The influence of power-to-gas on natural gas quality & applications

The H₂-capacity of the German gas grid, experiments on the hydrogen tolerance of gas heating appliances and the regional scientific approach in North Rhine-Westphalia

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Abstract

In the future, the end users might be confronted with increasing proportions of hydrogen (H_2) added to the natural gas. The additional amounts of hydrogen may stem from power-to-gas technologies that currently attract attention in the natural gas sector. The power-to-gas or briefly PtG technologies convert electrical power via electrolysis to a well storable, chemically bound energy form: molecular hydrogen. This regenerative gas can be used directly, for example in hydrogen-powered vehicles equipped with fuel-cells. Or, it can be fed into the natural gas grid. This option yields an access for regenerative hydrogen to the existing gas infrastructure with its broad extension and delivers it to the end users hundreds of kilometres away without the need to establish a new transportation system. However, questions concerning gas quality and interchangeability [1] need to be answered in advance.

In general natural gas transportation and storage systems tolerate a small concentration of hydrogen well [2]. For the German grids it is expected that concentrations up to 10 vol.-% H_2 will be allowed in the next years. Limitations will apply in sub-grids with sensitive gas technologies, which are mainly seen in gas turbines, specific industrial processes and in the car-fuelling sector (compressed natural gas, CNG).

Here, we calculate the potential amount of hydrogen that could be added to the natural gas grids in Germany per year. Furthermore, as part of a DVGW project within the DVGW Gas Innovation Campaign [3], we experimentally investigate how the appliance technology in households reacts to suddenly occurring high concentrations of hydrogen without any adjustments made in advance.

I Capacities for hydrogen in the German natural gas grids

I.1 Background

When the power-to-gas approach gained more and more attention, one of the first opening questions that rose was which quantity of hydrogen could possibly be stored in the natural gas infrastructure in the near future. We addressed this issue for the German natural gas grids in order to calculate an approximate number for the hydrogen feed-in potential in Germany.

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I.2 Method

The addition of up to 10 vol.-% H_2 to the natural gas is currently discussed for Germany. For our calculations, we restricted our calculation to a rather conservative average concentration of 5 vol.-% in the mixed gas. Furthermore, since heat supply is the foremost market for natural gas in Germany our analysis was carried out with regard to seasonal oscillations in the natural gas consumption.

When the feed-in of hydrogen into the grid reaches the threshold of maximum H_2 concentration, the relevant parameter will be the volume flux (the load) in the specific grid. In this borderline case it will only be possible to feed in the exact amount of hydrogen that equals the consumption at the same time. The deduction of this minimal load in the natural gas grids is visualised in the Sankey diagram (figure 1).

Minimum Feed-In Potentials of Additive Gases and Replacement Gases in Germany

Total natural gas sales

904 TWh/a — Direct delivery to power plants and industry

Local distribution

677 TWh/a — Constant mass flow needs to be provided (summer load)

Summer load

331 TWh/a — Minimal load occurs at night

Minimal night load

212 TWh/a

Biogas:
Potential for additive raw gas: 6 TWh/a
and conditioned replacement gases

Hydrogen:
Potential for 5 vol.-% additive gas*: 10.8 – 15.0 TWh/a (LHV)
(corresp. electric energy input** = 16.6 – 23.1 TWh/a)

Maximum feed-in rate equals the current consumption within the same grid

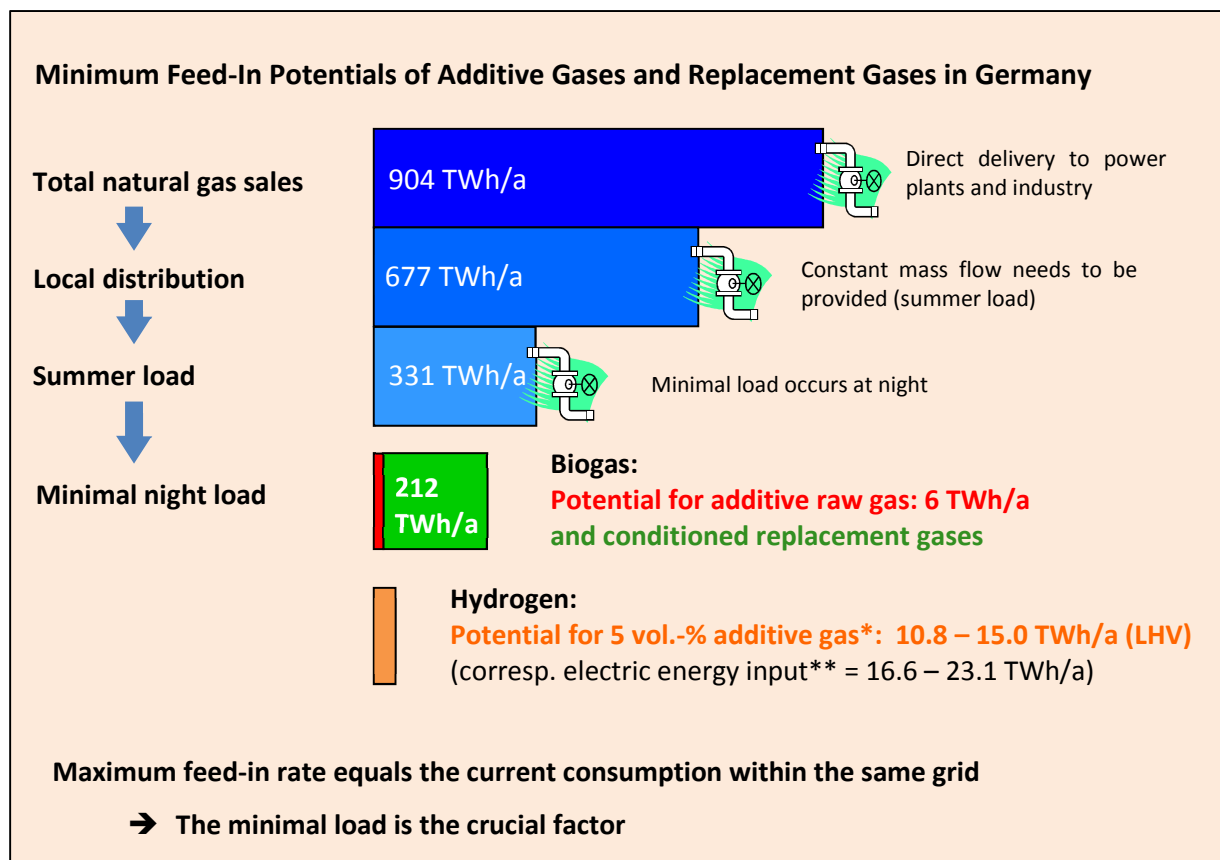➔ **The minimal load is the crucial factor**

Figure 1 – Deduction of the feed-in potentials of additive biogas (raw gas) and conditioned replacement biogas in the German natural gas infrastructure. Data from [4] supplemented with the overall hydrogen feed-in potential according to [5]; * local limitations will apply; ** at 65 % electrolyser efficiency (conservative estimation); LHV = lower heating value.

With the aim to make a conservative estimation of the hydrogen storage capacities we used the total natural gas consumption of the year 2002 [6] where the natural gas use was lower than in the following years [7]. Subsequently we subtracted the following amounts: first, all industrial users that are supplied by the transport grids, second, reduced the consumption to an average summer day and third, further reduced the consumption to the minimal flow rate at night-time. The consumption load curves as a function of time are not straight forward to obtain and beyond that the load varies strongly in between different distribution grids. This mainly depends on the percentage of industrial and commercial gas usage, which exhibit a rather constant consumption as compared to households, which are characterised by strong day/night fluctuations. Thus, a detailed classification of the natural

gas distributors was carried out considering the delivered amount of natural gas per client and the ratio of summer vs. winter consumption. These two parameters help to quantitatively describe the composition of end users in a specific grid. For example, small gas consumption and strong summer/winter oscillation represents grids which are dominated by residential areas. Higher consumptions per client and/or reduced summer/winter oscillations gradually represent higher ratios of commerce or industry within a certain grid. The model was developed based on typical load curves in cooperation with six local gas suppliers who provided data. The computational method was described in detail in reference [4]. For the electrolysers we assumed an effectiveness of 65%. This agrees well with average efficiencies reported elsewhere [8][9]. For the future large-scale application in the PtG context considerably higher efficiencies are expected [10][11].

I.3 Results and discussion

The calculation results in a minimal hydrogen feed-in potential of 2.47 – 3.87 bio. m³ per year in the distribution grids plus 1.14 bio. m³/a that are not delivered to the households [5]. Converting these volumes[2] to an annual amount of energy by using the lower heating value (LHV) leads to 10.8 – 15.0 TWh/a stored in a chemical form. This corresponds to an electric energy of 16.6 – 23.1 TWh/a used as input for electrolysers.

Assuming 8,000 hours of operation, this corresponds to a potential for an installed electrolyser capacity of about 2,000 – 3,000 MW at full load in continuous operation. Nevertheless, it is noteworthy that modern alkaline electrolysers and especially state-of-the-art PEM electrolysers are capable of changing their load within minutes (the latter even faster) and offer a broad range of partial load. Both are suitable candidates for the power-to-gas application [9] [10] [12].

Due to the limited capacities for hydrogen in the gas grids, regions with exceptionally high natural gas flow rates provide the highest feed-in potentials for hydrogen. In Germany the federal land *North Rhine-Westphalia* stands out with more than two times the storable amount of hydrogen than any of the remaining 15 lands. About 3 – 5 TWh/a could be fed into the natural gas grids here.

In contrast, methane (synthetic natural gas or treated biogas) can be regarded a replacement gas instead of an additive and therefore has the potential of 212 TWh feed-in per year [5]. It may stem from the same electrolysers and is processed in an additional methane synthesis stage. The methane synthesis technologies for the power to gas application are being developed right now and already reached the demonstration stage of technology maturity [13]. Chemical synthesis is the state-of-the-art technology these days [12] but biological reactors will follow within a delay of only a few years.

Further research is inevitable and should focus on PtG location identification in grids with high volume fluxes. The variety of industrial, commercial and household natural gas applications and the broad spectrum of local conditions within the grids remain largely unknown and call for technical modelling with a high level of detail in order to provide a reliable evaluation of potential PtG sites.

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[2] Volumes relate to T = 0°C = 273.15 K and atmospheric pressure p = 1013.25 mbar = 101.33 kPa.

II Experiments

Within the DVGW Gas Innovation Campaign (project G5/01/12-b) GWI and its collaboration partners E.ON Technologies, E.ON Hanse and DVGW-EBI study the feasibility of injecting up to 10 vol.-% hydrogen into the natural gas distribution grid. Along with the joint efforts in the field of hydrogen tolerability the partners share their experience and knowledge with one another and thus develop a common understanding of the technical status quo and upcoming challenges [3].

II.1 Background

The combustion properties of gaseous hydrogen considerably differ from the properties of natural gas. To give a first impression fig. 1 indicates the lower and higher heating values as well as the higher Wobbe index for a mixed gas consisting of methane (left) and hydrogen (right) [14]. Further parameters like the limit of flammability [15], the air requirement, and the adiabatic flame temperature are given in table 1.
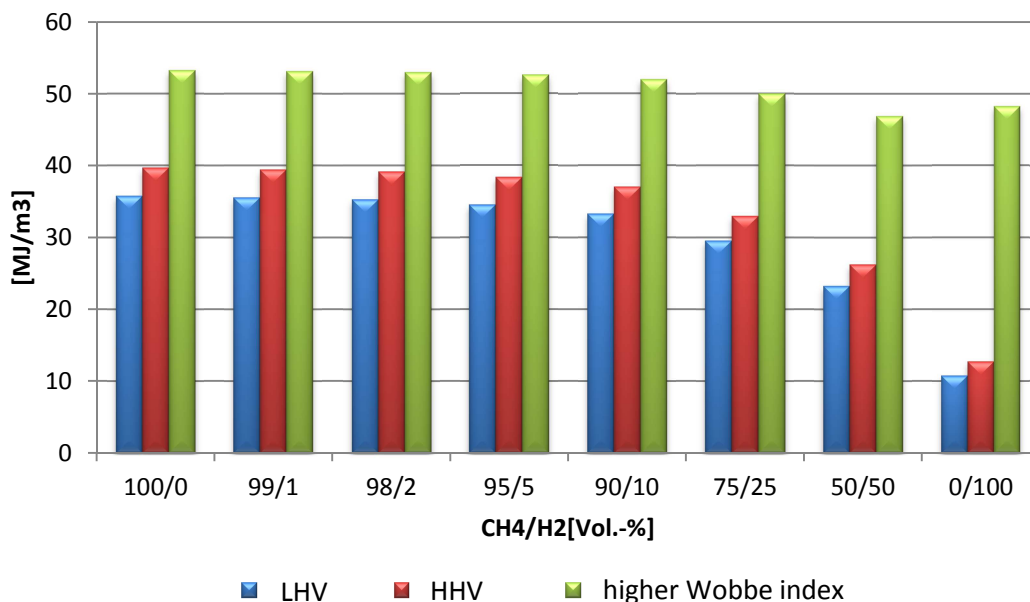

Figure 2 – Comparison of the lower heating value, the higher heating value and the higher Wobbe index for gaseous methane / hydrogen (CH$_4$/H$_2$) mixtures [14].

II.1 Choice of gas applications

In cooperation with manufacturers as well as research institutes (DVGW Gas Innovation Campaigne project no. G5/01/12-b, GERG project DomHydro) a matrix was developed that covers all appliance technologies in the field of gas usage in households. Based on this matrix we identified categories that are sensitive to the given research question. The matrix shown in figure 3 classifies the appliances by burner technology, control system and parameters such as air ratio and burner load. Applicable standards as well as experiences from other research projects were taken into account. Especially the segmentation deduced in the international GasQual project is given in the matrix as a reference [16].

For the hydrogen tolerance experiments a choice of 10 gas-fired boilers were selected. The devices represent a variety of burner designs, combustion air supplies and controls. The experiments represent typical state-of-the-art condensing boilers as well as different designs of non-condensing boilers as well as low-temperature non-condensing boilers, which are still the predominant technique in the households. The results for these appliances will be published after finalization of the experiments in 2015. Here, we present first results from our ongoing experiments for an exemplary condensing boiler.

Appliance category	Norm	Device Type	Segment (GASQUAL)	Atmospheric Burner		Jet Burner	Modulating fully premixed surface burner with fuel/air control		
				air ratio primary < 0,8	air ratio primary > 0,8	stages 1/2	pneumatic	electronic	controlled combustion I2N
							Burner Load Specification < or > 1.000 kW/m²		
Boilers	EN297	Type B - partial premix/conv	11						
		Type B - Low NO$_x$ partial premix	4						
		Type B - Full premix	12						
	EN 303-	Type B / Type C - Jet burner	3						
	EN483	Type C - partial premix/conv	7						
		Type C - Low NO$_x$ partial premix	5						
		Type C - Full premix	8						
	EN677	Condensing boiler – partial premix	25						
		Condensing boiler – full premix	1						
Cookers	EN 30	Type A - Built-in Hob - Single Ring	2						
		Type A - Built-in Hob - Multi Ring	18						
		Type A - Built-in Oven	16						
		Type A - Free-standing cooker - including grill	6, 14						
		- including oven	10						
Water Heaters	EN26	Type B - Inst. Water Heater, open flued	9						
		Type C - Inst. Water Heater, room sealed	20						
	EN89	Type B - Storage Water Heater open flued	19						
		Type C - Storage Water Heater room sealed	28						
Space Heaters	EN1327	Different types of gas fires	26						
	EN1482		23						
	EN613		13,15,21,22,2						
	EN778	Ducted Air Heater	27						
Other	EN1458	Tumble Dryer	29						
	EN509	Decorative Gas Fires	17						
		Micro CHP - Gas Engine							
		Micro CHP - Stirling engine							
		Micro CHP - Fuel Cell							
		Gas Heat Pump							

Figure 3: Matrix for gas appliance classification. As a reference, the respective segments from Gasqual [16] are given. Adapted from [17].

II.2 Experimental Setup

After the fuel gas flow (yellow lines in fig. 4) has passed a fine particle filter the mass flux is measured by a hot wire anemometer at a pressure of 100 mbar. After passing a pressure reducing valve it relaxes to 21 mbar. Subsequently the volume of the fuel gas is measured by a standard bellows-type gas flow meter. The latter is used for data analysis, while the hot wire anemometer is used for real-time monitoring during experiments. Before being fed into the test device, temperature and pressure of the gas are determined. In the exhaust gas flow (orange lines) we measured the gas temperature as well as the CO, CO_2, O_2, NO, and NO_x concentrations, and the peak CH_4 concentration after cold starting. The CO and CO_2 concentrations were measured via infrared absorption, O_2 was measured with a paramagnetic oxygen analyser and NO and NO_x were measured with an electroluminescence analyser. In the closed heating circuit we measured the supply temperature (13) and installed a circulating pump (14) to maintain the water flow. The pump could be bypassed in case the test devices possessed sufficient internal pumps. The supply water was cooled by a plate heat exchanger (15) and the resulting temperature was monitored (16) to serve as a control signal for the fresh water circuit (see below). The volume flow of the cooled water was controlled (18) its mass flux was measured (19). The fresh water circuit used for cooling of the heating circuit passed the heat exchanger at a volume flow which was controlled (23) as a function of the heating circuit temperature (16). All experiments were carried out at a fixed temperature spread.
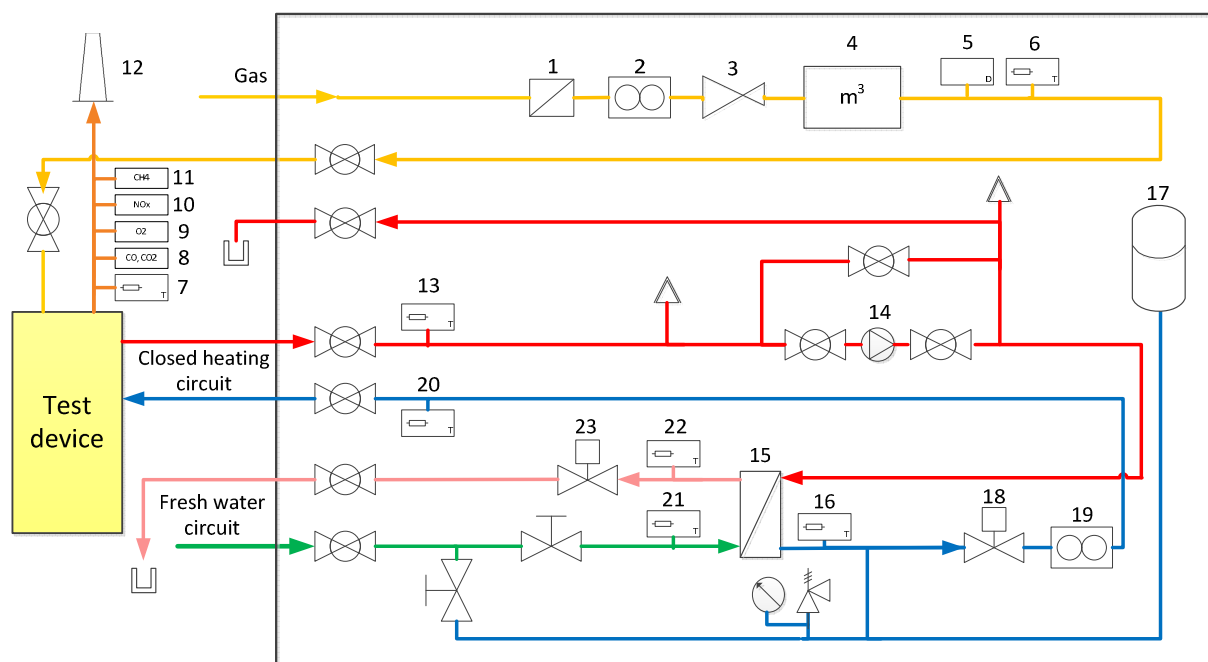

Figure 4: Schematic representation of the experimental setup. Facilities and measurements of the gas circuit (yellow and orange): (1) fine particle filter, (2) mass flux (hot wire anemometer), (3) pressure reducing valve, (4) volume flux (bellows-type gas flow meter), (5) gas pressure, (6) gas temperature, (7) exhaust gas temperature, (8-11) concentrations of CO and CO_2, O_2, NO_x, CH_4 (12) flue; closed heating circuit (red and blue lines): (13) supply temperature (water), (14) circulating pump, (15) plate heat exchanger, (16) return temperature (water), (17) expansion vessel, (18) return flux control, (19) mass flux (water), (20) return temperature at device input (water); fresh water circuit (green and pink lines): (21) fresh water inlet temperature, (22) fresh water return temperature, (23) fresh water volume flow controlled as a function of temperature no. 16; adapted from [18]. All water temperatures are determined via resistor-type platinum thermometers.

II.3 Fuel gases used for the experiments

We chose natural gas H as well as the test gas G20 (100% methane) as a reference and mixed a hydrogen enriched test gas consisting of 30 vol.-% H_2 and 70 vol.-% CH_4 for the hydrogen tolerability experiments. Table 1 gives an overview of selected characteristics of these gases. In addition, the hydrogen concentration was reduced to 20 vol.-% and to 13 vol.-% for selected test devices.

Figure 5: Photograph of the test rig [18].

Parameter	Natural gas H	G20 (100% CH$_4$)	Hydrogen enriched G20 (30% H$_2$)
Higher heat value [kWh/m³]	11.55	11.06	8.80
Lower heat value [kWh/m³]	10.44	9.97	7.87
Density [kg/m^3]	0.8004	0.7175	0.5292
Limit of flammability [vol.-%]	4.71 – 14.38	5-15	4.7 – 32.8
Air requirement L$_{min}$ [m$^3_{air}$ / m³$_{fuel}$]	9.99	9.57	7.40
Adiabatic flame temperature [K]	2223	2240	2265
Lower Wobbe index [kWh/m^3]	13.269	13.383	12.313
CO$_{2,max}$ [vol.-%]	12.11	11.73	10.48

Table 1 - Specifications of the gases used for our experiments. Relevant parameters for natural gas 'H' as well as the test gas 'G20' and a test gas mixture consisting of 70 vol.-% methane and 30 vol.-% hydrogen are given.

II.4 Test procedure

First, each test device was analysed with respect to emissions, exhaust gas temperature, inlet and output water temperatures and output power transferred to the heating circuit for both, natural gas H and test gas G20. For further experiments G20 is used to guarantee constant fuel gas composition.

Second, we performed continuous operation experiments for each test device comparing G20 with the hydrogen enriched mixed gas. The burners were set to the following power stages: Minimal power (Q_{min}=25%), 50% power (Q_{50}), 75% power (Q_{75}), and maximal power (Q_{max}). Each stage was held for 20 minutes. Some test devices could only be operated at maximal power. The fixed heating water temperature spread was chosen 70 °C : 50 °C in order to resemble typical values. The switching from G20 to hydrogen enriched G20 and vice versa was done within 5 minutes for each power stage.

Third, the test devices were repeatedly started with cold combustion air in a worst case scenario for start procedures. A temperature of -15 °C was chosen, representing a cold winter day in Europe. All other experiments were performed at our laboratory air temperature 19 °C. The cold devices were initially started with maximal power. For the starts no. 2-5, we waited until the supply temperature had reduced to 20 °C. The cold start experiments were carried out five times for both, G20 and hydrogen enriched G20.

II.5 Results and Discussion

In general the devices tested so far tolerate these extreme conditions. The devices did not show any unusual behaviour at 25%, 50% and 75% part loads and at full load. Ignition proceeded without problems and all test devices reached a stable state of combustion.
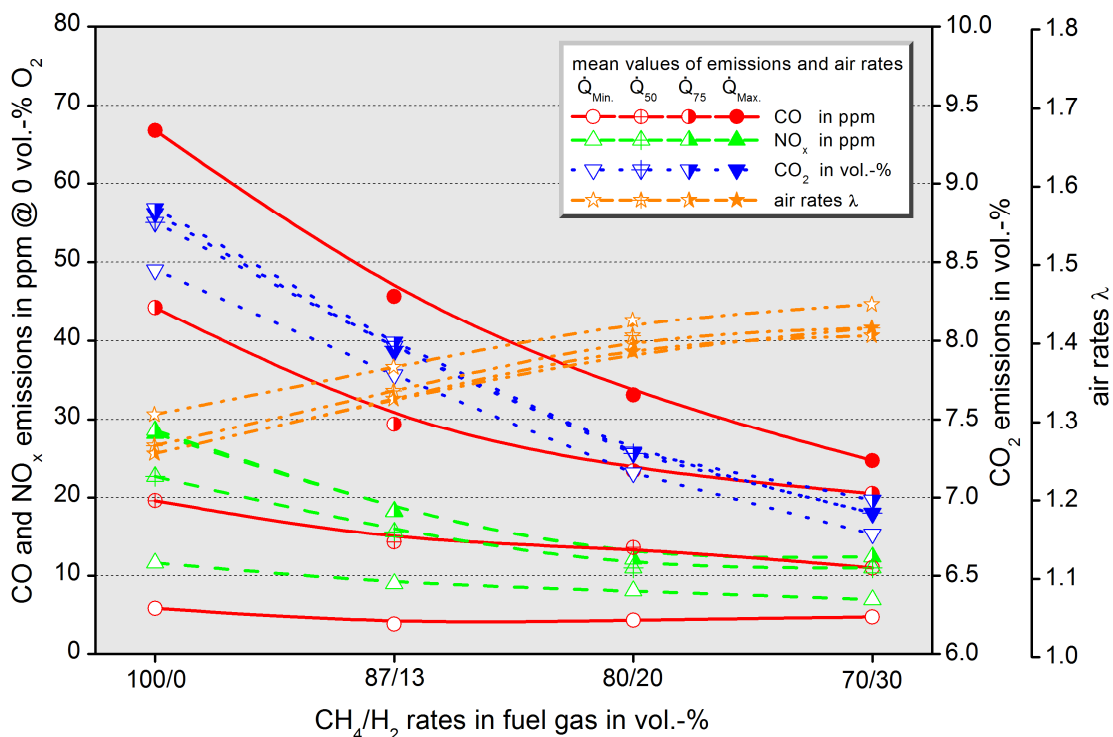

Figure 4: CO and NOx emissions as well as the CO2 emissions and air rates for an exemplary condensing boiler are plotted as a function of the methane/hydrogen composition. Each data set consists of 4 curves representing different thermal loads Qmin, …, Qmax

As a result we found reduced CO, CO_2 and NO_x emissions for all boilers exposed to the 70/30 mixture of methane and hydrogen[3]. We observed this behaviour for all part load settings. Since we did not modify the tested devices in any way, the air feed was not adapted to the experimental conditions. In order to achieve a given power output the boilers needed more fuel gas volume when supplied with the hydrogen enriched gas. At 'full load' the devices did not reach their maximum power output as specified by the manufacturers. The maximum thermal load was reduced by -4% to -12%, depending on the specific device. This is due to the fact that the addition of hydrogen decreases the energy content per gas volume as well as the air requirement and the devices experience limitations of the gas feed at the given CH_4 pressure depending on their design. Here 21 mbar were chosen, resembling a typical connection pressure in households.

Figure 4 shows the emissions and air ratios as a function of the hydrogen exposure for an exemplary condensing boiler. The 23% reduced air requirement of the 70/30 CH_4/H_2 mixture (see table 1) leads to an oversupply of oxygen reflected in an increased air ratio λ (orange curves).

II.6 Conclusion and Outlook

We conclude that the gas-fired boilers tested so far tolerate high additions of hydrogen well. No malfunctions were experienced for the selected new devices. Besides a decrease of the maximum achievable power output by 4-12% the devices operate as usual. Emissions were reduced for all devices at all output power settings. Our cold-start experiments (from zero to maximum power) did so far not show irregularities.

From our first results it is not possible to deduce a complete overview of the hydrogen tolerability of the vast variety of end user appliances in the households. In order to achieve a representative overview the experiments are complemented by similar tests performed in the laboratories of international partners in the DomHydro project group. In addition, the DVGW Gas Innovation Campaign faces the upcoming challenges in the field of gas technology in various projects [3].

Albeit first positive results for the tolerability of high H_2 concentrations we recommend further research in the field of hydrogen tolerability in end user devices, which will be a crucial point in the further discussion concerning the implementation of power to gas technologies in distribution grids.

III Foundation of a *Virtual Institute for Power-to-Gas*

In the German federal land *North Rhine-Westphalia* leading institutes from the scientific community specialized on hydrogen and natural gas joined their efforts and prepared the foundation of a *virtual institute* for power-to-gas and related technologies [12]. Virtual means that the expertise and infrastructure of its partners is combined without creating a new physical office. Due to close distances in North Rhine-Westphalia the partners meet at one of the existing institutes instead and share data over the internet. The portfolios of the collaborating institutes cover all stages of the energy carrier *regenerative gas* from its production over processing, transportation and storage, trade, as well as application. The portfolio includes basic science on state-of-the-art and future electrolysis and catalytic as well as biological methane synthesis reactors, fuel cell technology,

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[3] The experimental studies reported here are part of an ongoing DVGW project (project no. G5/01/12-b) thus the data will be completed with further results and more detailed information in the final report in 2015.

combined heat and power technologies, hydrogen-fuelled transportation, liquefied natural gas, appliance technology from the household to the industrial scale, and economic market modelling, simulations and analysis of the current and future European energy system. One year of technical pre-project ends in October 2014 and the respective final report will be available soon. The details of the scientific programme for the next three years are about to be determined. An informative brochure can be ordered at the Cluster EnergieForschung[4] or by contacting the authors directly.

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