion controlled condensing boilers are provided by between three or even up to ten different manufactures (Germany). There is already a competitive environment so this type of appliances may develop interesting prices for the end-user and will be further improved technically.

In Figure 34 the countries allowing the respective category I_{2N} for combustion controlled appliances due to EN437 (2003 and A1 2009) and prEN427 (2017) are marked in green additionally. Obviously 18 of the 26 countries are supplied with combustion controlled appliances without allowing the category I_{2N}. Manufacturers explained that in this case these combustion controlled condensing boilers are imported under the category I_{2EL} or other national categories. In consequences neither end-users nor the installers may really recognize the technical and handling advantages of this boiler type.

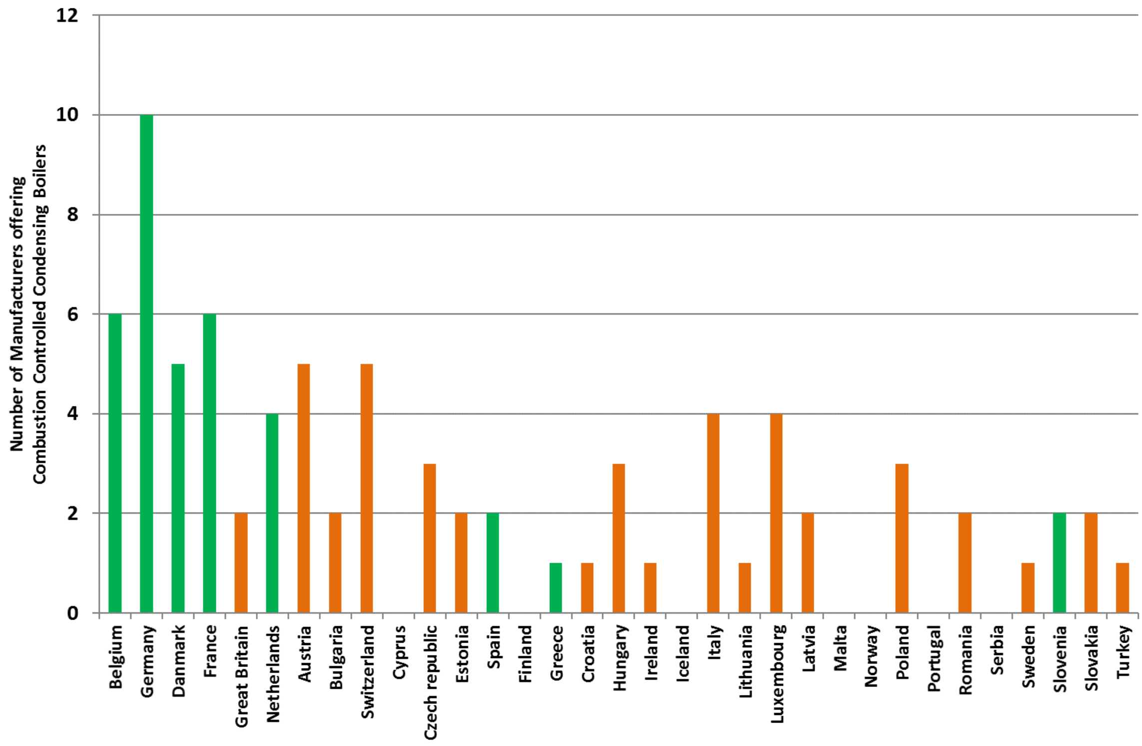


Figure 34: Number of Manufacturers offering combustion controlled condensing boilers in the respective European countries.

Especially for Great Britain currently looking to enlarge the Wobbe range it is not understandable, why they do not accept the respective category in their national standard.

8.4 Development of the Market and Market Share

The development of the market and market share is an important hint for the acceptance of these appliances by installers and end-users as well as for the technical reliability.

As a first example the market is investigated for Germany.
Already 2001 the first manufacturer brought a combustion controlled appliance with a load of 20 kW on the German market.
Meanwhile nine different manufacturers offer this type of boilers in the range of up to 150 kW or will deliver it in the next year 2018.
A market investigation of the BDH for a project on gas quality for the DVGW [5] showed that the selling of combustion controlled appliances increased from 2010 to 2014 by 50%. In 2014 nearly one third of the new installed Condensing boilers were combustion controlled, see Figure 35.
For domestic use versions with direct and indirect hot water production, as well as with Integration of thermic solar collectors are on the market. Some versions with higher load are prepared for installation in cascades, so that buildings with high heat demand may be equipped.
Figure 36 points out the increase of appliance diversity and load range in Germany. Today a suitable appliance for nearly each application is available.

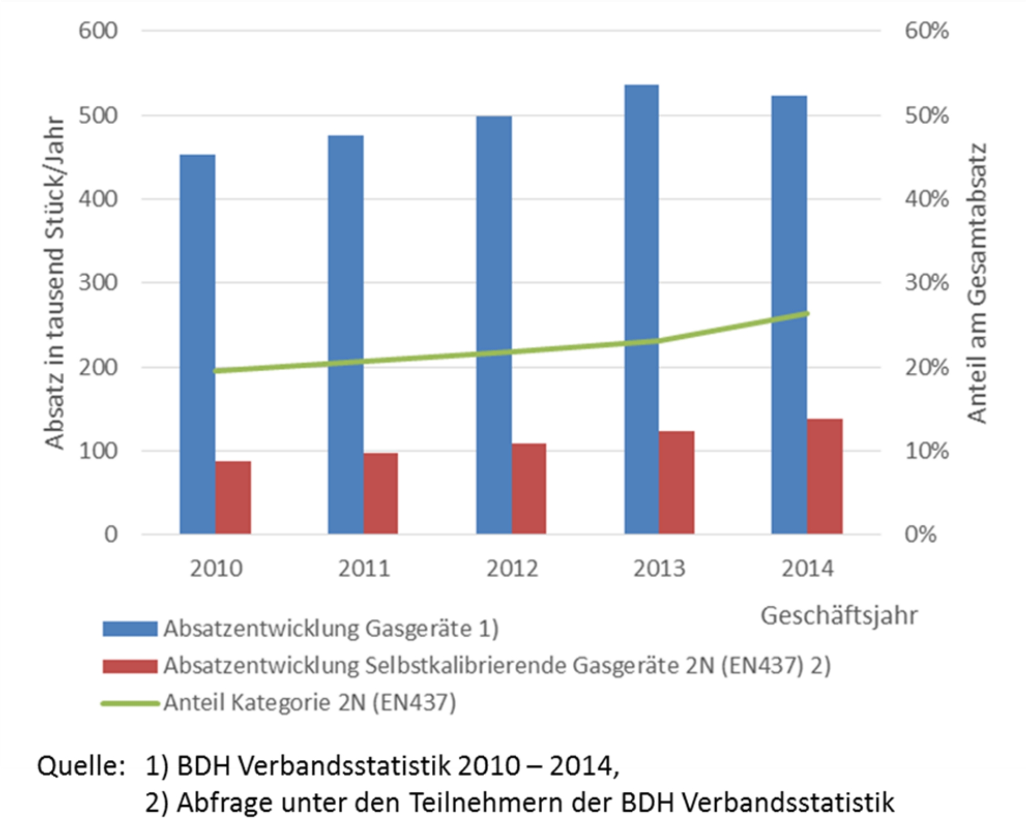


Figure 35: Development of the sales of combustion controlled condensing boilers in Germany compared to the sales of conventional condensing boilers
Columns: Sales in thousand per year (left axis)
Line: Share of sales of combustion controlled condensing boilers in sales of all gas heating appliances (right axis)
Source: BDH, [5], page 78

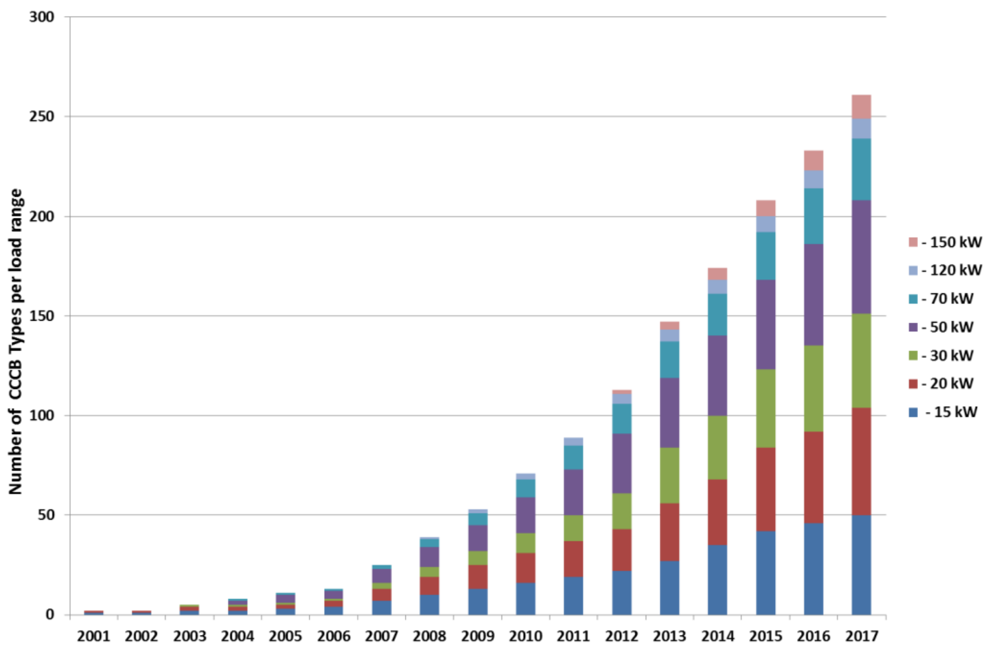


Figure 36: Increase of the load range and diversity of types of condensing boilers with combustion control offered on the German market.

Some manufacturer offer complete model lines exclusively with combustion controlled appliances. In this case the customer has not to count for additional costs. Other manufacturers provide combustion controlled appliances in the premium appliance line only.

Concerning the installed appliance market reliable data for the German market are not available. From the inquiry of the installed appliances in the L/H adjustment projects some data are communicated. The share of condensing boilers in total varies much in dependence of the single distribution areas. The share of condensing boilers with combustion control in the number of condensing boilers might locally go up to even 25% in dependence of the preferred manufacturer in the region, see [17].

For **Denmark** market share and prices are very difficult to obtain as well. However it seems that the combustion controls are increasingly used in the condensing boilers both to adapt to gas quality change and to reduce the NOx emissions.

9 Phase II Lab Tests of six different CCCB

9.1 Goal of the Lab Tests of Combustion Controlled Condensing Boilers

The experimental study consists of carrying out tests on condensing gas boilers equipped with combustion self-controlled devices in order to check their behavior when they are fed under different gas quality conditions than the standard gas conditions under which they are calibrated or set.

The tests are performed to check the following items:

1. Effect of gases of I_{2N} category, i.e. gases from group E and group LL (Wobbe range 34.3 MJ/m³ to 54.7MJ/m³) on the air/gas ratio, the load of the boiler
2. Effect of the all gases on emissions of CO and NOx and combustion efficiency
3. Effect of all the gases on flame ionization current (when possible)
4. Effect of bio methane and mixtures of hydrogen with G20 on the air/gas ratio, the load of the boiler
5. Effect of rapid change of gas quality, (dynamic response).
6. Start stop operation
7. Follow up of the calibration process when the appliance is set for the reference gas but supplied with gases in the upper and lower limits of I2N category and further (richer and poorer). Effect on emissions of CO and NOx (dynamic)
8. Effect of gas pressure (min and max)

Optionally, other combustion characteristics have been checked. For example:

9. Effect of combustion air temperature on the operation of the boiler (emissions)
10. Influence of the air and flue gas over pressure (blockage of the ducts) on the boiler operation
11. Influence of voltage variation during the boiler operation

Note that the list above is a “want list” that laboratories have been free to adapt slightly in view of the laboratory and boiler constrains. Especially, the optional test has not been carried out by all labs.

A reference test is required with the reference gas (in this case it is G20 for group H) at nominal and minimal and if possible at intermediate heat input.

All the important parameters (emissions, efficiency, ionization current, flue gas temperature, etc.) are registered during operation with nominal gas G20 and are used as reference values to be compared with those obtained with the different gases to be tested (
Table 4).

All the above tests can also be performed with other air factors (λ) above and below the reference measured value to check the effect of the excess air on the appliance operation.

The appliances are not adjusted at all. They are tested at the same conditions used for the reference gas.

Only for the test with the reference gas, the boiler is adjusted to the CO_2-value declared by the manufacturer, if that is possible and foreseen (requested by the manufacturer’s instructions).

9.2 Test gases and selected appliances

9.2.1 Test gases

The test gases are agreed between the project partners to cover the whole range of the test gases defined to appliance category I2N (EN437) and to consider also biogas and mixtures of natural gas with hydrogen, see Figure 37 and Table 4.

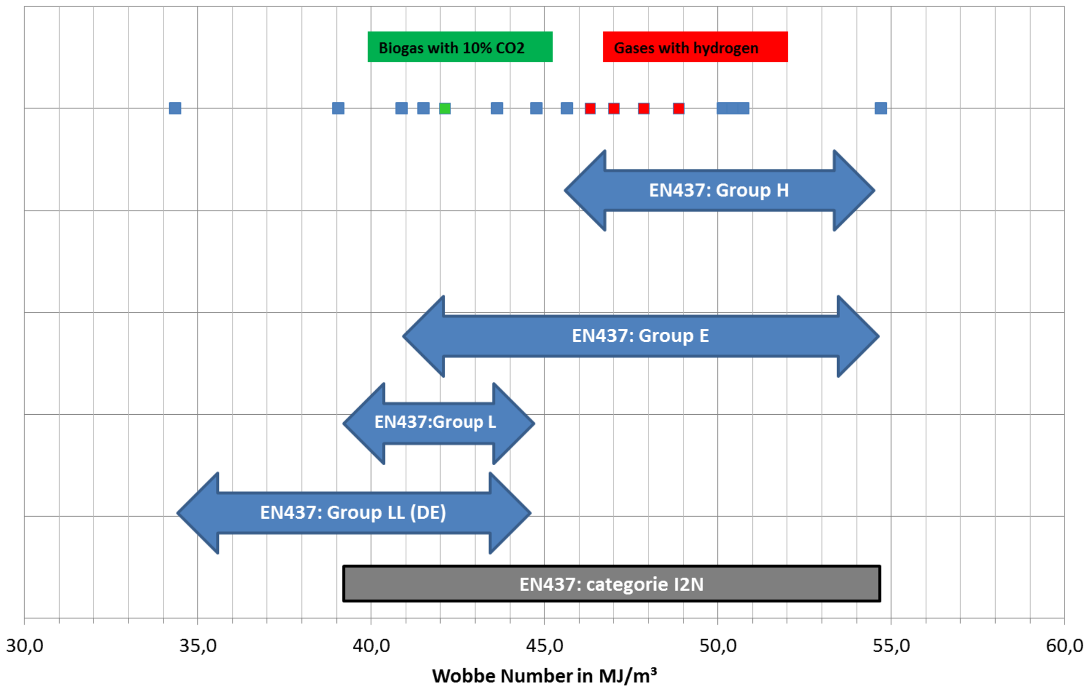


Figure 37: Overview of the Wobbe ranges of gas groups from EN437 and the test gases to be used in phase II of the project including bio methane and mixtures with hydrogen

9.2.2 Selection of test appliances

For the tests, 6 different appliances (instead of 5 initially planned) representative for the European market were selected, see Table 5. The manufacturers were contacted to provide test boilers and for support during installation and startup of the boiler. For the early tests done, results have been discussed with the respective manufacturers. However, for the recent tests done, manufacturers still have to be contacted.
Five of the appliances are equipped with a combustion control system based on the ionization signal. One boiler is controlled by the CO-signal.

Gas composition	methane	nitrogen	carbon dioxide	ethane	propane	hydrogen	superior calorific value 25/0	superior calorific value 15/15	relative density	Wobbe index 25/0	Wobbe index 15/15	Maximum CO2	Min. Air required	Cetiat	E.ON	DGC	Engie	gas.be
Symbol	CH4	N2	CO2	C2H6	C3H8	H2	Hsv	Hsv	d		Ws	CO2 drymax	O2 min					
Unit	mol%	mol%	mol%	mol%	mol%	mol%	kWh/m³	MJ/m³	-	kWh/m³	MJ/m³	%	m³/m³					
G271	74,0	26,0					8,18	27,94	0,66	10,06	34,34	11,27	7,07	yes	yes	yes	yes	yes
G20 +21% N2	79,0	21,0					8,74	29,83	0,64	10,91	37,25	11,38	7,55				yes	
G27	82,0	18,0					9,07	30,97	0,63	11,43	39,05	11,44	7,84	yes				yes
Natural Gas H + 15%N2	76,9	15,8	1,7	4,1	1,1		9,77	33,35	0,67	11,90	40,63	11,91	8,44				yes	
G231	85,0	15,0					9,40	32,10	0,62	11,97	40,88	11,50	8,13	yes	yes	yes	yes	
G25	86,0	14,0		0,0	0,0		9,51	32,48	0,61	12,15	41,50	11,52	8,22	yes			yes	yes
Natural Gas H + 13%N2	77,9	13,3	0,7	5,0	2,0		10,58	36,11	0,68	12,84	43,84	11,96	9,15			yes		
Biogas(L)	90,0		10,0				9,96	34,01	0,65	12,34	42,13	12,87	8,61		yes			
Pipeline Gas L (1)	83,6	10,2	1,7	3,6	0,6		10,24	34,95	0,64	12,77	43,63	11,93	8,85		yes			
Pipeline Gas L (2)	83,9	10,0	1,4	3,7	0,6		10,32	35,23	0,64	12,90	44,06	11,91	8,92					yes
G26	80,0	13,0	0,0	0,0	7,0		10,78	36,82	0,68	13,11	44,76	11,92	9,33	yes				
G23	92,5	7,5	0,0	0,0	0,0		10,23	34,94	0,59	13,37	45,66	11,62	8,85	yes				
G20 + 30% H2	70,0					30,0	8,80	30,05	0,41	13,76	47,00	10,72	7,40	yes	yes	yes		yes
G222	77,0		0,0	0,0	0,0	23,0	9,33	31,85	0,44	14,01	47,87	11,01	7,91	yes	yes	yes	yes	yes
G20 + 20% H2	80,0					20,0	9,55	32,62	0,46	14,12	48,24	11,12	8,12				yes	
G20 + 15% H2	85,0					15,0	9,93	33,91	0,48	14,31	48,86	11,30	8,48			yes		
G20 + 10% H2	90,0					10,0	10,30	35,18	0,51	14,48	49,45	11,45	8,84	yes	yes	yes	yes	yes
Pipeline Gas H (2)	88,7	0,8	1,9	6,9	1,3		11,64	39,75	0,63	14,68	50,14	12,17	10,07		yes			
Pipeline Gas H (1)	90,5	0,9	0,2	4,8	1,3		11,19	38,20	0,57	14,58	49,77	12,14	9,94				yes	
G20	100,0		0,0	0,0	0,0		11,06	37,78	0,55	14,85	50,72	11,74	9,57	yes	yes	yes	yes	yes
G21	87,0				13,0		13,23	45,16	0,68	16,02	54,69	12,29	11,45	yes	yes	yes	yes	yes

Table 4: Test gases used for the boiler tests of phase II of the 5 partners. Pipeline Gases are an example and may vary due to lab site. test gases may differ slightly due to local mixing. The use of the different gases respectively is indicated for each partner.

Appliance	CCCB 1	CCCB 2	CCCB 3	CCCB 4	CCCB 5	CCCB 6
Load Qn (H_i)	2 – 12 kW	24 kW	4.5 – 33.7 kW	4,2 – 24,7 kW	2,0 – 14,0 kW	5,0 – 21,0 kW
Heat output Pn	4.5 – 26.0 kW 50/30°C 3.6 - 12 kW 80/60°C	3.4-24 kW 80/60°C 3.7 – 26.1kW 50/30°C	4,8 – 36 kW 50/30°C 4.3 – 33.4 kW 80/60°C	4,1 – 24,1 kW 80-60°C 4,5 – 26,0 kW 50-30°C	1,9 – 13,7 kW 80-60°C 2,2 – 15,0 kW 50-30°C	3.8 – 18.9 kW at 80/60°C 4.4 – 20.4 kW at 50/30°C
Category	EU: II_{2Es}	II_{2Er3P}	I_{2H} for UK	EU: II_{2N3P} BE: I_{2N}	II_{2N3P}	DE : II_{2N3P} AT, CH : II_{2H3P} LU : $II_{2N3B/P}$
Gases	Natural Gases LPG P	Natural gases LPG	Natural gases LPG	Natural gases, LPG P	Natural gases LPG	Natural gases, LPG P
Flue gas system	C13/C33/C43/C43P/ C53/C63/C83/C93/ B23/B23P	C13 - C33 - C43 - C53 - C63 - C83 - C93 - B23	C13 – C33 - C53	B23, B23P, B33, C13(x), C33(x), C43(x), C53(x), C63(x), C83(x)(P), C93(x)	B23, B33, C13, C33(x), C43(x), C53(x), C63(x), C83(x), C93(x)	B23P, B33P, C13(x), C33(x), C43(x), C53(x), C63(x), C83(x), C93(x)
Year of construction	2016	2018	2016	2016		2018
efficiency	108% at 30% load and 50°C return temp.	97,1% (80/60°C)	94 % (80/60°C)	105% (50/30°C)	99,2% (40-30°C)	98 % (full load 60/80 °C) Hi
Nominal CO_2	8.5% natural gas H (G20) 8.4% natural gas L(G25)	8.7% (8.2%-9.3%)	8% - 10.5% All natural gases	8.5% natural gas H 8.4% natural gas L 10.0% LPG P		7,8% – 9,8% for E / H / LL
Nominal O_2	6.5% (G20) 5.5% (G25)	5.4% (6.3%-4.3%)	6.71% - 2.2% 9%- 11.8% (LPG)	5.7%	5% (Natural Gas) 5.3% (LPG)	
Nominal air factor	1.33		1.11-1.46			
CO emissions	7 - 24 mg/kWh			7 - 53 mg/kWh	15 mg/kWh	
NO_x emission class	6	6	6	5	6	
NO_x emission	15 - 25 mg/kWh		37	27 - 30 mg/kWh	28 mg/kWh	

Table 5: Test appliances selected for the lab tests

9.3 Results

The tests were executed by the five project partners in the respective labs following as far as possible the common test procedure and test conditions agreed before, see appendix 11.4. Each partner elaborated a detailed test report, which is attached in the appendix **Fehler! Verweisquelle konnte nicht gefunden werden.** to **Fehler! Verweisquelle konnte nicht gefunden werden.**. The results are summarized in the following.

Result 1, Combustion controls and boiler installation and maintenance:
All six boilers are compact, quick and easy to install. Because of the combustion control no on site adjustment is necessary.

This means that the operations of commissioning and maintenance or repair should be faster and easier. This will result in cost savings.

Result 2, Air factor:
The combustion control system of all boilers keeps the air factor (e.g. O_2 and CO_2) quite constant over the whole range of Natural Gases with W_s from 34.3 MJ/m³ to 54.7 MJ/m³.

In stationary tests with the test gases (Table 4) the partners investigated the influence of the gases on the six appliances when solely the test gases are switched and no adjustment of the appliance has been done. In Figure 38 and Figure 39 the measured air factor is plotted over the Wobbe range for the different gases and the two different investigated control technologies.

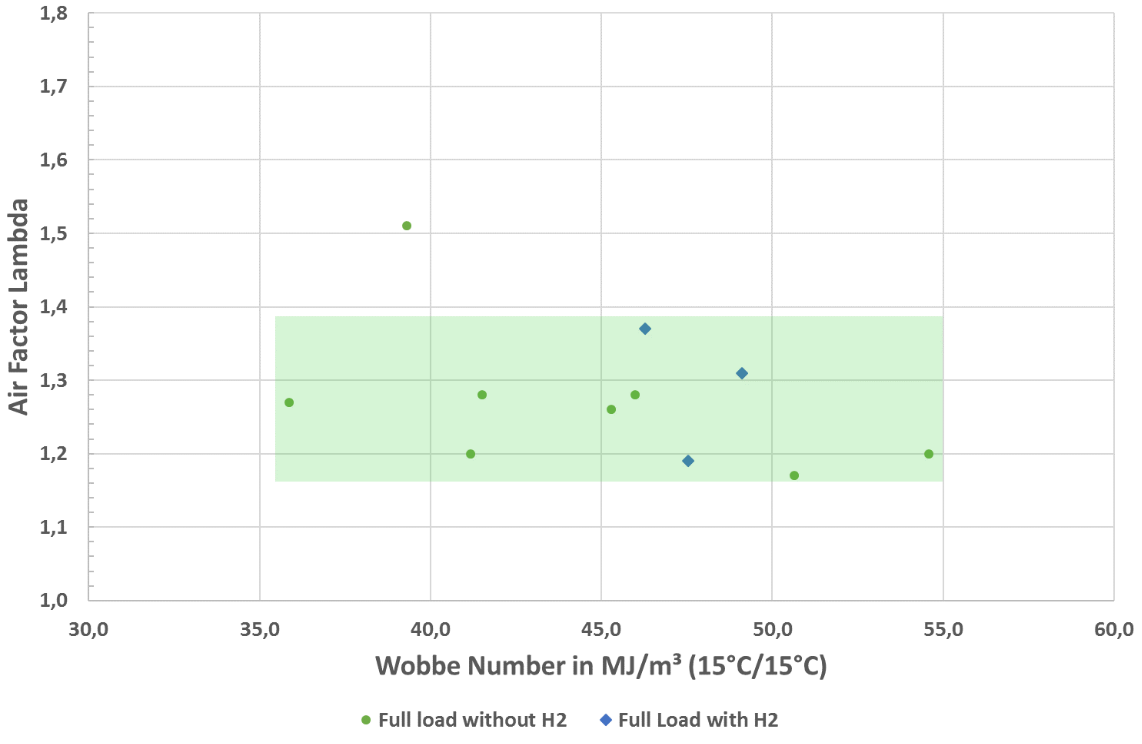


Figure 38: Stationary operation of the CCCB 3 equipped with CO-control with test gases over the whole range of Natural Gases including gases with hydrogen admixture without any adjustment of the boiler. The graph plots the air factor over the Wobbe number of the different gases.

Figure 38 shows that the boiler with CO control is performing well for all investigated gases including hydrogen containing gases, e.g. the air factor is kept in a "green zone" of around 1.2 to 1.4, where condensing boilers usually operate. (The one exception measuring point that is outlying might be a measuring mistake.)

Also, the measured air factors of all five boiler with ionization based combustion control are laying in the range of 1.2 to 1.4 for all investigated gases, see Figure 39. However, hydrogen gases are not included here, but discussed in result 4. The ionization control keeps the air factor of each boiler much more constant over the Wobbe range. Obviously different manufacturers fixed the nominal air factor at different values.

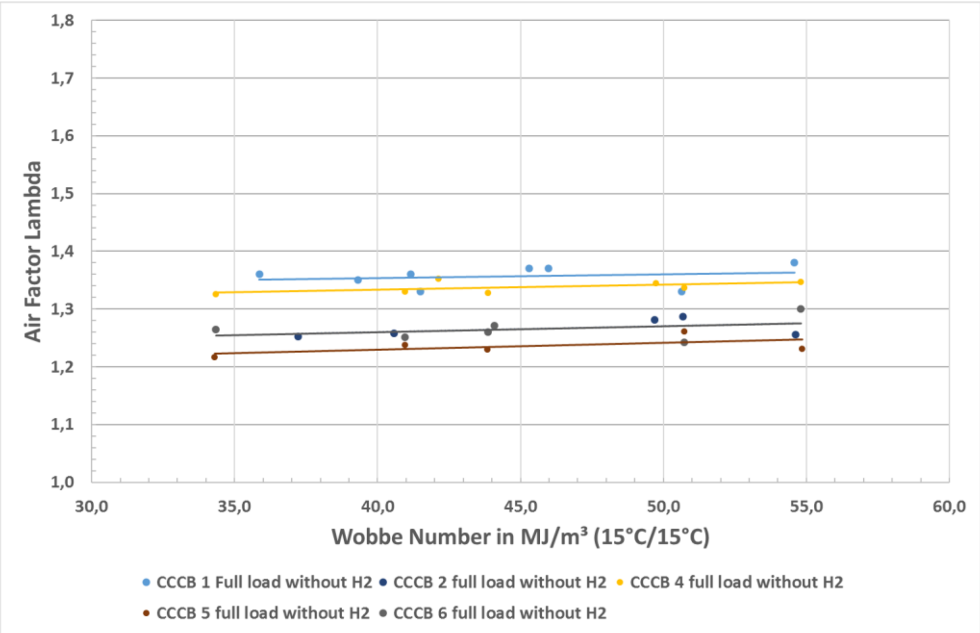


Fig 39 a

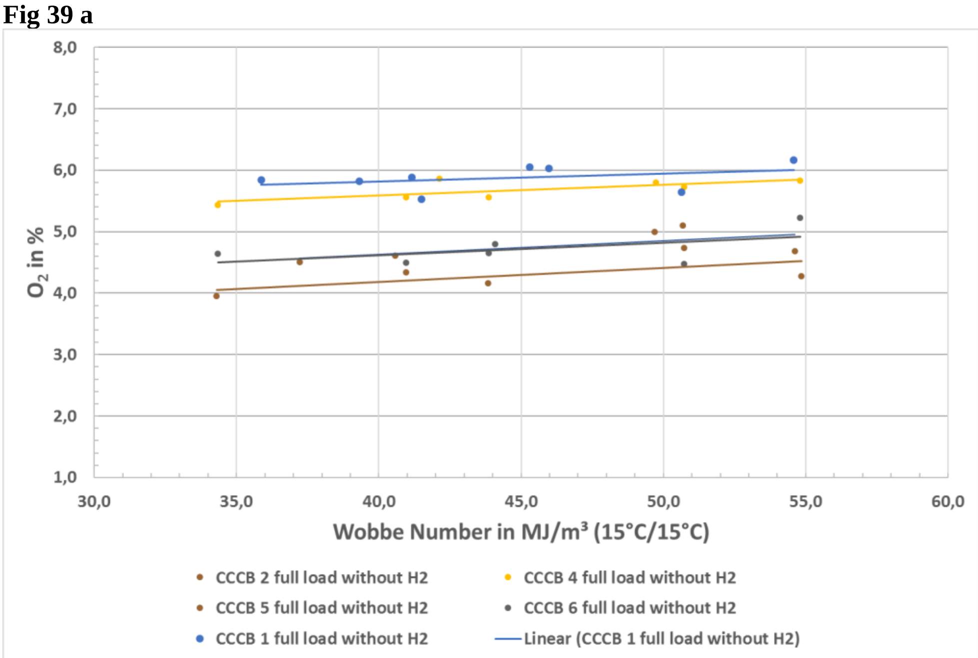


Figure 39 and b: Stationary operation of the five boilers equipped with combustion control based on ionization signal with test gases over the whole range of Natural Gases without any adjustment. The graph plots the air factor (a) and the O_2-content (b) over the Wobbe number of the different gases. Hydrogen containing gases are not plotted.

This constant air factor for both technologies over the whole Wobbe range of natural gases from lowest L-Gas to the highest H-Gas is an important advantage compared to condensing boilers without combustion control, where the air factor would increase to about 1.9 for the gas with the lowest Wobbe number, when adjusted to 1.3 for G20, see Figure 40

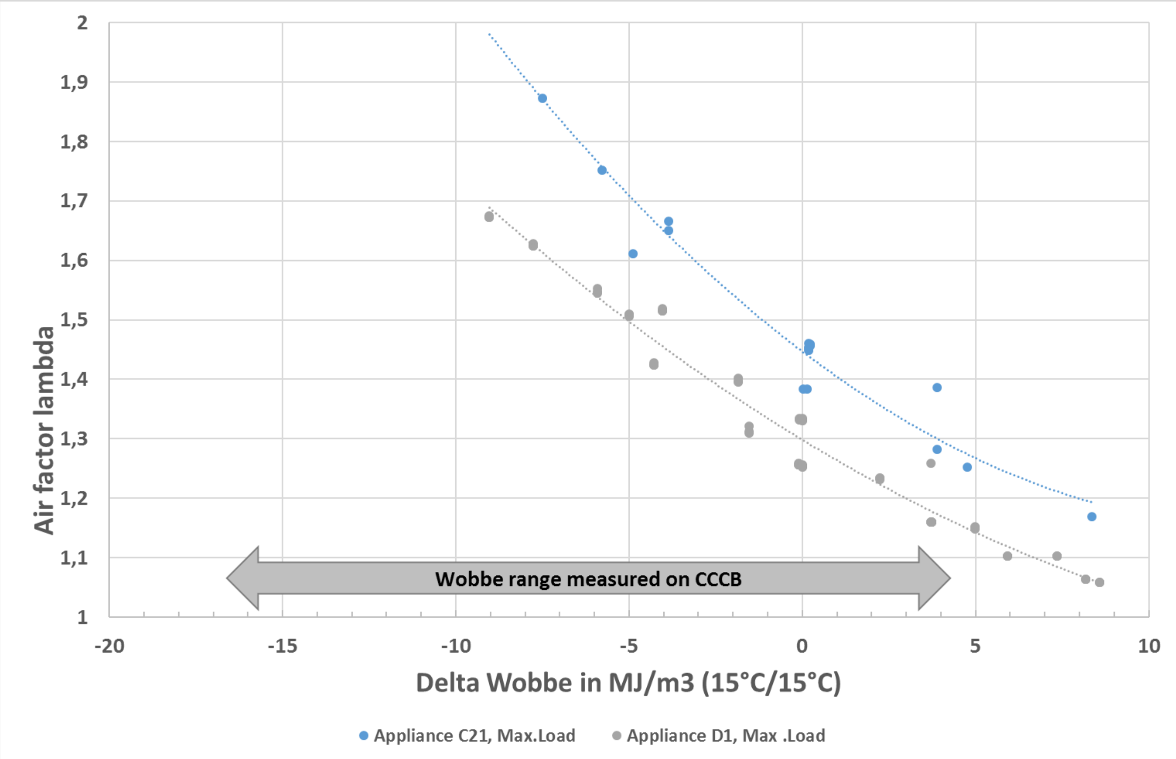


Figure 40: Increase of air factor with decreasing Wobbe Number for condensing boilers without combustion control. The results of two condensing boilers of the GasQual project are plotted over Δ Wobbe Number, e.g. the difference between the Wobbe Numbers of the supply gas and the adjustment gas. *(Note that the scale covers a variation of 30 MJ/m3 as shows as well on the figure for the air factor with control system.)*

Result 3, Emissions:
Because of the constant air factor emissions of CO and NOx stay at their low level over the whole range of Wobbe number.

In Figure 41 the emissions of the investigated boilers are plotted over Wobbe number respectively for maximum load (left side of the figure) and minimum load (right part of the figure). Obviously, the level of CO- or NO_x-emissions doesn't change with Wobbe number apart for the boiler with CO control that is more sensitive but at maximum load only. This effect is especially interesting at the ends of the very wide Wobbe range, where, due to experiences of GasQual emissions often increase significantly. This result was expected considering that one of the main influence parameter for emissions is the air factor and as the control is maintaining the air factor more or less constant (result 2) emissions are also quite stable.
The level of emissions depends on the construction of the individual burner and boiler.
CO emissions:
All measuring results for minimum load and most results for maximum exhibit low CO-emissions far below to slightly over 100 mg/kWh (this is about 100 ppm dry, air-free). This however not true for two boilers at maximum load for which one is reaching respectively

about 200 mg/kWh (this is about 200 ppm dry, air-free) and about 300 mg/kWh (this is about 300 ppm dry, air-free). The latest being the boiler with CO control. Note that this result is excellent as in any case the emissions are under the most severe requirement for the certification of appliances (1000 ppm dry, air-free). So, the combustion controls are clearly improving the safety of the appliances.

NOx-emissions:

NOx-emissions stay below 60 mg/kWh (40mg/kWh) for maximum load (minimum load) for nearly all measuring points. Only four measuring points (from the CO-controlled appliance are laying between 60 mg/kWh and 110 mg/kWh.)

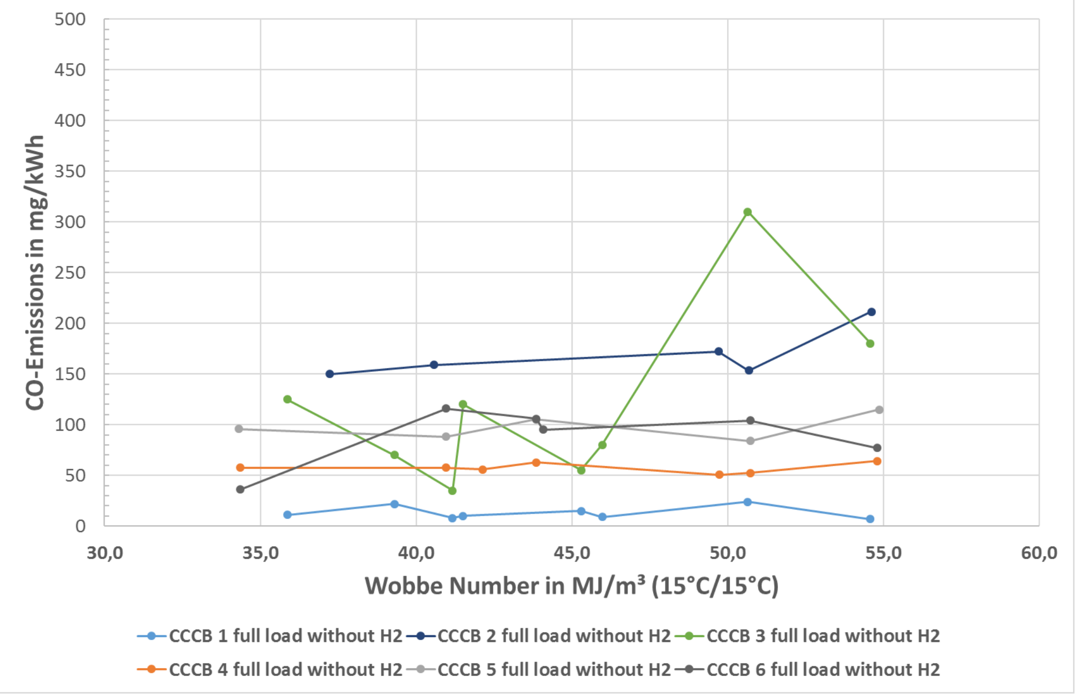


Fig. 41 a

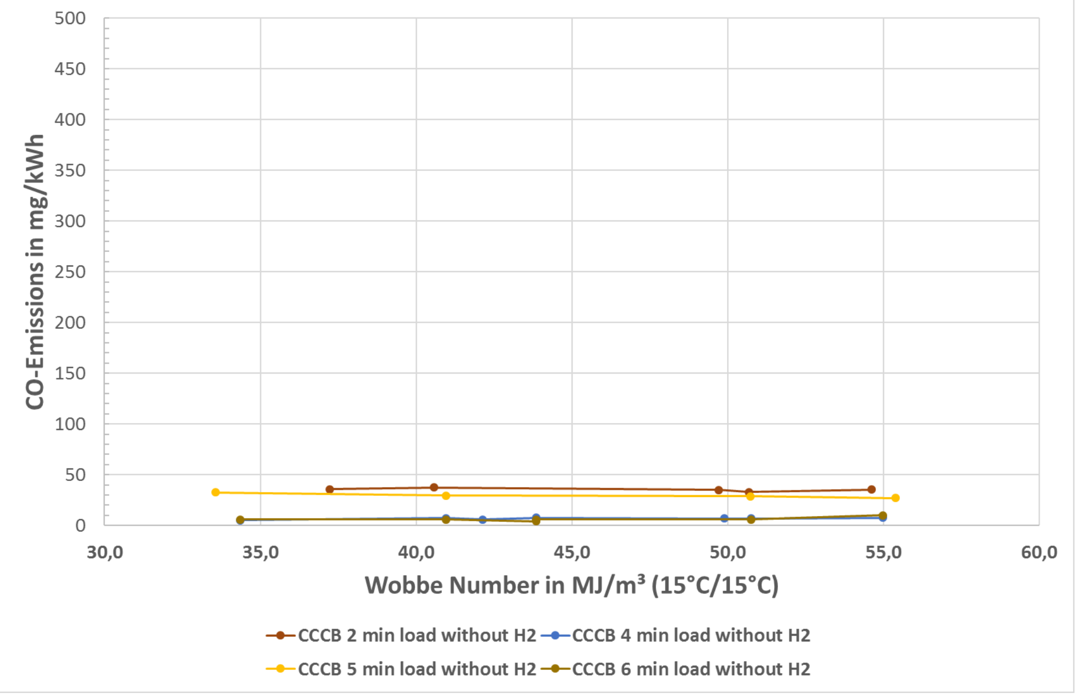


Fig. 41 b

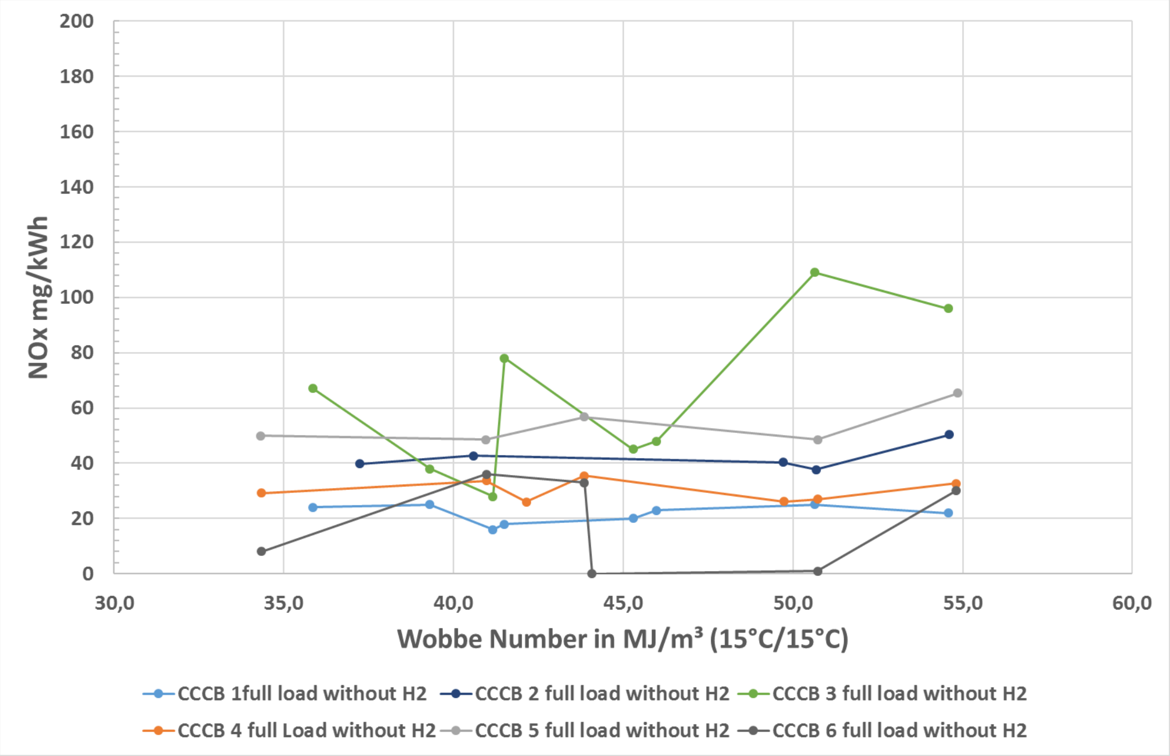


Fig. 41 c

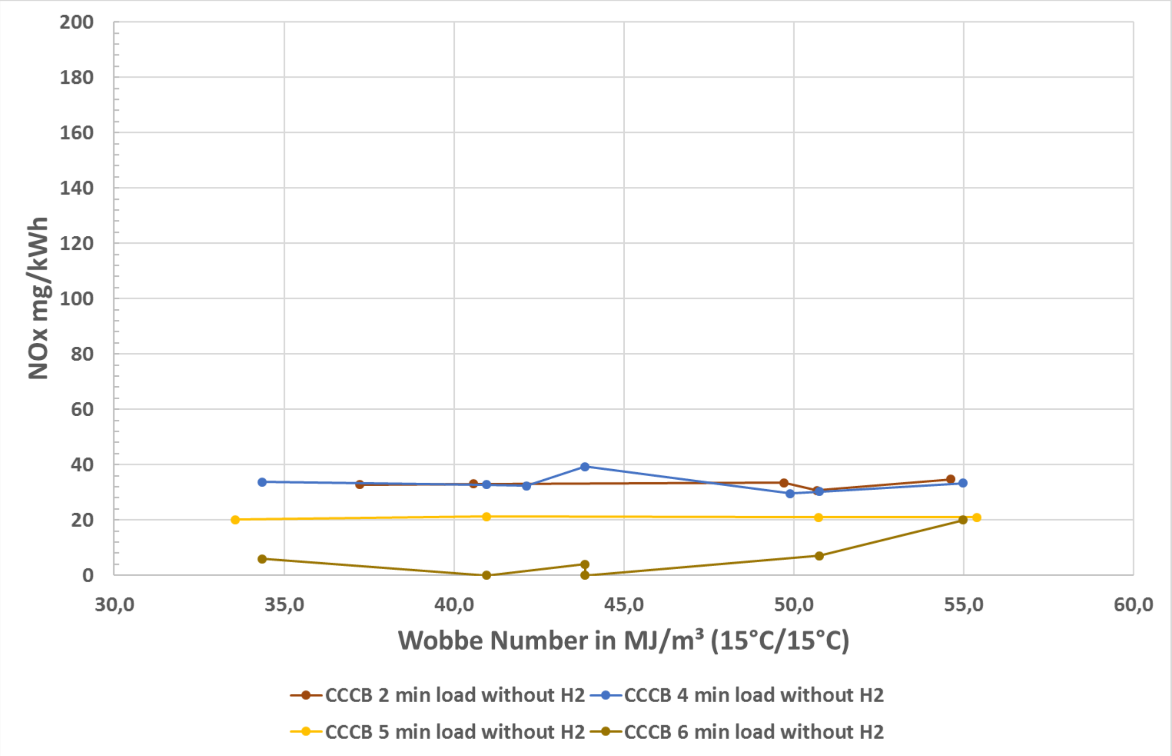
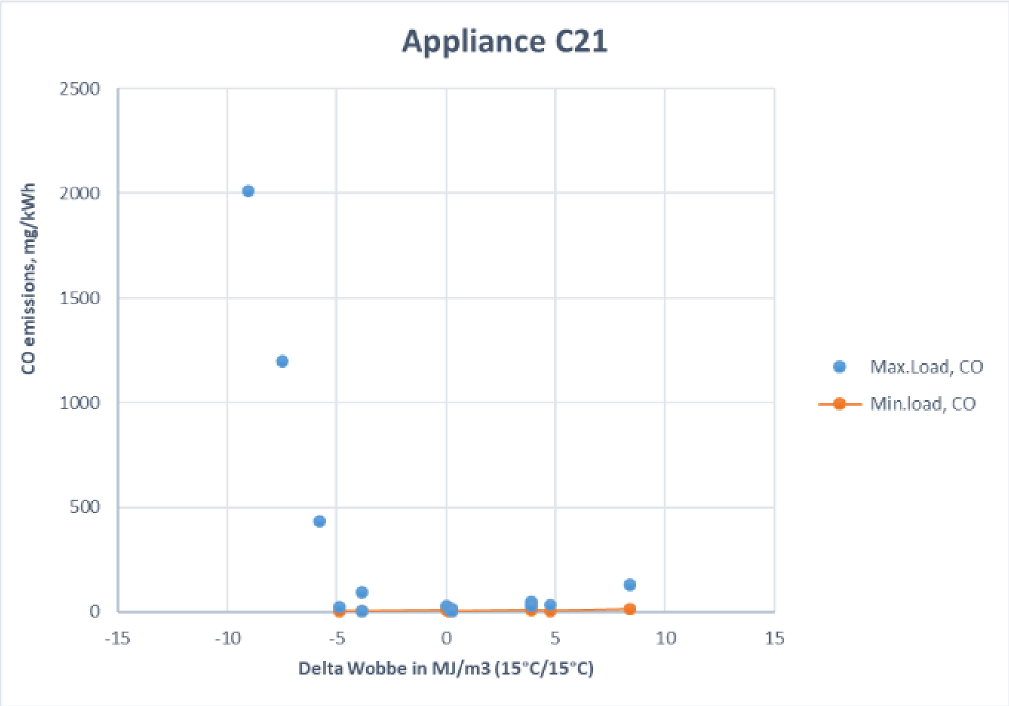


Figure 41 a-d: Emissions of CO and NOx over Wobbe Number for all six boilers. The level of emissions stays low and quiet constant over the whole range of Wobbe Number.

When comparing with boiler without combustion control systems, the difference is very obvious. The following figures are from the project GASQUAL are showing that the CO may increase severely when the Wobbe increases or decreases.



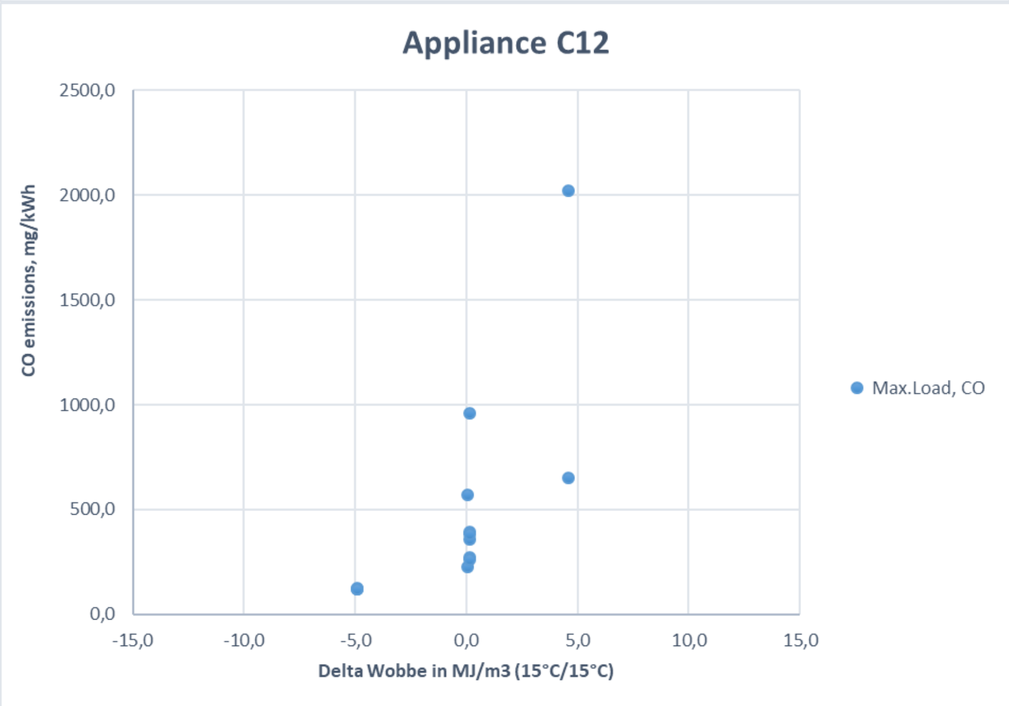


Figure 42: Emissions of CO over Wobbe Number for few boilers tested under GASQUAL project. *(Note that the scale of measurement for CO is very different compared to the previous figures)*

But GASQUAL also shows that some boilers are doing quite well, despite not being equipped of control system. The increase of CO is however very clear with a typical "U" shape.

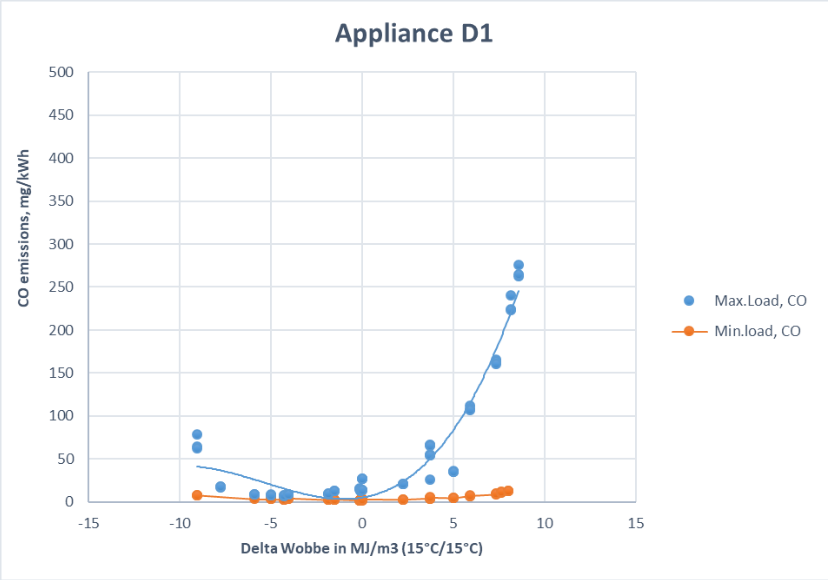
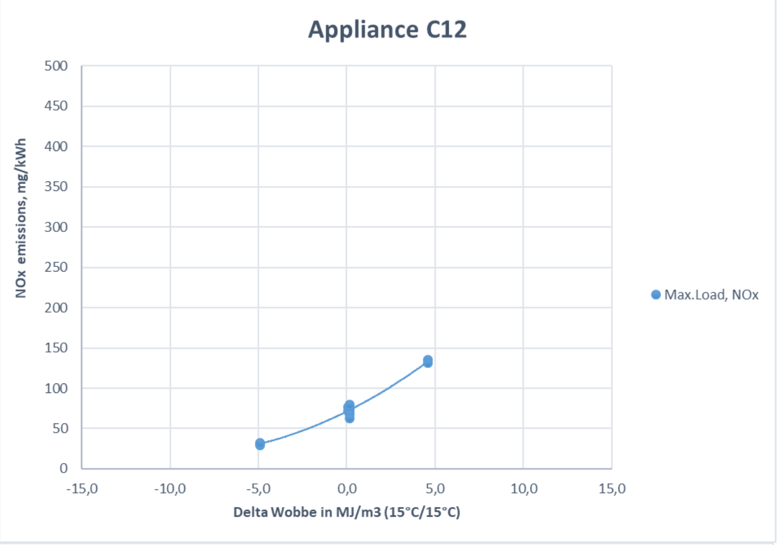


Figure 43: Emissions of CO over Wobbe Number for few boilers tested under GASQUAL project. ***(Same scale as for figure with combustion control)***

Finally, for the NOx emissions of appliances without controls, we see an increase of emissions with the Wobbe:



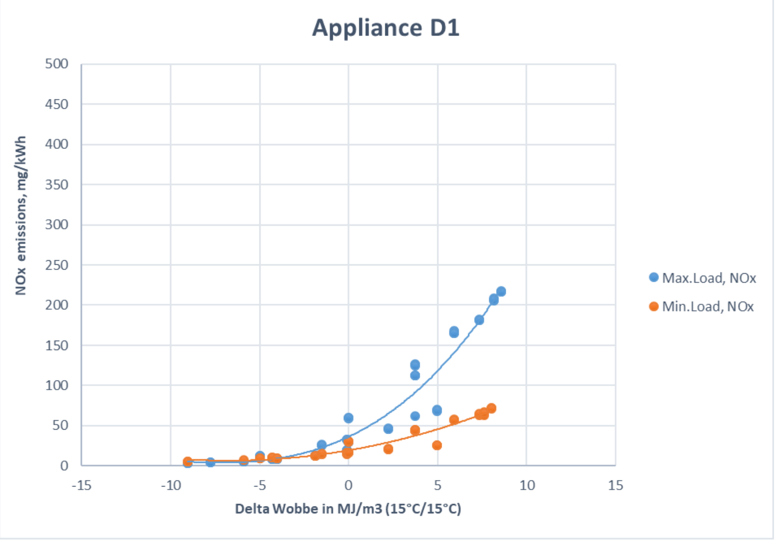


Figure 44 Emissions of NOx over Wobbe Number for few boilers tested under GASQUAL project. ***(Same scale as for figure with combustion control)***

Result 4, Gases with hydrogen:
The boilers operate safely and with low emission with gases containing up to 30% hydrogen. Emissions of CO and NOx are even reduced. However, the combustion control system does not work as exactly as for gases without hydrogen admixture.

In
Figure 45 the measuring results for hydrogen containing gases are added to the emission curves of Figure 41 as squares in the same color of the appliance respectively. Obviously, all emissions in CO and NOx are reduced compared to the respective curves of gases without hydrogen admixture.

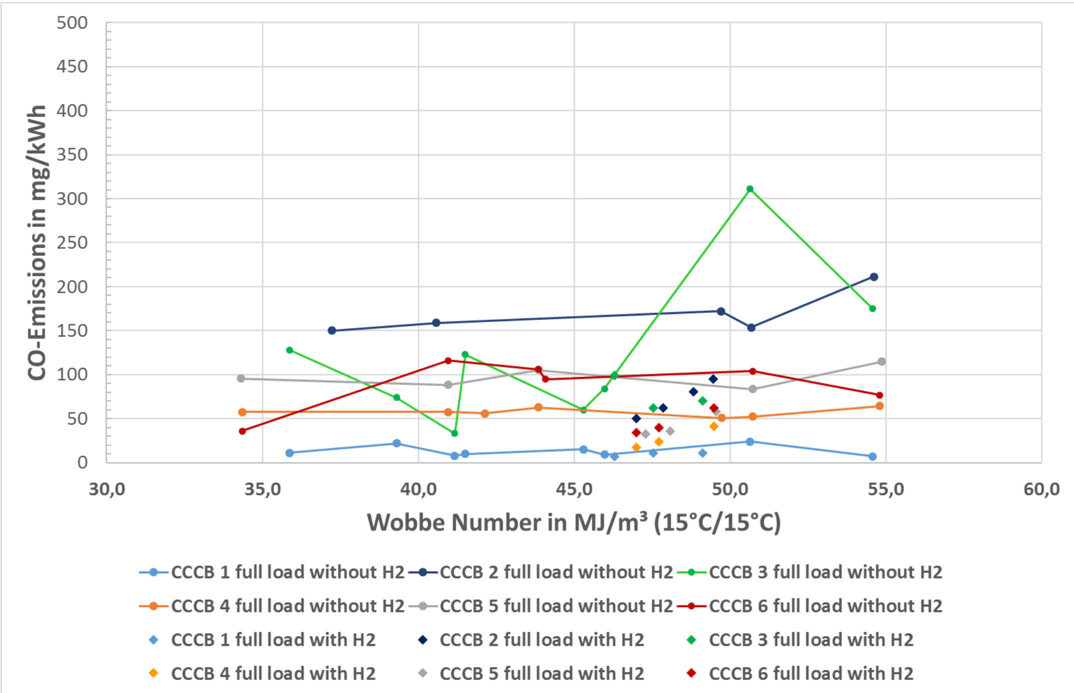


Fig. 45 a

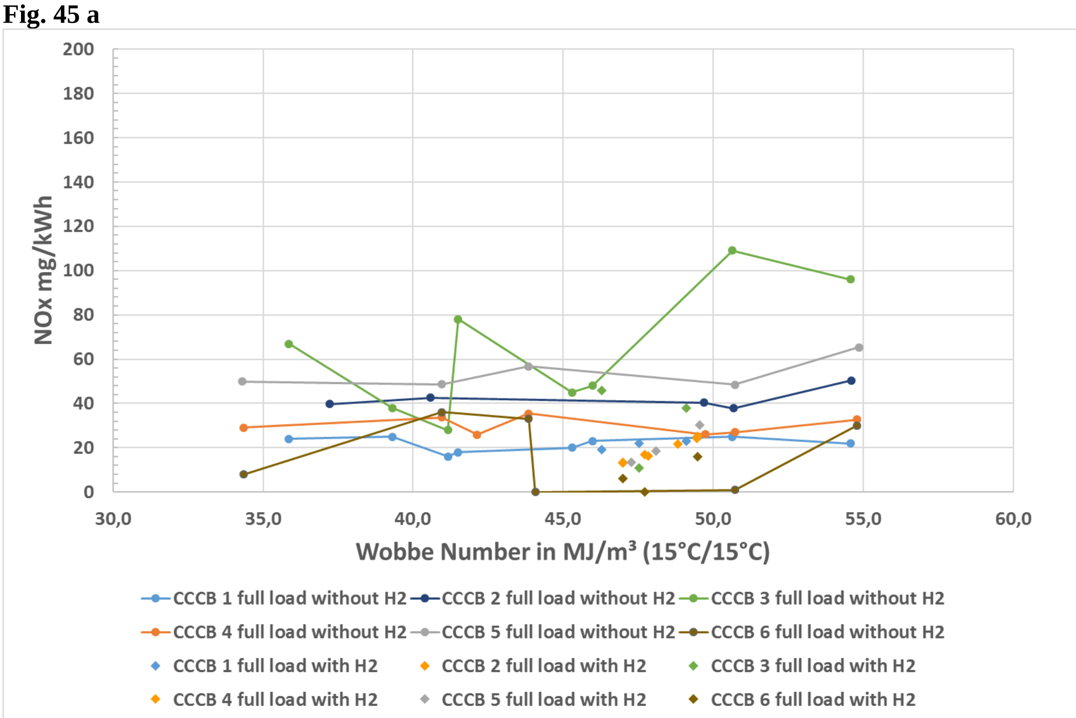


Figure 45 and b: Emissions of CO and NOx over Wobbe Number for all six boilers including results with hydrogen-containing gases.

This effect is easily to understand looking at Figure 46. The addition of hydrogen is mostly "not seen" by the control based on ionization signal and is therefore resulting in a higher air excess and so lower emissions.

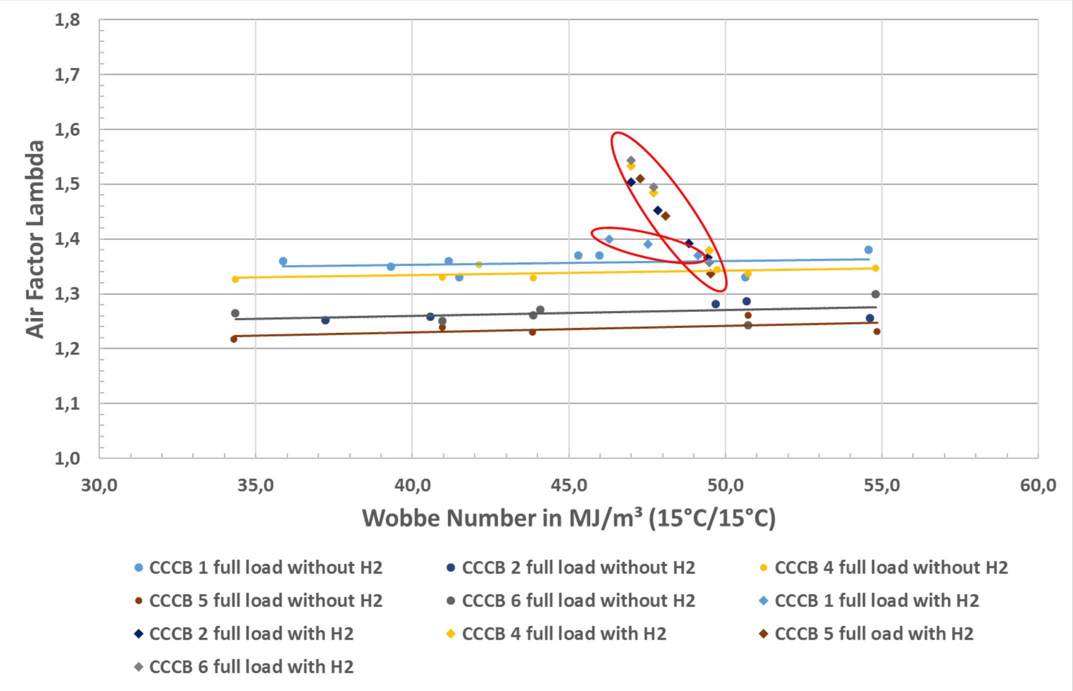
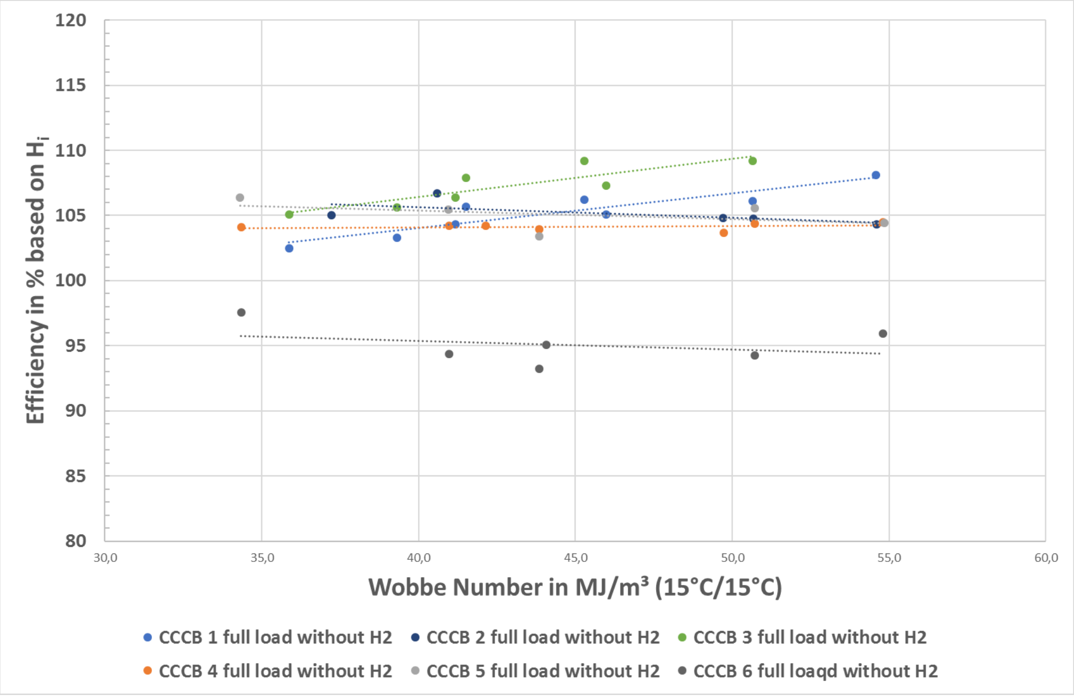


Figure 46: Stationary operation of the six different CCCB with test gases over the whole range of Natural Gases without any adjustment. The graph plots the air factor over the Wobbe number of the different gases. Results for hydrogen-containing gases are marked in the same color as squares

Result 5, Efficiency:

The efficiency (maximum load) stays quite constant within the measurement accuracy of < ∓ca. 2% for four of the boiler.



In

Figure 47 the measured efficiency based on the lower calorific value is plotted for all six boilers over the Wobbe range for all gases without hydrogen. Within the measurement accuracy the efficiency stays constant for all boilers over the Wobbe range, but may differ in value for the different boilers. The same result is observed for minimum load and for most boilers and measurements with gases with hydrogen.

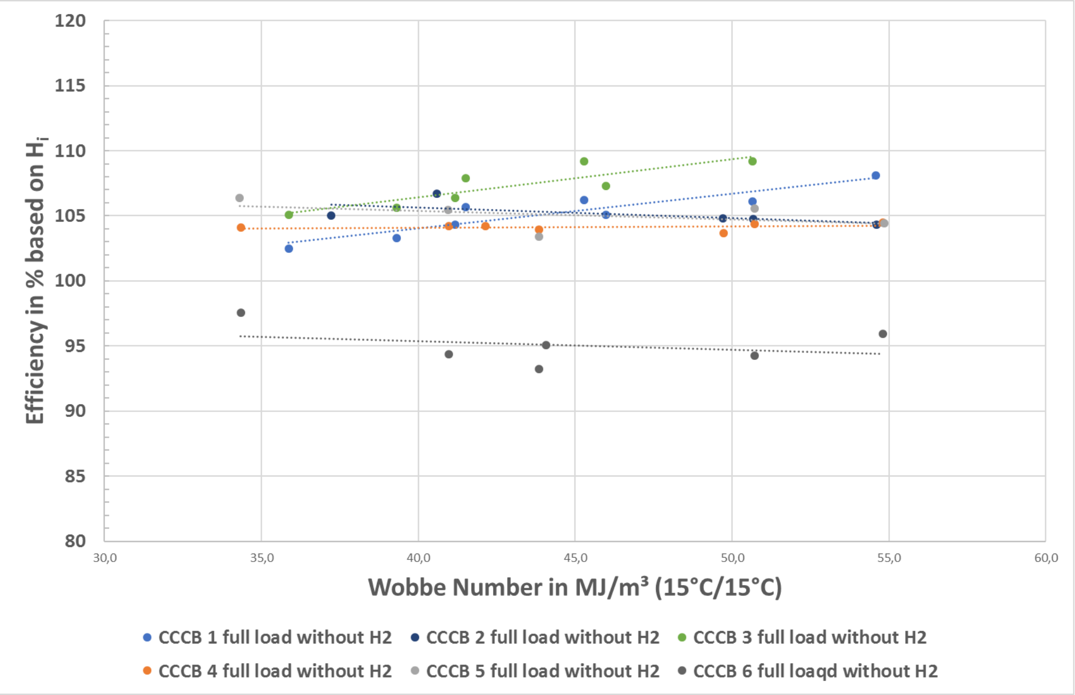


Figure 47: Measured efficiency for maximum load on all six combustion-controlled condensing boilers. Within the measurement accuracy, the efficiency stays constant for each respective boiler over the whole range of Wobbe number. ***The increase in efficiency for some of the boilers is explained by the lack of stability during the measurements (as the main purpose of the test was not the efficiency measurement, some labs did not wait thermal stability to make the measurement of efficiency)***

Result 6, Safety and operation under rapid change of gas quality:
All boilers are able to cope with instantaneous jumps of gas quality from minimum to maximum and vice versa under safe conditions and without any interruption of operation. The time to return to nominal operation (stabilization time) is less than 2 to 3 minutes.

The test procedure of the dynamic tests is shown in Figure 48. Gas quality was changed instantaneously from maximum to minimum and vice versa, so much stronger than would ever happen in reality.

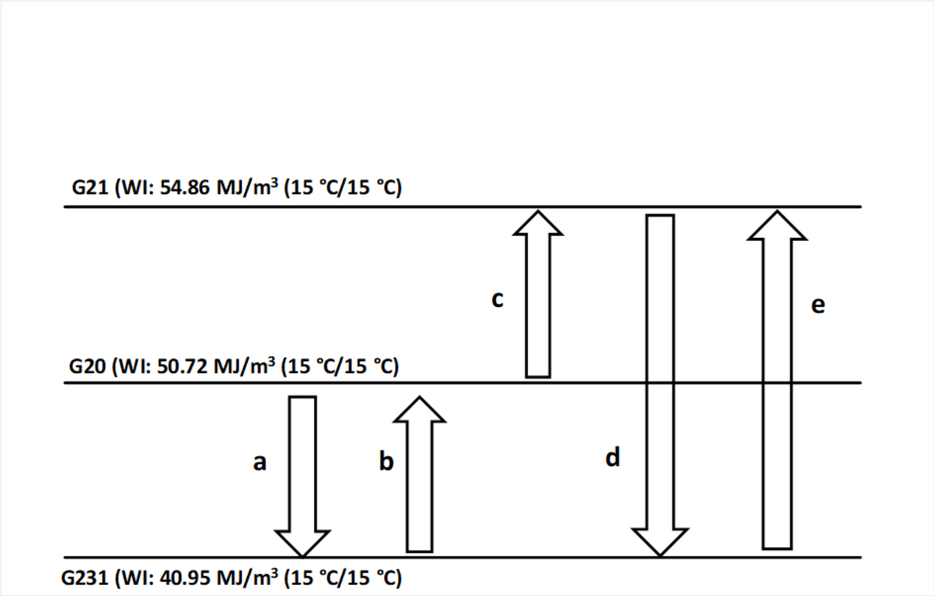


Figure 48: Test procedure for the dynamic tests of gas quality switch. With switches d and e maximum changes are done instantaneously, so much stronger than ever arrives in the praxis.

Figure 49 gives one example of CO-emissions during the gas changes of the dynamic test procedure on the CCCB 2. After the gas switch co-emissions increase for a short time up to less than 300 ppm (measured value, not corrected from air excess). Less than 50 seconds are needed to control and stabilize the combustion to the former level of about 80 ppm CO.

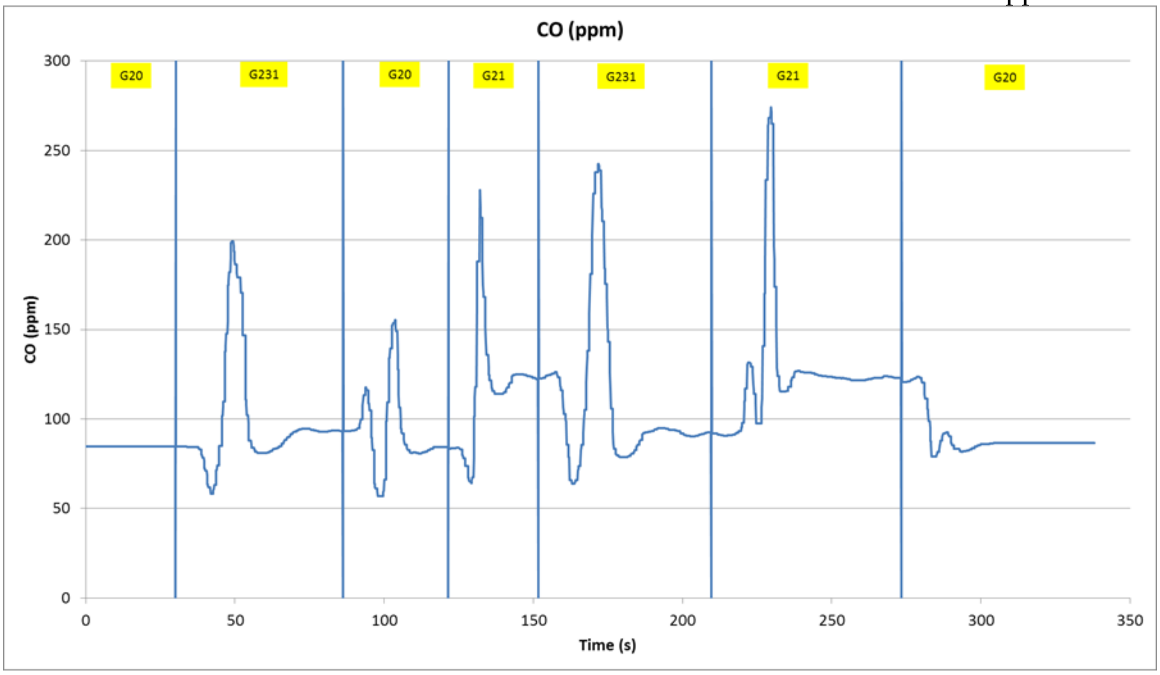


Figure 49: Example of results of CO-emissions during switch of gases for the CCCB 2. Stabilization time after gas switch is less than 50 seconds.

In some other cases, we have higher peaks of CO during the rapid changes of gases, however those are observed in few seconds only and cannot be considered as a problem unless the boiler is in a situation of extremely frequent gas quality changes. The results of all boilers are summarized in Table 6.

		CCCB 1	CCCB 2	CCCB 3	CCCB 4	CCCB 5	CCCB 6
CO peaks with rapid gas change? *(1)*	**(y/n)**	Y	N	N	N	N	N
Stabilization time a *(2)*	**min**	2	< 1	1	1.5	1.6	2
Stabilisation time b	**min**		< 1			1.6	1.5
Stabilisation time c	**min**	1.7	< 1	1.5		2	1.5
Stabilisation time d	**min**	2	< 1	1.5	3	1	2.5
Stabilisation time e	**min**	2	< 1	1	1.5	1	2.5

Table 6: Summary of the results of dynamic tests with changing gas qualities.

(1) We consider there is a peak if CO is measured >2000 ppm for more than 10 s.
(2) See Figure 48 under Result 6.

Result 7, Stable heat input and heat production:
Boilers with ionization controls are, for most of them, able to maintain the heat input of the appliances.

Note that this does not apply to mixtures of gas with Hydrogen (addition of H2 results in the decrease of the heat input). This feature is also interesting, as variation of gas quality would not affect the power available for boilers equipped with such controls. It is maybe not very important for heating as boilers are generally oversized, but it can be an interesting feature for hot water production and other applications in case the technology is used in the future on other appliances (cookers, etc..). As the efficiency is also constant, the heat output is also constant. As a result, the gas quality change doesn't impact the performances of the appliance for the end user.

Result 8, Abnormal operation situations:
Test has shown that control based on ionization can compensate variations of voltage, gas pressure and blockage (air inlet and flue gas).

The combustion controls are bringing an additional safety to the user. Testing of abnormal operation situation was tested on one boiler with combustion control based on ionization (CCCB 5), full results are given in the individual test report. Air inlet blockage and flue gas outlet blockage could be done up to more than 75% without any appliance stopping, increase of CO_2 content in the flue gases or significant emission increase. As all ionization controlled boilers behave similarly, we expected those positive results would also apply for the other boilers, but this was not tested.

9.4 Conclusions

The work carried out was aiming at evaluating the combustion controls presently used on condensing boilers on the European market.

Following a literature work, five laboratories have been executing extensive testing of 6 boilers equipped with different combustion controls (one based on CO the 5 other on flame ionization).

The testing of boilers equipped with combustion controls have proved that such appliances can cope with very large variations of natural gas (from lowest L to highest H!). The combustion controls are maintaining the air factor almost constant and this is resulting in a high stability of emissions and efficiency over the wide range of Wobbe.
The O2 variations are limited to maximum 0.5 % (abs.) over the whole gas range tested.

The boilers are operating safely all over the wide range and this without impacting efficiency, performances or emissions.

Beside this, boilers with combustion controls are potentially cheaper and easier to install and maintain.

The safety of the user is improved not only under normal working condition (low CO over the whole range of Wobbe), but also under extreme situations (blockage of the flue, etc.) (Test on one boiler only).

The positive results obtained in the laboratory have been compared to test data available on boilers without combustion control: The results are showing the significant advantages of combustion controls.

Detailed information on the cost of the combustion controls is mostly a confidential information that manufacturers do not want to share, but according some the discussions with some of them, it seems that the additional cost is low in % of the boiler total cost especially in view of mass productions.

Many manufacturers have adopted the technology and more and more appliances sold are equipped with controls. It would be clearly a positive move if all new boilers on the market would be equipped with combustion controls. This may need to be encouraged by specific actions.

A development of market for boiler with combustion controls will improve the safety of the end user, make the installation and maintenance of boilers easier and cheaper and it will ultimately broaden considerably the range of Wobbe of that the gas appliance can burn and contribute positively in the harmonization of gas quality.

This could be a formidable positive example for other technology manufacturers, demonstrating that solution exists to gas quality variations.

10 References List

[1] "GasQual Final Report," 2011.

[2] *EN 16726: 2015 E "Gas infrastructure - Quality of gas - Group H,* Brussels, 2015.

[3] P. Nitschke-Kowsky, A. Martino, W. Weßing and M. Vogt, "Gas quality and gas quality fluctuations in E.ON distribution networks - The impact on gas usage," *ZI Ziegelindustrie International Brick and Tile Industry International,* pp. 22 - 33, 5 2016.

[4] DVGW, Ed., *Technische Regel Arbeitsblatt DVGW G 260 (A) März 2013 "Gasbeschaffenheit",* Bonn, 2013.

[5] H. Krause, A. Giese, H. Dörr and H.-J. Brückner, "Abschlussbericht Hauptstudie zur Gasbeschaffenheit Phase I," Bonn, 2016.

[6] G. Berthold, "Gas Burner Technology & Gas Burner Design for Application".

[7] V. Holsteijn, "Eco-design of Boilers and Combi-boilers," https://www.vhk.nl/research/reports.htm, 2006 - 2007.

[8] D. E. Agency, "Technology Data for Energy Plants Individual Heating Plants and Energy Transport," October 2013.

[9] R. Cordier, "New appliances and systems for Wobbe Index measuring and regulation in industry," in *IGRC,* Paris, 2008.

[10] M. Hoppe and R. Sonnemann, "Combustion Control Systems for Varying Gas Qualities," in *IGRC 1998,* San Diego, California, USA, 1998.

[11] M. Dzubiella, "Selbstkalibrierende Verbrennungsregelung - die bewährte Antwort auf Herausforderungen durch zukünfite Gasqualitäten," *gwf-Gas|Erdgas,* pp. 160 - 165, März 2011.

[12] ASUE, *Sytem zur Verbrennungsregelung und - überwachung mit CO-Sensor,* Kaiserslautern, 2004.

[13] Fa. Lamtec, Weber, Harald, *CO-Regelung, die bessere Alternative zur =2-Regelung bei Gasfeuerung,* Walldorf, 2011.

[14] P. Nitschke-Kowsky and H. Radtke, "Testing commercially available gas-fired condensing appliances equipped with a combustion control system," *gwf international,* pp. 3-11, 2011.

[15] H. Dörr, K. Kröger, F. Graf, W. Köppel, F. Burmeister, J. Senner, P. Nitschke-Kowsky and W. Weßing, "Untersuchungen zur Einspeisung von Wasserstoff in ein Erdgasnetz," *energie|wasser-praxis,* pp. 50-59, 11 2016.

[16] P. Nitschke-Kowsky and W. Weßing, "Impact of hydrogen admixture on installed gas appliances," *World Gas Conference (WGC), Kuala Lumpur,* 2012.

[17] M. Brune, P. Nitschke-Kowsky, A. Brandes, T. Lotze and U. Masuch, "Regelkonforme Anpassung von Brennwertkessel vor der Schaltung erfolgreich umgesetzt," *gwf Gas+ Energie,* pp. 104 - 110, 11 2017.

[18] "bdh-koeln.de," [Online]. Available: http://www.bdh-koeln.de/fileadmin/user_upload/Daten_Fakten/BDH_Marktentwicklung_2005-2015.pdf. [Accessed 12 12 2016].

11 Appendix

11.1 List of manufactures delivering combustion controlled condensing boilers

Country		BE	DE	DK	FR	GB	NL	AT	BG	CH	Cy	CZ	EE	ES	FI	GR	HR	HU	IE	IS	IT	LT	LU	LV	MT	NO	PL	PT	RO	RS	SE	SI	SK	TR
EN437 (2003 und A1 2009) : I2N Categorie permitted ?		y	y		y									y		y											y				y		
pr EN437 (2017): I2N Categorie permitted ?		y	y	y	y		y							y		y											y				y		
Company	**Brand**																																	
ACV																																		
Ariston																					1													
Atlantic																																		
Attag							1																											
Baltur																																		
BDR Thermea																																		
Bosch	Buderus		1					1		1													1											
	Junkers		1					1		1													1											
	e.l.m. leblanc (FR)																																	
	Dakon(CZ)																																	
	IVT (SE, FI, DK, NO)																																	
	Nefit (NL)																																	
	Vulcano(PT)																																	
	Worcester (GB, IE)																																	
	Ferroknepper (LU)																																	
	FHP (USA)																																	
Brötje		1	1	1	1							1						1			1						1							
CIB Unigas																																		
COPA																																		
Cosmogas																																		
E.C.A.																																		
ELCO																																		
Enertech																																		
Ferroli																																		
Fondital																																		
Hansa		1	1																															
Hoval																																		
Immergas																																		
Interdomo		1	1																															
Remeha																																		
	Baxi (GB, ES)																																	
	De Dietrich (FR)																																	
	Brötje (DE) see above																																	
	Chappee (FR)				1																													
	baymak (Turkey)																																	
	utica boilers (USA)																																	
	Andrewswaterheaters (GB)																																	
	Dunkirk Helix (USA)																																	
	Oertli																																	
	Potterton																																	
Riello (UTC)																																		
Rotex (Daikin)			1	1																														
Vaillant			1		1																													
	Saunier Duval (FR)																																	
	awb (NL)																																	
	Bulex (BE)																																	
	DemirDöküm (Turkey)																																	
	Glow worm (GB)																																	
	Hermann Saunier Duval (IT)																																	
	protherm (Central and East Europe)																																	
Viessmann		1	1	1	1	1	1	1	1	1		1	1	1			1	1			1	1	1	1			1		1		1	1	1	1
Weishaupt		1	1	1	1		1	1		1																								
Wolf		1	1	1	1	1	1	1	1	1		1	1	1		1		1	1		1		1	1			1		1			1	1	
Number of Manufacturers per country		6	10	5	6	2	4	5	2	5	0	3	2	2	0	1	1	3	1	0	4	1	4	2	0	0	3	0	2	0	1	2	2	1

11.2 List of additional Literature

							Sensor Technology				Control	Burner types				Gases						
Nr (chronology)	Reference Nr (in our report)	Year	Language	Author	Titel	Source	Ionisation control	CO-Sensor	O2-Sensor	Sensors general	control	Atmosph. Burner	Fully premixed surface burner	Jet burners	others / not specified	Natural Gas	LNG	Bio Methane	Hydrogen	others	Comment	Short resumé
1		1998	EN	Technical Information -11.2	FIS Meatl Oxide Lambda Sensor: LS-01 for Combustion Controls	personal contact		x	x				x			x						
2		1998	EN	R.Sonnemann, M. Hoppe	Combustion Control Systems for Varying Gas Qualities	IGRC	x				x		x			x						
3		1999	GE	F.Durst, J. Glass, K. Pickenäcker, D. Trimis, K. Wawrzinek	Luftzahlkontrollierte Verbrennung durch Wobbeindexbestimmung	Gaswärme International 48 (1999 07/08)				x					x	x						
4		2000	Ge	Stiebel Eltron , HydroTherm	Die Weltneuheit der Verbrennungstechnik	Company Paper	x						x			x					http://www.ikz.de/1996-2005/2004/22/0422030.php	
5		2000	GE	Hans Berg, Manfred Hoppe, Heiner Hüppelshäuser R. Merker	Das Scot-Verfahren auf dem Weg in die Praxis	gwf-Gas|Erdgas 09/2000	x						x									
6		2001	Ge	Heiner Hüppelshäuser, Manfred Hoppe	Intellignete Brenner mit SCOT gehen in Serie	gas 02/2001	x						x									
7		2001	EN	Heiner Hüppelshäuser, Hans Berg, Manfred Hoppe	Application Aspects of Combustion Control using Ionisation Signal	IGRC	x				x	x				x						
8		2002	EN	Nicolas Docquier, Sebastien Candel	Combustion control ans sensors: a review	Progress in Energy and Combustion Science 28 (2002)107-150	x	x	x	x					x	x	x			x		
9		2003	GE	VSG Verband der Schweizerischen Gasindustrie	Basis-Information	personal contact	x						x			x						
10		2004	GE	Innovation Price ASUE	System zur Verbrennungsregelung und -überwachung mit CO-Sensor	ASUE		x					x			x						
11		2008	Ge	Guido Dubielzig	Durchführung von Praxisuntersuchungen an Gasgeräten mit selbst kalibrierender Verbrennungsregelung.	GWI, unpublished	x	(x)														
12		2011	EN	Petra Nitschke-Kowsky, Harald Radtke	Testing commercially available gas-fired condensing appliances equipped with a combustion control system	GWF international 01/2011	x	x					x			x						
13		2011	Ge	Manfred Dzubiella	Selbstkalibriende Verbrennungsregelung - die bewährte Antwort auf Herausforderungen durch künftige Gasqualitäten	gwf-Gas|Erdgas	x						x			x	x	x				
14		2011	GE	Harald Weber	CO-Regelung	Lamtech		x	x					x		x						
15		2012	GE	Manfred Dzubiella	Mit innovativer Verbrennungsregelung wechselnde Gasqualitäten beherrschen	Fach.Journal 2012	x						x			x	x	x				
16		2012	EN	Petra Nitschke-Kowsky, Werner Wessing	Impact of hydrogen admixture on installed gas appliances		x					x	x			x	x		x			
17		2014	GE	Fran Hammer	Sensorische Verbrennungsoptimierung von Gasfeuerungsanlagen	gwf-Gas|Erdgas 04/2014		x	x	x				x		x	x	x	x			
18		1998	GE	Martin Herrs, Roland Merker, Rolf Naumann, Hubert Nolte	Verbrennungsregelung mittels Flammensignal	gwf Gas Erdgas 1998 01	x				x		x			x						
19		2014	DK	Mikael Näslund	Combustion control in domestic gas appliances Hydrogen containing fuel gases	DGC Project Report February 2014				x			x				x		x			
20		2011	EN	B.K. Slim*, H.D. Darmeveil, S. Gersen, H.B.	The combustion behaviour of forced-draught industrial burners when fired within the EASEE-gas range of Wobbe Index	Article in Journal of Natural Gas Science and Engineering			x					x		x					Sensor not the main scope of the article, but O2 mentionned	
21			EN	Sander Gersen (DNV GL/Gasunie) Pieter Visser (DNV GL/Gasunie) Frits Bakker (ECN) Ger de Graaf (TU Delft) Reinoud Wolffenbuttel (TU Delft) Ruud Westerwaal (TU Delft) Bernard Dam (TU Delft)	*A control system for all gas compositions - Project: Sensors for new gases*																From Ref 19	We dont have the document -- BUT SEE Nr 80
22		2013	EN	Viessmann	Boiler and combustion management system for the Vitodens 200-W, B2HA and Vitodens 222-F, B2TA **SEE also the film HERE https://www.youtube.com/watch?v=5B0V07iE5uw**																From Ref 19	
23		2004	GE	Bornscheuer, W., Richter, K.,	CO-geführte Verbrennungsregelung,	IKZ-Haustechnik, 22, 2004															From Ref 19	
24		2006	GE	Krause, H., Giesel, S., Kautz, M.	Entwicklung einer Flammenüberwa-chung für Brenner zum Betrieb mit wassers	DVGW Workshop F&E in der Brennstoffzellentechnologie, 2006															From Ref 19	We dont have the document
25		2006	EN	Kautz, M., Walter, G., Giesel, S., Krause, H.	Development of a flame monitoring for surface and pore burners using hydrogen rich gas	IV In-ternational Scientific Conference Refractories, Furnaces and Thermal Insulations, Strbske Pleso, April 24 – 26 2006															From Ref 19	We dont have the document
26		2012			SOL01 WGC2012-703.00-rev5																Check relevance	
27					SOL02 Industrial use New appliances and systems for Wobbe Index IGRC2008 fullpaper_RCo																Check relevance	
28		2015			SOL03 WGC 2015Gas quality a growing concern for the end user M. Eskes TS WOC55 Final Contributions																Check relevance	
29		2015			SOL03b WGC 2015Gas quality a growing concern for the end user M. Eskes-TS. WOC 5 5																Check relevance	
30		2009			SOL04 A service offer in combustion control of GDF SUEZ Glassman 2009																For industrial applications	

Nr (chronology)	Reference Nr (in our report)	Year	Language	Author	Titel	Source	Ionisation control	CO-Sensor	O2-Sensor	Sensors general	control	Atmosph. Burner	Fully premixed surface burner	Jet burners	others / not specified	Natural Gas	LNG	Bio Methane	Hydrogen	others	Comment	Short resumé
31		2015			SOL05 EDGAR 2015 Gersen_control_system_gas_composition_2015																**SEE ALSO 81**	
32					SOL06 IGRC2014 FO1-4_Doerr																Check relevance	
33					SOL07 Ajustement large burners in DK WP1-13_Rasmussen																Check relevance	
34					SOL08 Micro Wobbe meter Mekenkamp_MA_EEMCS																Check relevance	
35					SOL09 NETL lng-interchangeability-rpt																Check relevance	
36					SOL10 Fuel-flexible Combustion System-2012 AFRC Meeting																Check relevance	
37					See Fiche12 marcogaz																For industrial applications	
38					See Fiche13 marcogaz																For industrial applications	
39		2014		TTp	PRESS RELEASE New low-cost gas sensor technology from TTP uses speed of sound TTP's SonicSense delivers accurate gas sensing at a fraction of he cost of existing methods																	development phase?
40					Screeninig of sensors on the market DGC 2013 Gaskvalitetssensorer R1309_gaskvalitetssensorer (SOS20)					x						x					For industrial applications mostly	Scope = to be used for gas quality control for TSO/DSO -> techologies not adapted to small scale appliances
41					SOS21 SGC258 report on ionisation sensing SGC		x									x					Check relevance	
42					SOS22 heating value sensors icef2011-60197_paper_final															x		composition and heating value sensor system development for real-time characterization of producer of gas (eg gasification).
43		2012			SOS23 real time method for gas composition ASME_ICES_2012_final					x						x				x		Commercially available sensors and the Gas Quality Sensordeveloped by the Gas Technology Institute in collaboration with North Carolina State University are utilized to detect and measure fuels gas components. Used todetermine the compositions and heating values of blends of natural gas with landfill gas, syngas and refinery gas.
44					SOS24 real time method for gas composition IGRC 532					x						x				x		A Gas quality sensor for real time monitoring of composition and heating values of natural gas and natural gas blends.The sensor technology utilizes near infrared (NIR) absorption spectroscopy to monitor composition and heating value of bio gas, natural gas, and other hydrocarbon based gaseous fuels
45				DGC	Existing sensors (THE SENSOR STATE OF THE ART Survey of the existing sensor technologies . Features, standards, performances and costs)																	
46				Julie Delahaye /CRIGEN	Introduction GC detectors Spectroscopic device/detector Correlative device Other. How do they work? What can we use them for?	Marcogaz sensor Workshop															Marcogaz sensor Workshop	presentation not available
47				Stuart Macdonald / Shell	Gas quality challenges in transport and the role of sensors	Marcogaz sensor Workshop															Marcogaz sensor Workshop	presentation not available
48				Dr Jane Hodgkinson /	Capabilities and challenges of optical measurement of natural gas quality	Marcogaz sensor Workshop				x											General	paper on optical sensors: doesnt seem to be adapted for cheap applications like boilers
49				PRETRE Philippe. /Mems AG.	Gas Quality Sensing (gasQS™) at MEMS AG (SOS 14)	Marcogaz sensor Workshop				x					Transport, fuel cells, Wobbe meter	x					Marcogaz sensor Workshop- FUTURE & PROSPECT	Correlation sensors: Not yet a cheap technology for boilers, but it could be a future tecghnology (it is already used for fuel cells & engines)
50				Dr Ulrike Lehmann /MiCROSENS SA	Microsystems for selective gas sensing (SOS 15)	Marcogaz sensor Workshop				x					Commercial & industrial use?						Marcogaz sensor Workshop	A presentation about the different intelligent silicon sensors made by MICROSENS S.A. in Switzerland. Same as above - not for small applications due to costs
51				FARINE Gaël / QuantitativeEnergy LPM	Wobbe Index Sensor (SOS16)	Marcogaz sensor Workshop				x					Commercial & industrial use?	x					Marcogaz sensor Workshop- FUTURE & PROSPECT	Measure Wobbe Index before combustion.Compact, can be integrated directly into gas appliances and vehicles. Mostly for larger appliances due to costs?
52				Terry Williams / Orbital Global Solutions	GasPT instrument. (SOS 17)	Marcogaz sensor Workshop									Gas infrastructure	x					Marcogaz sensor Workshop	An Inferential/Correlative Device.Measure speed of sound & thermal conductivity. One type has CO2 sensor as well.Calculate gas properties such as RD, CV, Wobbe, Compressibility Factor . For larger appliances due to costs
53				Henrik Rödjegård /Senseair	Possibilities using non dispersive IR-technology for in vehicle measurement of methane gas quality. (SOS 18)	Marcogaz sensor Workshop				x					transport	x					Marcogaz sensor Workshop	IR-Sensors for determination of combustion properties of methane gas fules in vehicles. Determine fuel property for spark ingnitred engines. Advanced Signal processing Implemented in the Ignition System. Degigned for transporation sector
54				Mattias Svensson on behalf of Jakob Ängeby / SEM	Ionization current sensing (SOS 12)	Marcogaz sensor Workshop	x								Transport						Marcogaz sensor Workshop	ion sense applied to industrial lean burn engines for transportation

							Sensor Technology				Control	Burner types				Gases						
Nr (chronology)	Reference Nr (in our report)	Year	Language	Author	Titel	Source	Ionisation control	CO-Sensor	O2-Sensor	Sensors general	control	Atmosph. Burner	Fully premixed surface burner	Jet burners	others / not specified	Natural Gas	LNG	Bio Methane	Hydrogen	others	Comment	Short resumé
55				Dr Joachim Kastner / Elster Gmbh	New technologies for extended gas analysis	Marcogaz sensor Workshop															Marcogaz sensor Workshop	IR-Sensors for determination of combustion properties of methane gas fules in vehicles. Determine fuel property for spark ingnitred engines. Advanced Signal processing Implemented in the Ignition System. Degigned for transporation sector
56				VHK	Eco-design of CH Boilers Task 4 Report (FINAL) Technical Analysis (incl. System Model)	Marcogaz sensor Workshop	x	x	x				x			x					Marcogaz sensor Workshop	The objective with the project is to investigate which combustion process information that can be retrieved using ion sense applied to industrial lean burn engines using pre-chambers for the ignition in which case the spark plug is encapsulated in the pre-chamber.
57				GERG PC chairs	SHORT OVERVIEW ACTIVITIES OF the GAS INDUSTRY in relation to gas sensors	Marcogaz sensor Workshop															Marcogaz sensor Workshop- Metering appliaction NOT RELEVANT	
58				Dr.Bergemann- H.Petermann /AFECOR	Controls for Combustion Optimization	Marcogaz sensor Workshop	x	x	x				x	x		x						Overview and comparison of the solutions for boilers by AFECOR. Not much details, but clear view and positive message for the future developments of sensors.
59				Martin Kiefer / Bosch	Combustion Control based on Ionization Current Detection: Application in Condensing Heating Appliances	Marcogaz sensor Workshop	x						x			x					Marcogaz sensor Worksho	Combustion Control based on Ionization Current Detection. Slides frrom the Workshop. No details on performances and cost. Merely a description of the technology
60				Holger Doerr /DVGW EBI	Multi gas air ratio control platform (MGARCP) of DVGW-EBI to manage gas quality effects on appliance site	Marcogaz sensor Workshop															Marcogaz sensor Workshop- check relevance	
61				Erik Polman/ Kiwa Technology	GERG Project. The potential of MEMS for gas distribution systems	Marcogaz sensor Workshop															Marcogaz sensor Workshop- check relevance	
62				Pascal Favre / COSVEGAZ SA	Project "Qualigas" funded by FOGA (Swiss gas industry Fund) and Wika related to the determination of Wobbe Index and gas quality by means of a cheap gas sensor based on correlative techniques.	Marcogaz sensor Workshop															Marcogaz sensor Workshop- check relevance	
63				Martin Seiffert / SVGW	FOGA activities on Gas Quality determination	Marcogaz sensor Workshop																
64				Joost Lötters / Bronkhorst High-Tech	Integrated Micro Wobbe Index meter	Marcogaz sensor Workshop				wobbe			future			x					Marcogaz sensor Workshop- check relevance	Development of a micro Wobbe meter. Not yet a solution, but can show the way to go?
65				Gas- und Wärme- Institute Essen e.V. – Jö	Managing alternating gas qualities with a self-calibrating multi gas control system	Marcogaz sensor Workshop	x							x	x	x					Marcogaz sensor Workshop- check relevance	Ionistion sytem for larger installtion cost = 5000 euros
66			en		Figure with and without lambda control on wood boiler.jpg																	
67					Combustion Control - ENOx																	
68		IGRC2008		Main author Rémy CORDIER Gaz de France France	New appliances and systems for Wobbe Index measuring and regulating in industry																	
69					United States Patent Pechoux																	
70					Procédé pour la régulation du rapport air/gaz d'un brûleur et brûleur mettant en oeuvre ce procédé																	
71					United States Patent Sundberg																	
72					United States Patent Cordier																	
73					United States Patent Watanabe																	
74		2014		Wilfried Linke 27. February 2014 Technical Affairs Director	Views and visions from the appliance industry (on sensors)	Marcogaz sensor Workshop																
75				Dr.-Ing. Frank Hammer, ESCUBE GmbH & Co KG, D-70569 Stuttgart Dipl. Ing. (FH) Harald Weber, LAMTEC Meß- und Regeltechnik für Feuerungen GmbH & Co KG, D-69190 Walldorf	Sensorgesteuerte CO-Regelung zur Optimierung des Verbrennungsprozesses für Feuerungsanlagen kleiner und mittlerer Leistung																	
76		2009		Mouris Hobre Instruments BV - A.J.	Optimization of fired heater control utilizing the residual oxygen measurement principle				x													IR technology for CHP (turnines & motors applications)
77		2011	GE	MEMS (CH)	Low Cost Gasqualitätsbestimmung für den Massenmarkt																	MEMS technology is a correlative technology to get the gas quality. If the cost goes down it can be a solution for the market of applinaces like boilers
78		2012	EN	Bosch	Combustion control based on flame ionisation	WGC 2012	x															
79				Various	Brochures and press realese of boilers with CCCB								x									
80				Serguei Zelepouga Gas Technology Institute Des Plaines, Illinois, USA	GAS QUALITY SENSOR TO IMPROVE BIOGAS-FUELED CHP/DG					x										all		

							Sensor Technology				Control	Burner types				Gases						
Nr (chronology)	Reference Nr (in our report)	Year	Language	Author	Titel	Source	Ionisation control	CO-Sensor	O2-Sensor	Sensors general	control	Atmosph. Burner	Fully premixed surface burner	Jet burners	others / not specified	Natural Gas	LNG	Bio Methane	Hydrogen	others	Comment	Short resumé
81		2014		W.G. Haije (ECN) F.P. Bakker (ECN) S. Gersen (DNV GL) R. Wolffenbuttel (TU Delft) G. de Graaf (TU Delft) B. Dam (TU Delft) R. Westerwaal (TU Delft)	New Gas Sensors (see details in Nr 31)								x			x	x	x	x		We dont have the extended report only the slides. It would be of interest to get the whole report if possible. It may be a development with ATAG (to be checked) **SEE MORE DETAILS IN Nr 31**	Test of various sensors for gas quality + DEVELOPMENT OF A BOILER AIMING AT BURNING WIDE GAS QUALITIES.Boiler shows good performance for the following range of tested gaseous fuels – CH4/H2 up to 60% H2 – CH4/C3H8 up to 100% C3H8 – CH4/CO2 up to 50% CO2
82		2010	EN	Antonio Serafim de Souza Sobrinho serafim_fisica@yahoo.com.br Rigoberto Soares do Nascimento gobertosoares@gmail.com Renato Silva Pinheiro pinheiro.silva@gmail.com Lutero Carmo de Lima lutero@uece.br Universidade Estadual do Ceará	Measurements of the flue gases oxygen concentration by Lambda sensor				X													
83			EN	?	Sensor appliactions																	
84		2003	EN	Ian Cox	The effect of Blast Furnace gas quality and combustion controls on Stove performances																Academic paper	

11.3 Measured and Calculated Variables

The data to be measured during the boiler tests and the variable to be calculated are listed in Table 7.

Gas Parameters		**Units**
composition of the gas		
Density (15°C)	ρ	kg/m3
relative density	d	-----
max. CO_2 content in the dry flue gas	CO_{2max} (dry)	%
VFN_SUR_VA		----
min. air required	Vmin air	m^3 Air/m^3Gas
Gross calorifc Value	Hs	MJ/m^3
Gross Wobbe Index	Ws	MJ/m^3
Net Calorific Value	Hi	MJ/m^3
Net Wobbe Index	Wi	MJ/m^3
Flue gas parameters		**Units**
Temp flue gas	t flue	°C
Oxigen content in flue gas	O_2	%
Carbon dioxid content in flue gas	CO_2	%
air factor (calculated)	λ	-
Carbon monoxid measured in flue gas	CO	%
Carbon monoxid referred to dry airfree flue gas	CON	%
Nitrogen monoxid measured	NO	ppm
Nitrogen dioxid measured	NO_2	ppm
Sum of Nitrogen Oxides calculated as NO_2 in dry airfree flue gas @0%O2	NO_x	ppm
Ionisation current	I	µA
Other parameters		
Temp water leaving	Tout	°C
Temp water return	Tin	°C
Temp flue gas	Tflue	°C
Temp Ambiant	Tamb.	°C
Gas pressure	pgas	mbar
Atmospheric pressure	patm.	mbar
Water flowrate referred to 0°C	Vwater	m^3/h
Gas flowrate referred to 15°C	Vgas	m^3/h
Heat output (in water circuit)	Q	kW
Heat input referred to 15°C	QinGas	kW
Efficiency	η	%

Table 7: List of variables to measure or calculate respectively

11.4 Test conditions and Procedure of measurement

The final test conditions and procedure of measurement will be elaborated and agreed in detail within phase II of the project. The current status of discussion is given in the following sections of the chapter.

11.4.1 Stability condition

All stationary tests will be carried out at the following stability conditions:
Tolerance during stable periods should be:

- Return temperature: +/- 0,5 °C
- Average ΔT (outlet – inlet water temperature): +/- 0,5 °C
- Load: +/- 2 % (only for the initial test)
- If the boiler starts cold (e.g. doesn't run at night between tests), the first test heating period should be at least 1 hours.
- The tests should be conducted over a stable period of at minimum 30 minutes

11.4.2 Calibration of instruments

Emission measuring equipment will be calibrated at least twice a day (start and end) or when possible before and after each test
The sampling time used is 2 sec.

11.4.3 Measuring procedure

We will carry out 2 types of tests:

- Stationary tests aiming at checking possible impact of gas quality on efficiency or emissions
- Dynamic test with rapid gas quality changes aiming at observing the ability and rapidity of the CCCB to adapt to the new gases

The common test conditions will be

- nominal gas pressure: 20 mbars
- Temperatures of heating water circuit: 50°C/30°C
- Water heating function: off
- Load: full load and minimum load

Reference measurement
The boiler is set to nominal condition e.g. nominal heat input given by the manufacturer, dT and flow, when operating with G20.

The results (heat input, output, efficiency, air factor and emissions) will be compared to the declaration of manufacturer.
The boilers setting shall not be modified after the set up.

Calibration process
The description and characteristics of the calibration process are studied from the manual carefully. During the tests the calibration process is measured and documented dynamically if possible when the appliance is set for the reference gas but supplied with gases in the upper and lower limits of I_{2N} category and further (richer and poorer) including the effect on emissions of CO and NO_X (dynamic).

Stationary measurements
Stationary measurements will be executed with all test gases of
Table 4 available for the respective project partner. The stability conditions of 11.4.1will be respected and all data of Table 7 will be recorded. As the calibration process may depend on the history of supply gases a chronology of test gases has to be defined and will be respected for the tests. The following proposal is given by DGC:

- G21 (Max wob) (setting)
- Natural gas L (from pipeline) (heating up period)
- G21 (Max wob)
- G20 (reference)
- Natural gas L (NG from pipeline + X % N2)
- G231
- G222
- G20 + 10 % H2
- G20 + 30 % H2
- G271 (Mmin wob)

We expect to execute the tests according the following plan:

- Change of the gas
- Waiting for stability
- Measurement during stable period (30 min)
- Next gas (no cooling)

Part 1 of the test
Test at Pnom with all gases of the list above

Part 2 of the test (voluntary)
Test at Pmin with selected gases of the list above

Part 3 of the test (voluntary)
Test at Pmax with selected gases of the list above

Part 4 of the test
Test at Pmax and Pmin with selected gases of the list above with blockage of the duct
This should be carried out on both the inlet (air) and the exhaust (flue gas). The test will be conducted with increasing blockage, (slowly increased blockage when getting near of 100%)

Important: Note that the appliance setting (if there are) will NOT be modified after the first reference test

Dynamic measurement
In this test, the boiler will be exposed to a change in gas quality while operating. The purpose of the test is to show the effect of rapid change of gas quality (dynamic response).

- The water temperature should be to 50/30°C (output/input) with the corresponding flow.
- The flow and return temperature may not be constant during the test (rapid changes of gases).
- The boilers setting shall not be modified after the set up.
- Common test conditions of section 6.3 shall be respected
- **The stability criteria's described in section 3 shall NOT apply: the gas will be changed every 10 minutes**

The changing of gases are executed due to possibilities of the test stands at the respective project partners.
Proposal for the chronology for the dynamic tests:

G20 ⇨ G231
G231 ⇨ G20
G20 ⇨ G21
G21 ⇨ G231
G231⇨ G21

The boiler will be operated with the given gases for 10 minutes after what it will be switched to the next gas.

Cold start tests
The purpose of the cold start test is to show how the boiler behave after having been turned off (standby) for a period. This will have special focus on emissions.
Two tests will be conducted, one after a standby period of more than 8 hours and one after a standby period of > 24 hours.

Before the stop, the appliance will be operated on G21, full load with a water return temperature of 30°C to the boiler. The water flow should be about the same as for the 50/30°C full load.

After the standby period indicated above, the boiler will be operated with G231

Voluntary the cold start with G231 may be executed with combustion air temperature as cold as possible (-5°C).