Testing Hydrogen admixture for Gas Applications

Welcome to the 3rd THyGA Workshop

Presenters: Jörg Leicher (GWI), Stéphane Carpentier (ENGIE)

Host and Moderation: Johannes Schaffert, Gas- und Wärme-Institut Essen (GWI)
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Project Coordination: Patrick Milin, ENGIE
patrick.milin@engie.com

The THyGA project has received funding from the Fuel Cells and Hydrogen Joint Undertaking under grant agreement No. 874983. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.

ORGANIZATION OF TODAY'S WORKSHOP – CODE OF CONDUCT

- We are glad you could make it!
- Please keep your microphones muted when not needed
- Audience video should also be disabled during the presentations
- Calling-in per telephone is possible – the number can be found in your calendar invitation

ORGANIZATION OF TODAY'S WORKSHOP – CODE OF CONDUCT

- **This workshop will be interactive**. Nevertheless, with 300 registered participants we need to streamline the agenda and focus discussion.
- Therefore, **please feel free to make a posting in the chat any time** if you have a question and/or use the raise-hand tool, if you see it (not always the case)
- Johannes will read the questions or announce your questions and unmute your microphones so you can speak to each other in person.
- Optional (if chat function does not work): You can **send questions** to schaffert@gwi-essen.de and patrick.milin@engie.com at any time.
- All questions that remain open today will not be forgotten, promised.

ORGANIZATION OF TODAY'S WORKSHOP – AGENDA

Agenda of today's THyGA webinar on combustion theory	**10h**
Welcome to the meeting, rules for today, number and spectrum of attendees	Johannes Schaffert
Introduction by the THyGA Project	Johannes Schaffert
Impact of hydrogen admixture on combustion processes	Jörg Leicher, Stéphane Carpentier
➢ Questions and open discussion	Johannes, Jörg, Stéphane
End of meeting	**12h**

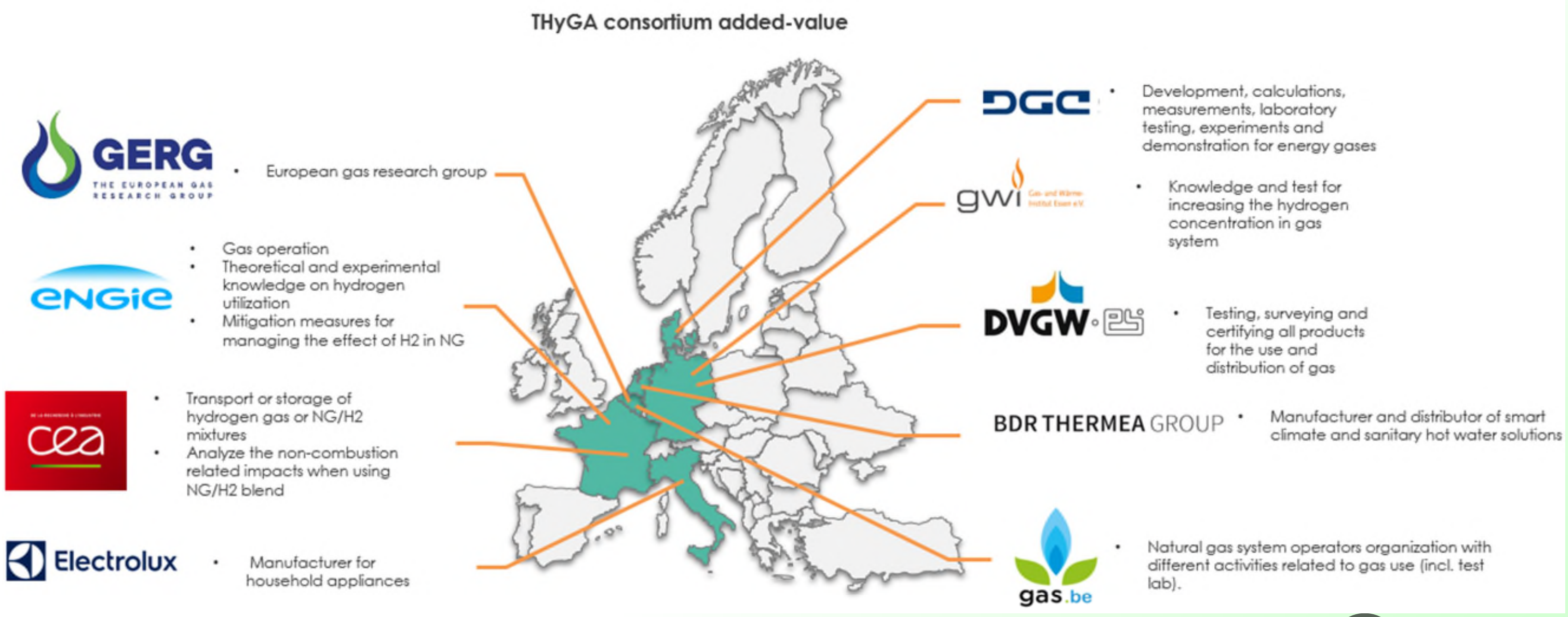
THE THYGA PROJECT & CONSORTIUM

The project has been created by 9 partners to answer the Horizon 2020 call FCH-04-3-2019.

- *"Research is required to identify and verify the impacts of … H2NG blends on the combustion characteristics … of appliances together with the potential impacts on appliance safety, efficiency, lifetime and environmental performance (e.g. NOx emissions)."*
- *Low, medium and high hydrogen concentrations in natural gas should be investigated:*
    - *Low = <10% Vol.*
    - *Medium = 10-30% Vol.*
    - *High = 30-60% Vol.*

The Project focus lies on testing. Up to 100 tests are planned, including various heating, cooking, catering, CHP, FC, ... appliances.

Project period: 2020-2022
project budget: 2,5M€.
visit: https://thyga-project.eu/



OBJECTIVES OF THE PROJECT

- THyGA project (Testing Hydrogen Admixtures for Gas Appliances) sets out to develop and communicate a detailed understanding of the technical impact of blends of natural gas and hydrogen on end use applications, specifically in the domestic and commercial sector.
  - Screening and segmenting the portfolio of appliance technologies in the domestic and commercial sectors and assessing the impact of hydrogen admixtures.
  - Testing up to 100 commercial and residential gas appliances to provide a generic protocol that can be adapted for virtually any appliance.

- To go further, the project consortium will identify and recommend appropriate codes and standards that should be modified or adapted to answer the needs, and develop a strategy for addressing the challenges for new and existing appliances.
  - Developing a validated certification protocol for different levels of H2 in natural gas
  - Making recommendations for manufacturers, decision makers and end-users along the gas value chain for appliance design, manufacture and certification.

THyGA

STRUCTURE AND INTERACTION WITH ADVISORY PANEL

WP2 – Status of gas utilization technologies

Segmentation and inventory of the gas utilization technologies in Europe **X** *Impact of hydrogen admixture on combustion processes* → *Test program & Selection of the appliances to be tested*

WP1 – Project management
General coordination, WP coordination and relation to FCH 2 JU

WP3 – Experimental work
What happens on the field with H2 injection ?
Generic test protocol (safety, efficiency, emissions, comfort)

Tests on ~100 appliances *for domestic and commercial end use (short and long term)*

WP4 – Standardization
How can we certify an appliance according to H2 rate in NG?
Development of test procedures including definition of test gases
Validation through tests

WP5 – Recommendations for mitigation measures
How can we increase the acceptable H2 rate?
Identification of mitigation measures to increase H2 rate
Validation through tests

Advisory Panel group
The objective is to ensure a constant challenge of the processed results and a great opportunity for a wide dissemination/communication plan to share results.

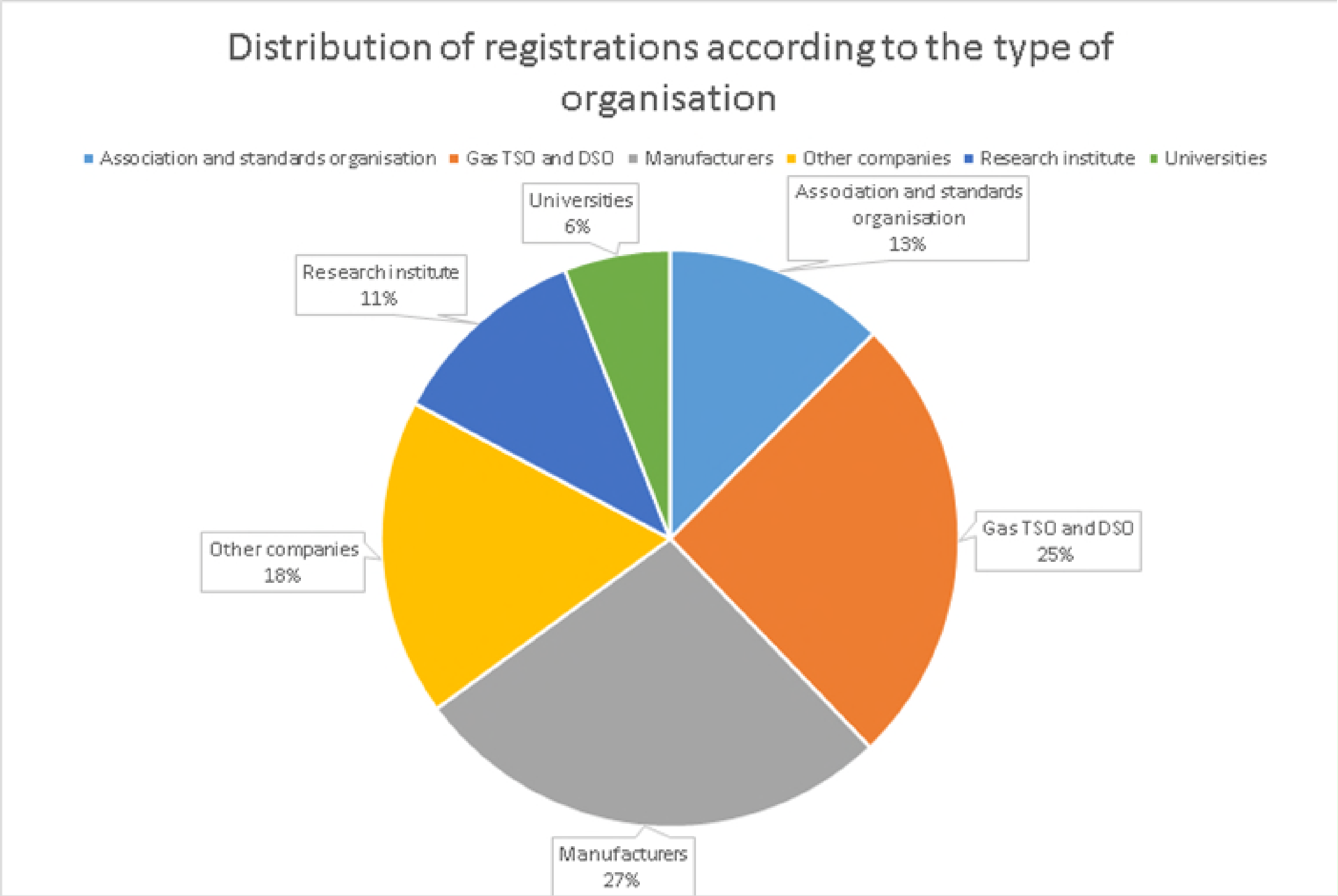
« market and dissemination »
Associations, DSO, academia

« Technology»
Manufacturers (appliances, burners, controls, sensors)

WP6 – Communication, dissemination and exploitation
dissemination to stakeholders, press, workshops, etc.
Green H2 admixture roadmap from the end-user point of view

TODAY‘S WORKSHOP – SPECTRUM OF PARTICIPANTS

386 registrations



Impact of hydrogen admixture on combustion processes – Part I: Theory

3rd THyGA Workshop

Jörg Leicher (GWI), Stéphane Carpentier (ENGIE)

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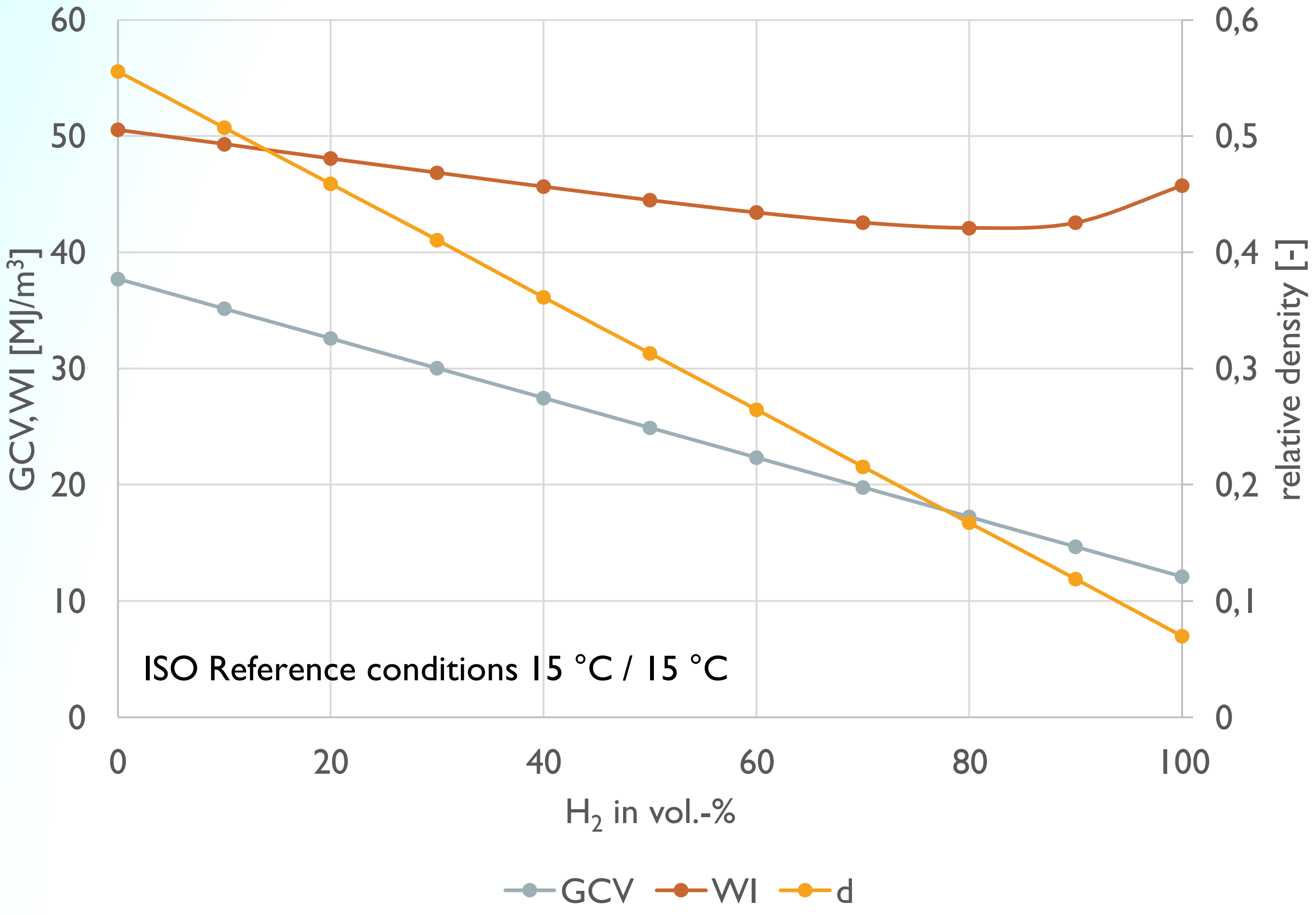
HYDROGEN ADMIXTURE: A GAS QUALITY ISSUE?

- In many ways, the question of hydrogen admixture into natural gas can be considered as **a gas quality issue**, especially from the perspective of an end user: something upstream changes the fuel gas composition and properties, and the user‘s process and equipment have to deal with it.

- Considering that hydrogen has very different properties compared to natural gas, it is to be expected that the impact of H_2 admixture on gas quality will be more severe than when switching from one natural gas to another. Therefore, **methane** will here be used as a **baseline gas**, representing natural gas … with a few exceptions, e. g. in the context of gas quality regulations and Methane Numbers).

- The impact of hydrogen admixture is **not only** a question of gas quality itself. The **combustion technologies** that are used in different appliances also play an important role.
  Two appliances may respond very differently in terms of performance, despite being supplied with the same levels of H_2.

GAS QUALITY CRITERIA – THE CLASSICS



- **Relative density**: $d = \frac{\rho_{n,fuel}}{\rho_{n,air}}$
- **GCV**: gross calorific value (the energy content of a fuel gas in volumetric terms)
- (superior) **Wobbe Index**:

$$\mathrm{WI} = \frac{GCV}{\sqrt{d}}$$

- The Wobbe Index is a criterion for fuel gas **interchangeability**. If two gaseous fuels have the same Wobbe Index, they will release the same amount of heat when burned at a nozzle **with constant pressure and diameter**.
- These **assumptions** are usually valid for residential appliances.

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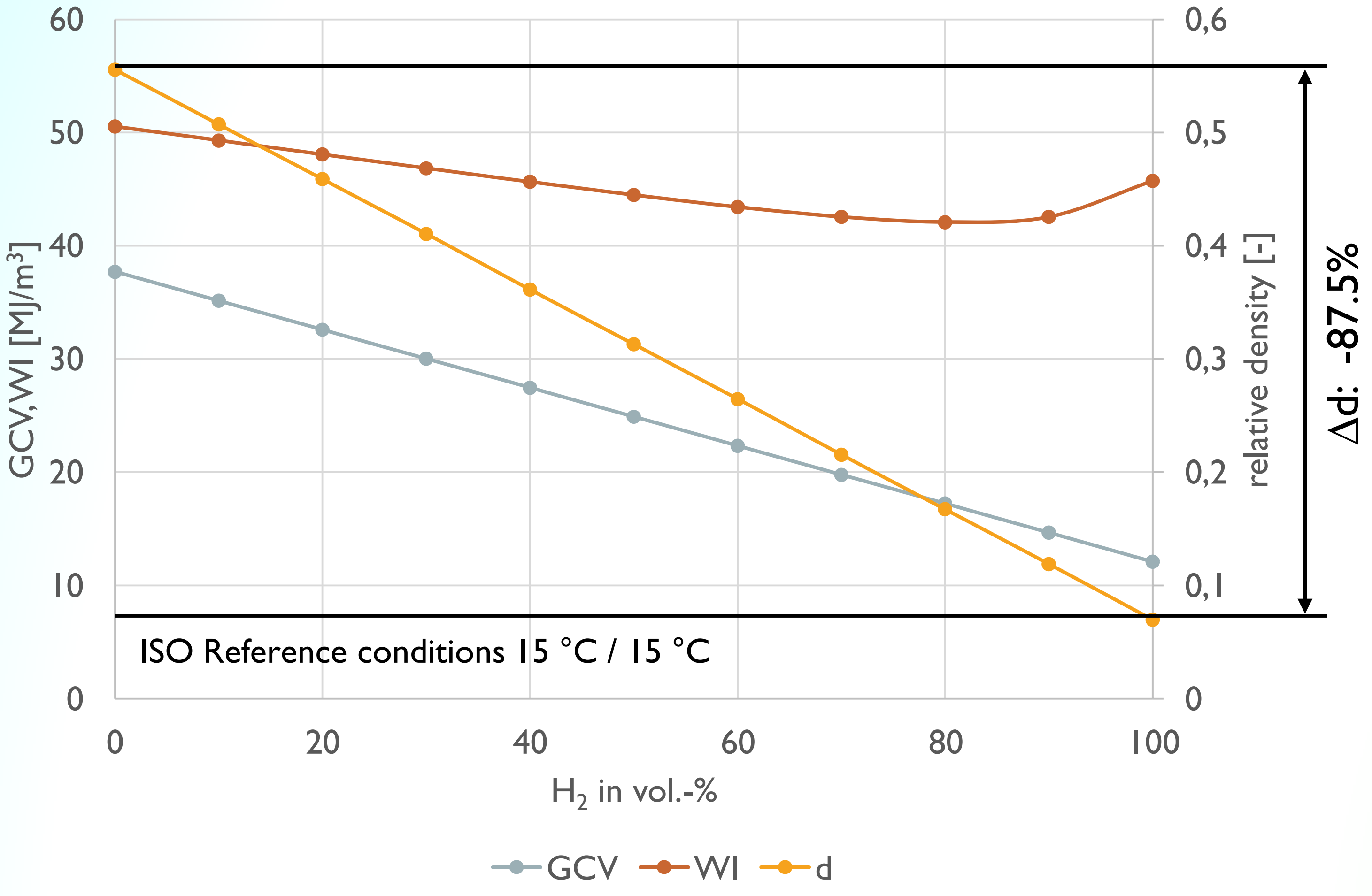

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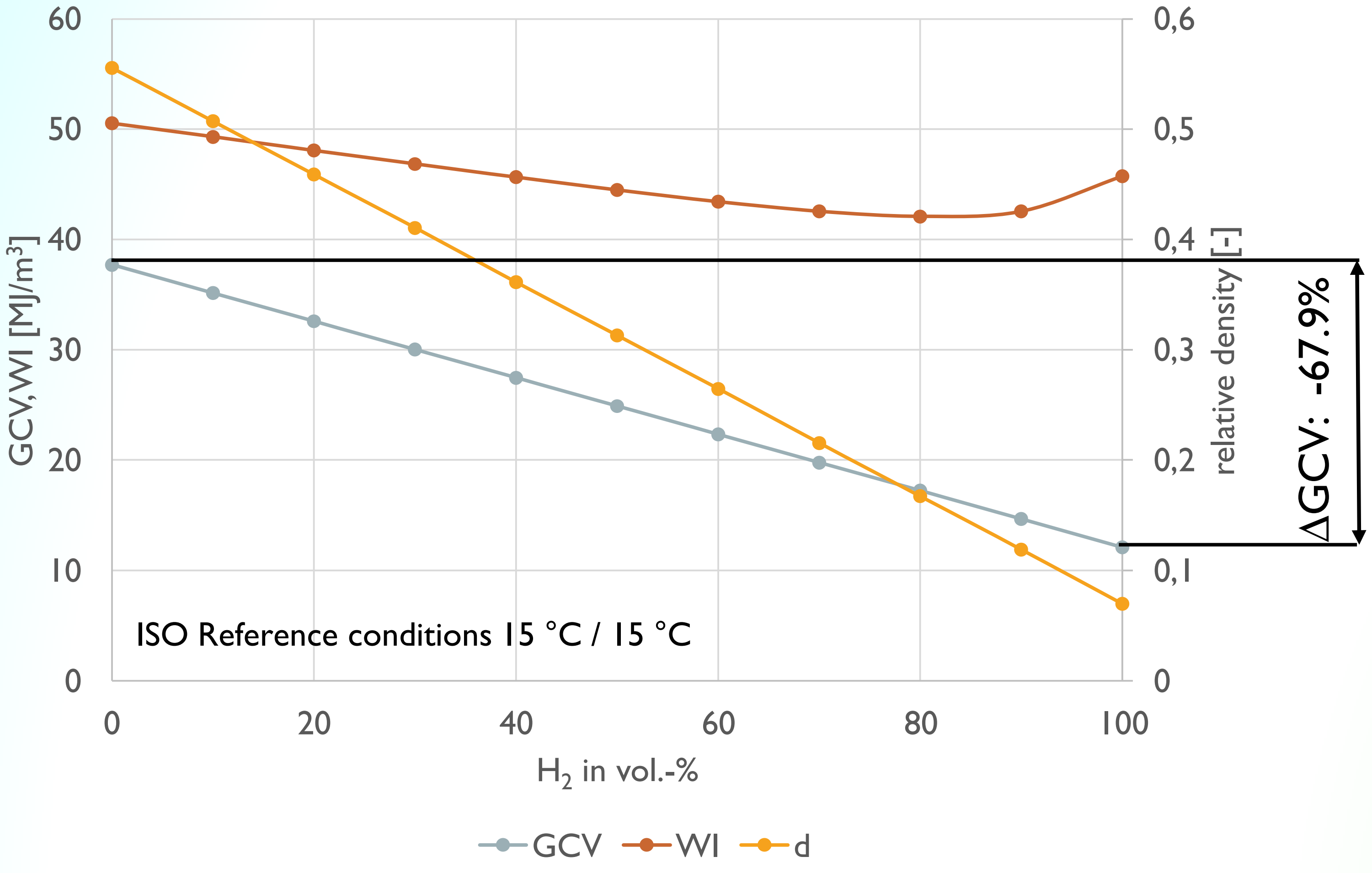

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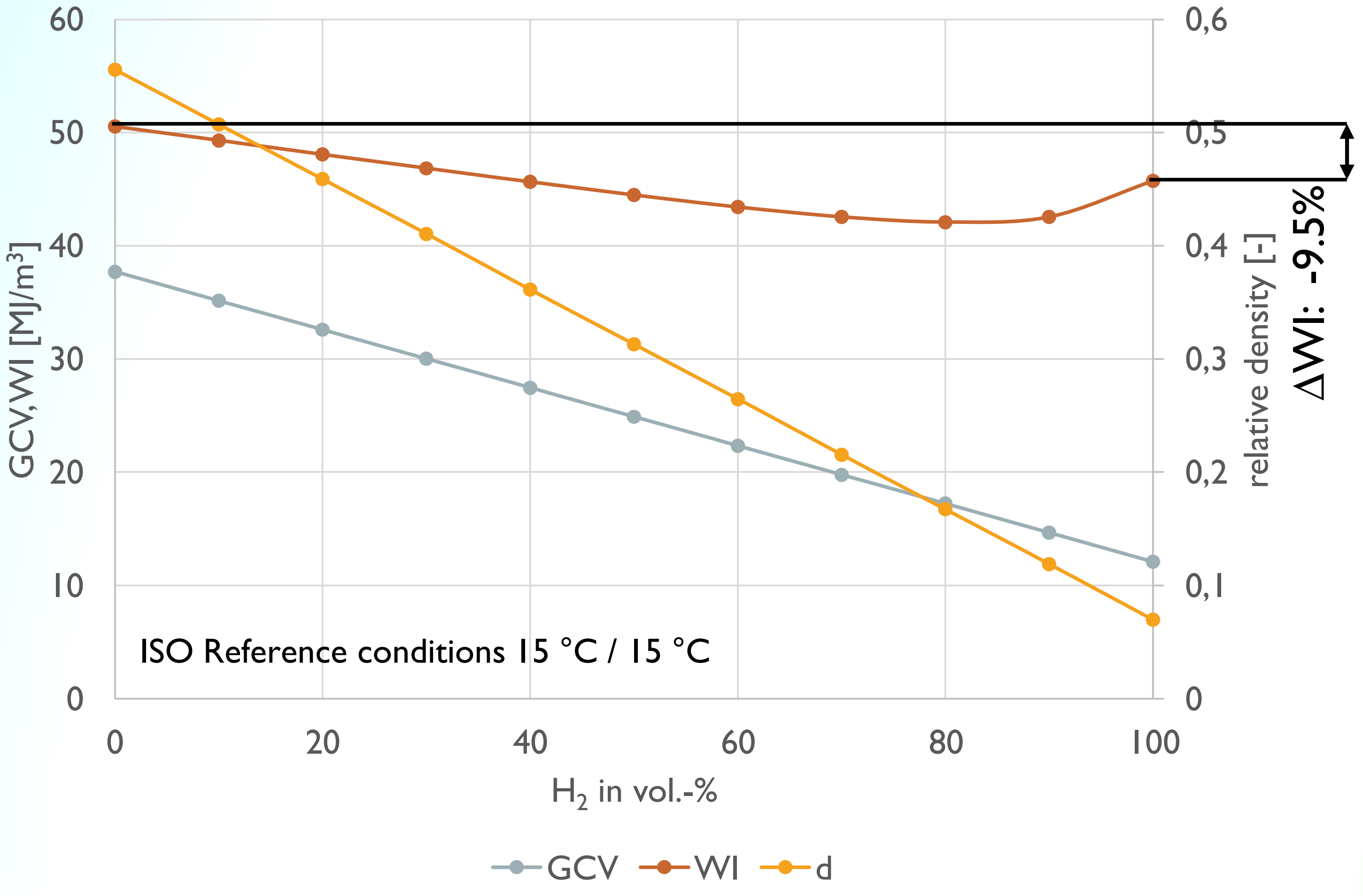

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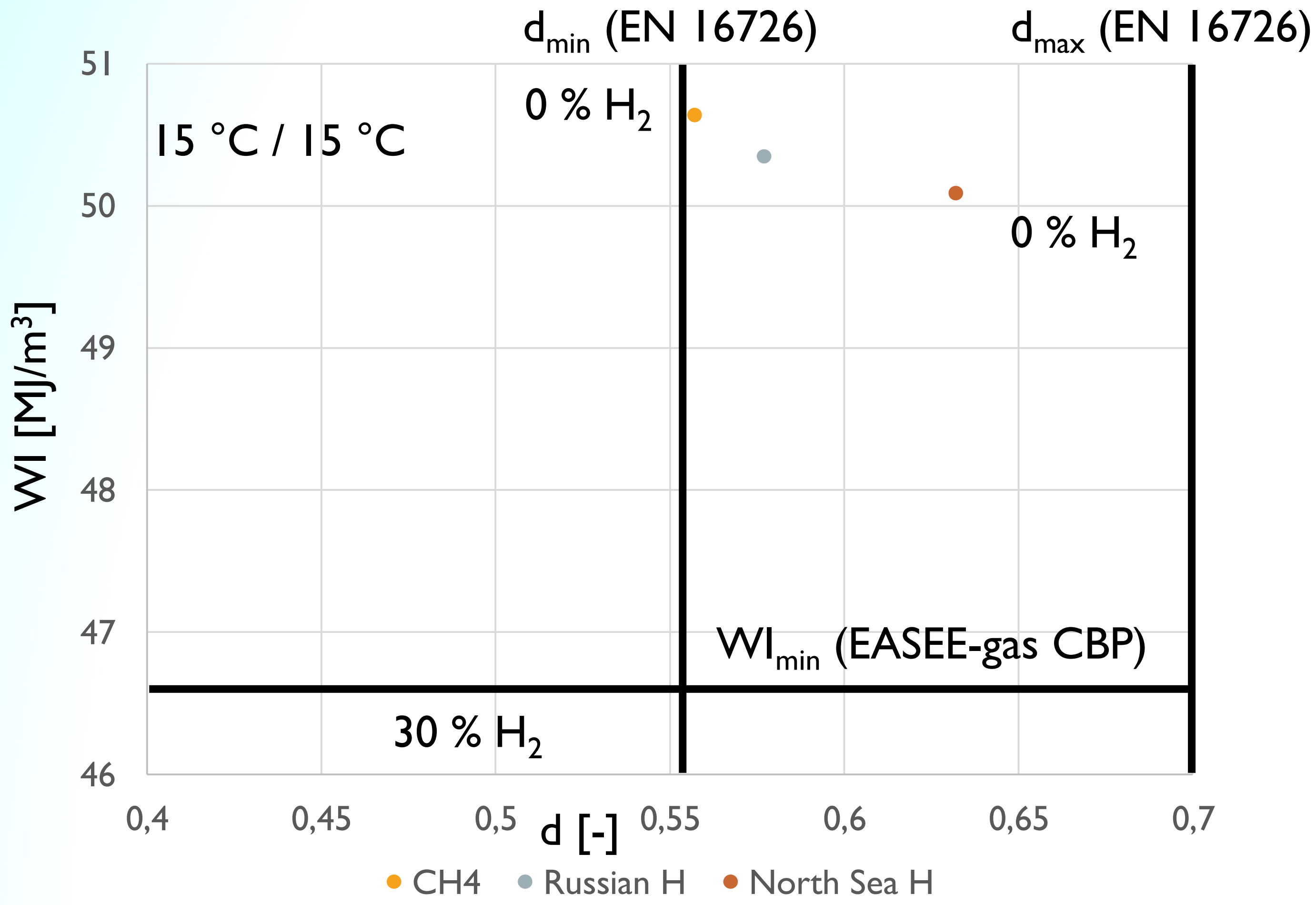
H_2 AND CURRENT GAS QUALITY REGULATIONS



- There a currently two documents governing gas quality in the EU, **EN 16726** and the **EASEE-gas Common Business Practice** of 2005.
- EN 16726 does not contain a WI range (yet) and only defines a range of permissible relative densities.
- EASEE-gas CBP recommends a WI range of 46.46 -54.0 MJ/m^3 (15/15).
- It is obvious that with the current setup of GQ regulations, the **relative density** is the criterion that most severely limits H_2 admixture.

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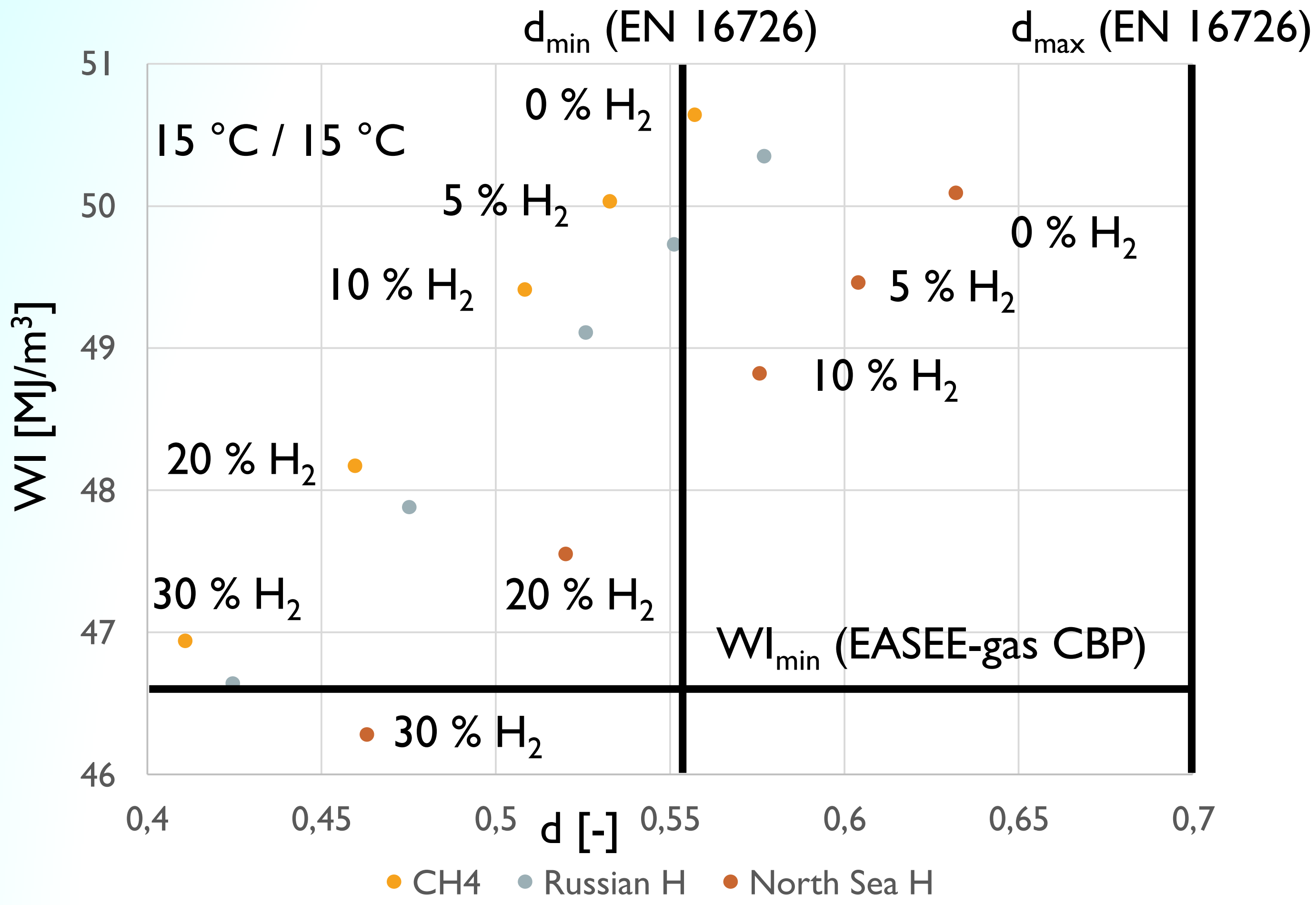

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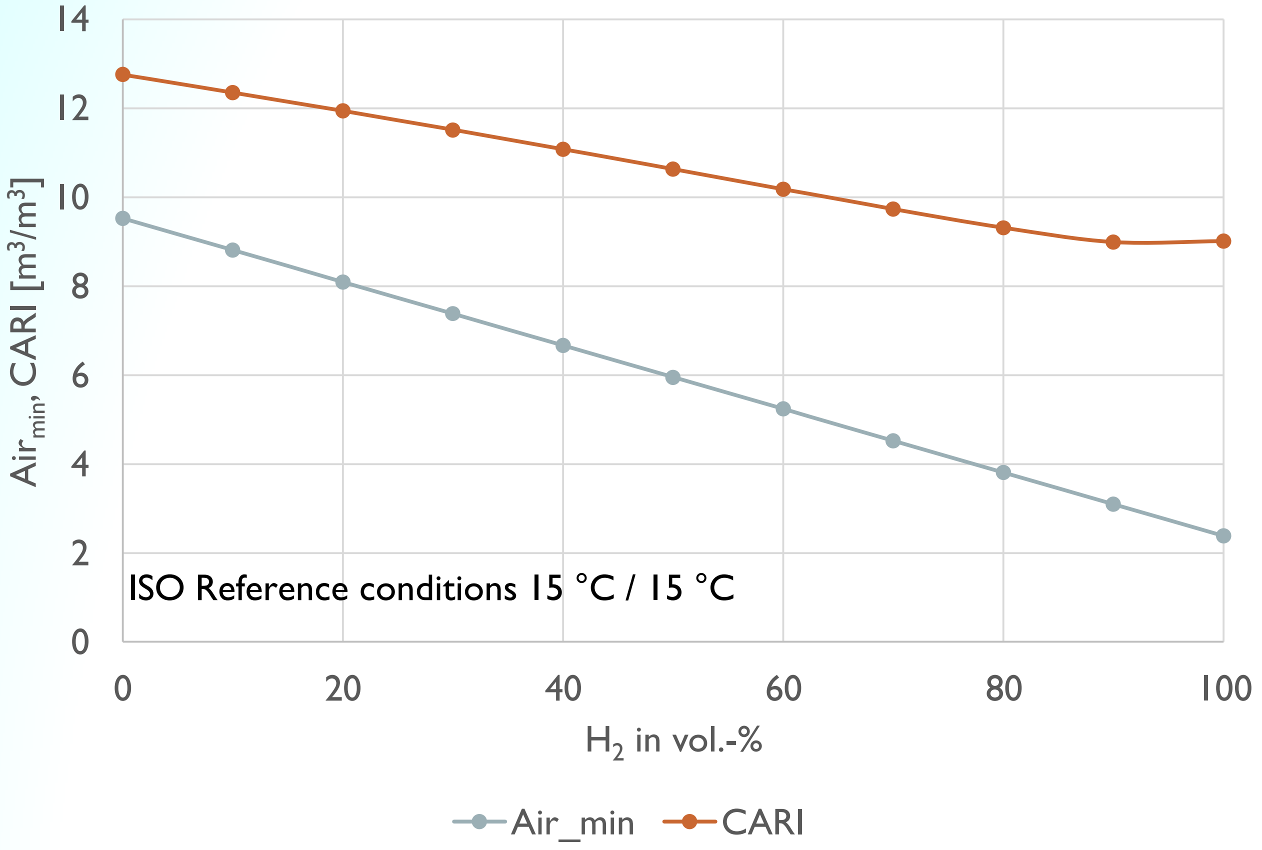
- It is obvious that with the current setup of GQ regulations, the **relative density** is the criterion that most severely limits H_2 admixture.
- Another limiting factor is the **Methane Number**.

OTHER GAS QUALITY CRITERIA: AIR_{MIN} & CARI

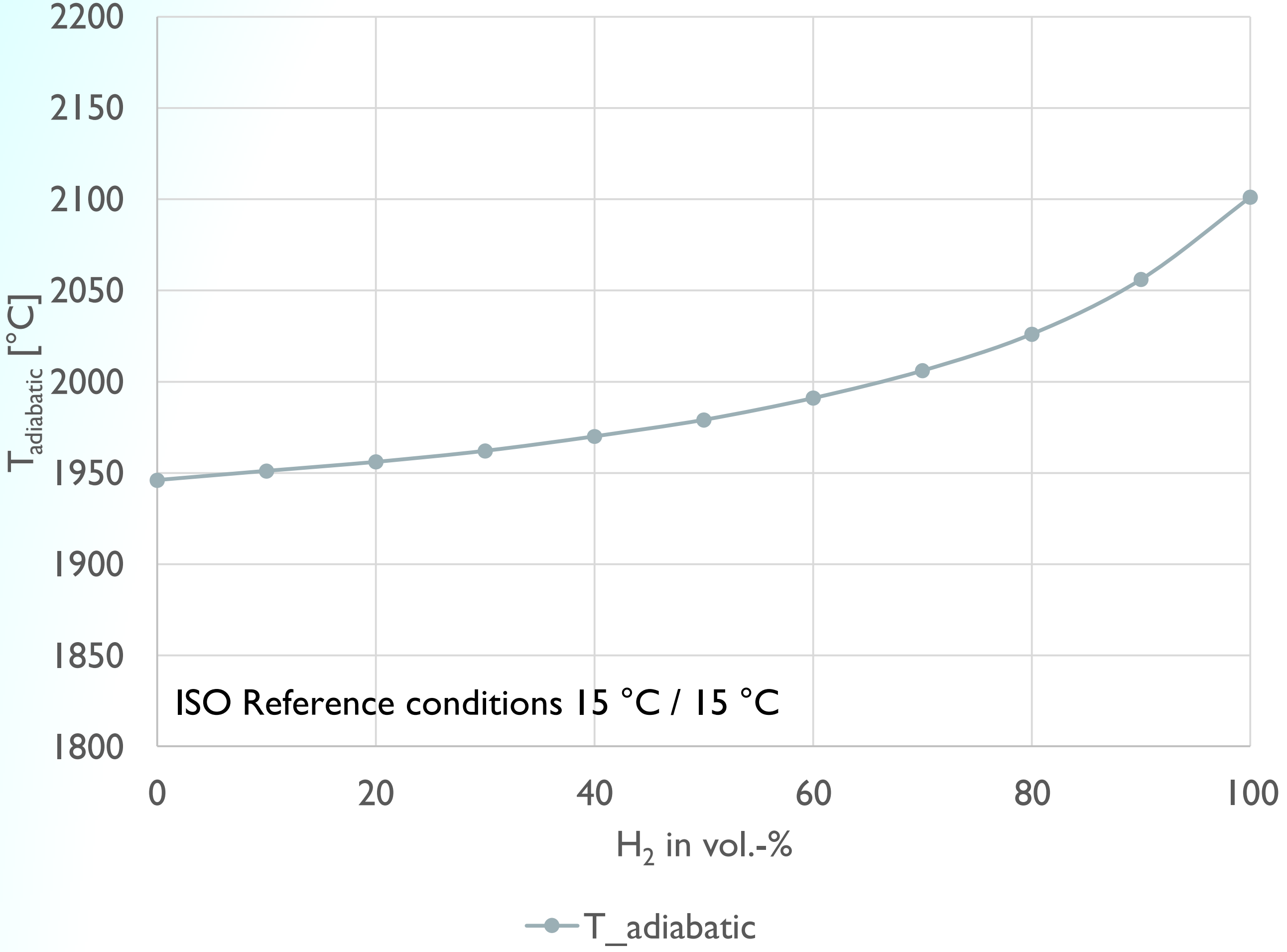


- Air_{min}: minimum amount of air (in m^3) that is required to completely burn $1 m^3$ of fuel
- CARI (**C**ombustion **A**ir **R**equirement **I**ndex): CARI can be used to calculate the minimum air requirement if only the Wobbe Index of a fuel gas is known.

$$CARI = \frac{Air_{min}}{\sqrt{d}}$$

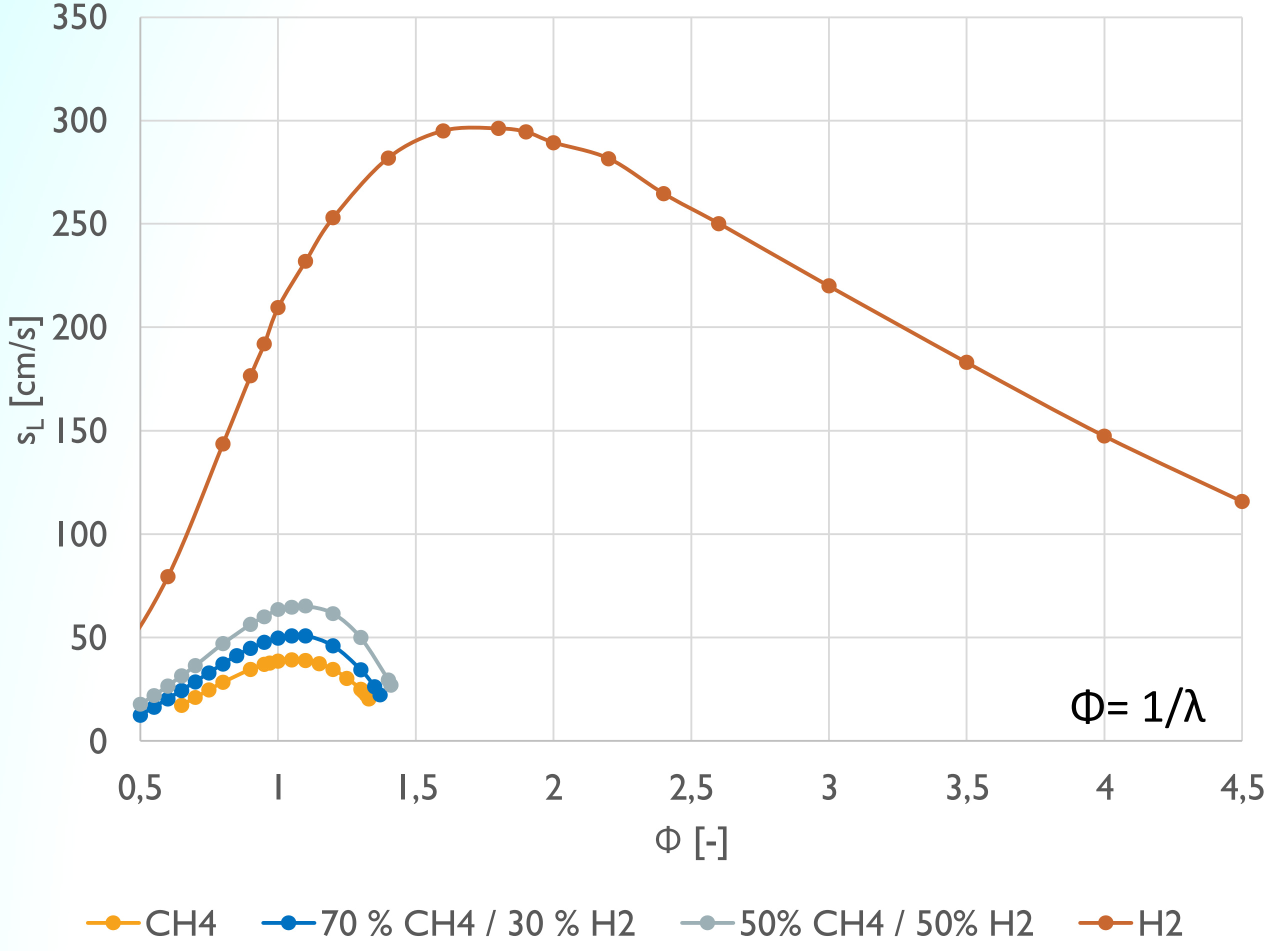
- ΔAir_{min} = -75 %
  ΔCARI = -29.4 %

OTHER GAS QUALITY CRITERIA: ADIABATIC COMBUSTION TEMPERATURE



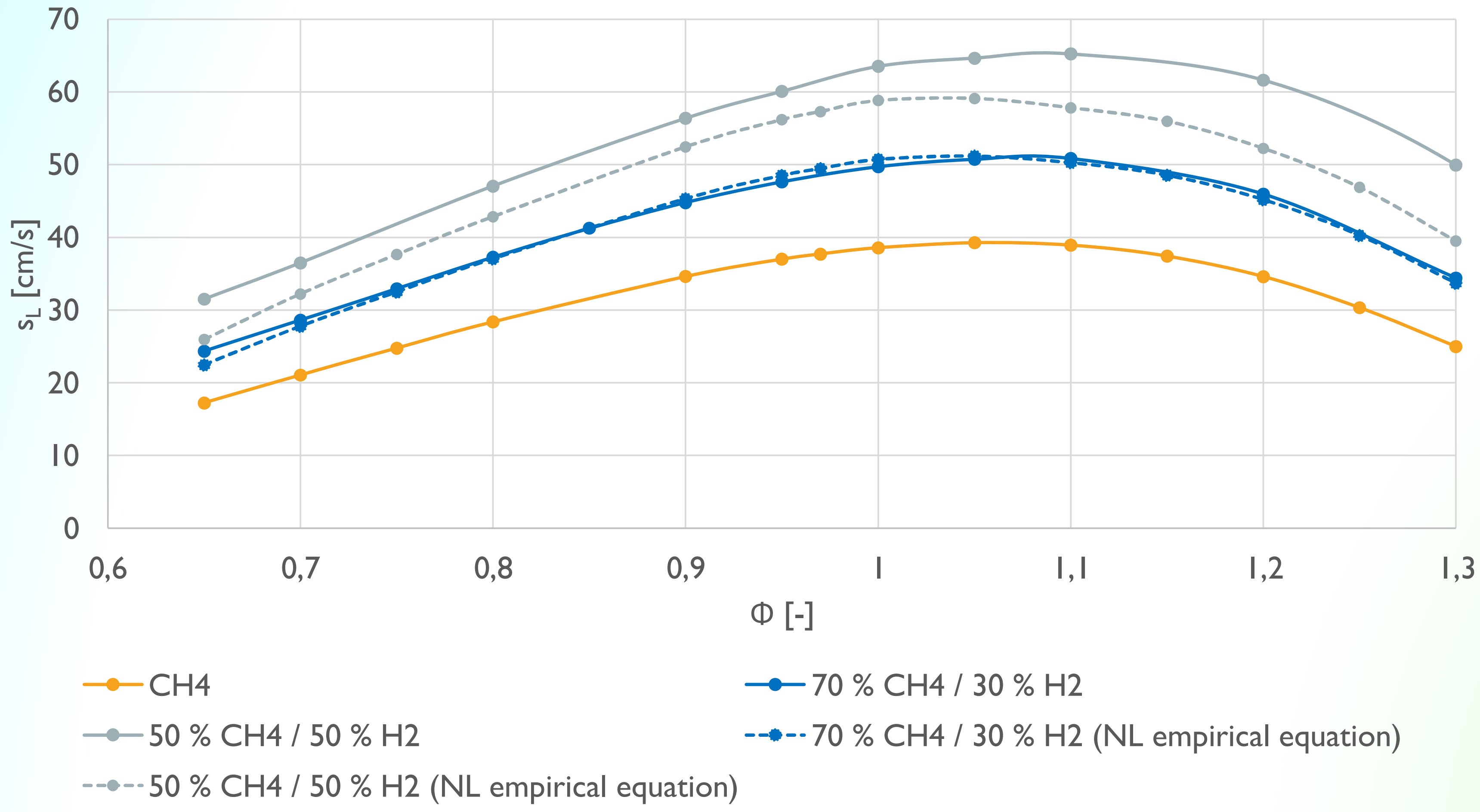
- To assess the impact of a fuel change on the temperatures, it is often useful to look at the **adiabatic combustion temperature** $T_{adiabatic}$.
- The adiabatic combustion temperature is the **theoretical maximum temperature** that can occur in a combustion process.
- It is assumed that the entire thermal energy that is released is used to heat the flue gas, i. e. there are **no heat losses**.
- $T_{adiabatic}$ is only dependent on the **compositions** of **fuel** and oxidizer, their temperatures, the system pressure and the **air excess ratio λ**.
- $\Delta T_{adiabatic} \approx 150$ °C

OTHER GAS QUALITY CRITERIA: LAMINAR COMBUSTION VELOCITIES



- The **laminar combustion velocity** s_L indicates how fast a flame front will propagate into a resting fuel-air mixture.
- It is therefore crucial for **flame stabilization**, especially for premixed burner systems.
- s_L is dependent on the **compositions** of **fuel** and oxidizer, their temperatures, the system pressure and the **air excess ratio λ**.
- s_L **cannot be easily calculated or measured.** The values in the diagram were calculated by simulating a freely propagating 1D premixed flame, using a reaction mechanism containing 53 species and 325 reactions.

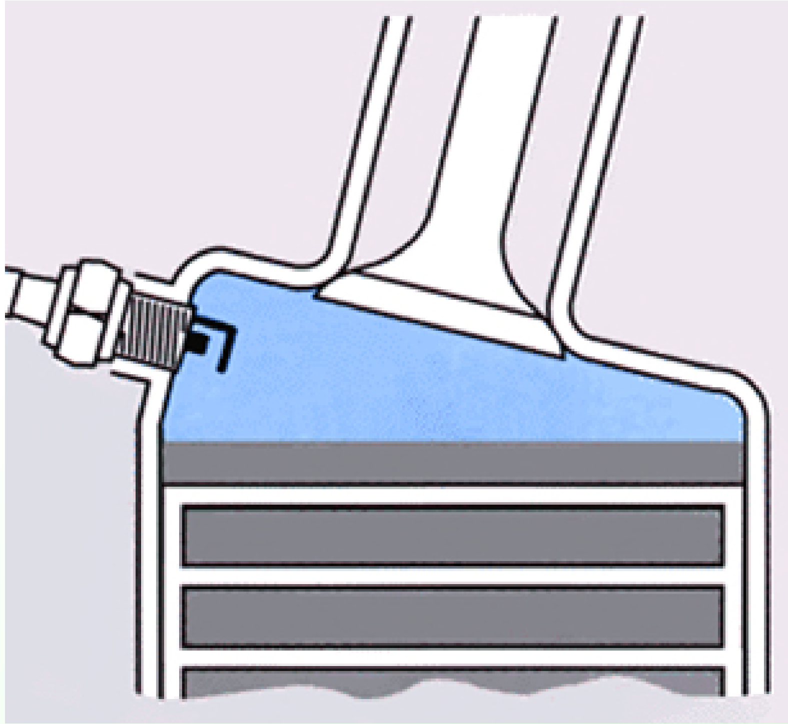
LAMINAR COMBUSTION VELOCITIES – EMPIRICAL APPROXIMATIONS



- Empirical **approximations** exist to estimate s_L of **natural gases** without detailed chemical kinetics simulations.
- They may include coefficients for hydrogen, but are usually **limited** in the amount of H_2 they can consider without producing serious discrepancies.
- The example in the diagram (taken from NTA 8837) achieves good agreement for H_2 concentrations of **up to 30 vol.-%**, but **underpredicts** s_L for higher H_2 levels.

OTHER GAS QUALITY CRITERIA: METHANE NUMBER

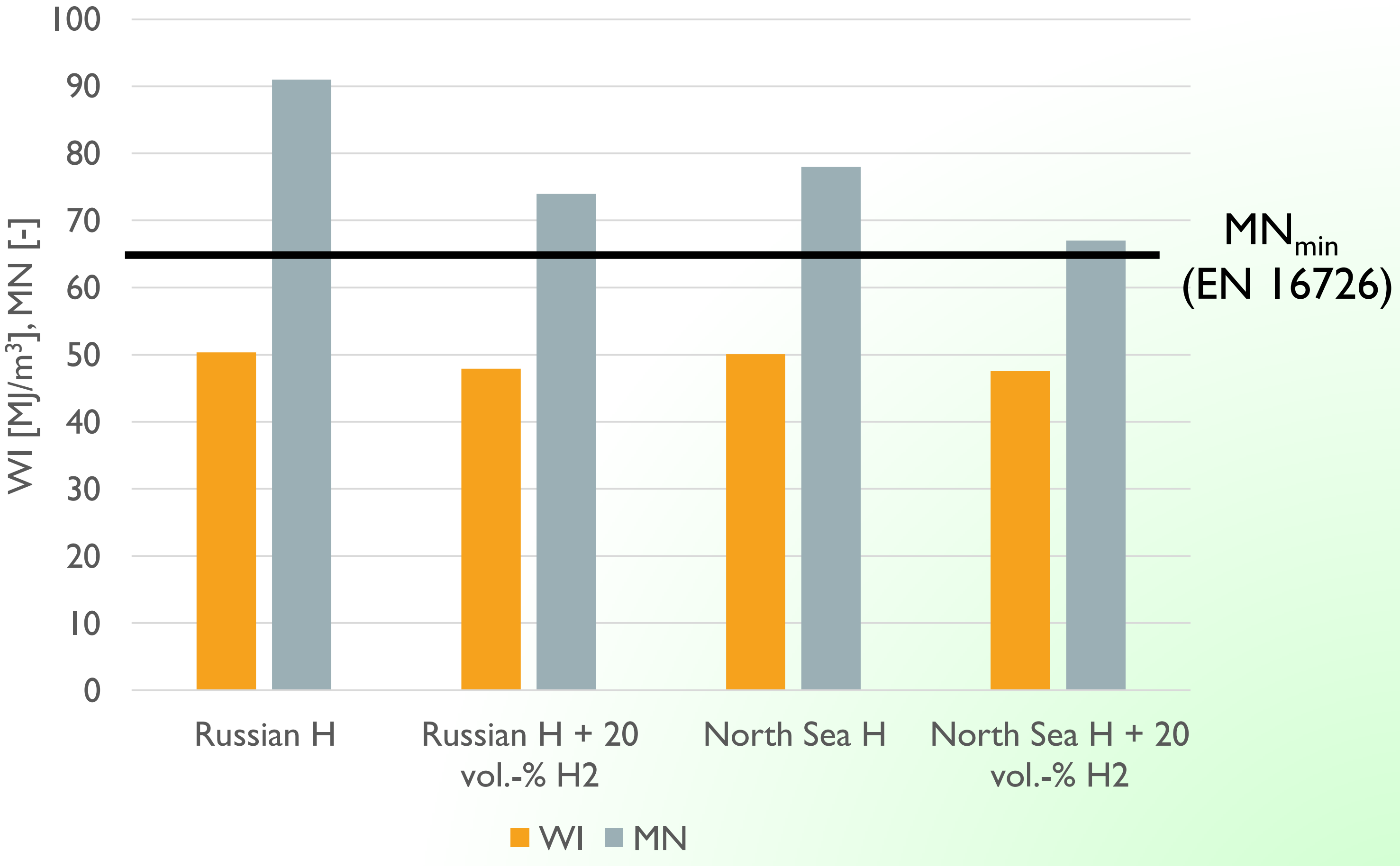
- For gas engines, the **Methane Number** (MN) is a crucial gas quality criterion. MN quantifies the propensity of a gaseous fuel for „knocking“, i. e. **the premature ignition in an Otto-cycle engine**. Knocking can cause uneven operation, efficiency loss, increased emissions and even damage.
- Knocking is a **complex phenomenon** that is not yet entirely understood. Similar to the Octane Number for gasoline engines, MN is an **empirically determined property**.
  The very knock-resistant CH_4 is set to a MN of 100. H_2 is very prone to knocking and is set to a MN of 0.
  Fuel gas composition has a significant impact on knocking propensity. **Higher hydrocarbons** increase the likelihood of knocking.
- A gaseous fuel with a MN of 80 shows the same knocking behavior (in a well-defined engine setup) as a blend of 80 vol.-% CH_4 / 20 vol.-% H_2.



Source: ARAL

OTHER GAS QUALITY CRITERIA: METHANE NUMBER

- The **actual composition** of the natural gas plays an important role for the MN of NG/H_2 blends.
- For example: Russian H-gas and North Sea H-gas have **almost identical Wobbe Indices**, but **very different MN** (due to the larger amount of higher hydrocarbons in North Sea gas).
- EN16726 prescribes a **minimum MN of 65**.



CH_4 VS. H_2: FUEL PROPERTIES OVERVIEW

	Unit	CH_4	H_2
density	[kg/m³]	0,678	0,085
relative density	[-]	0,556	0,070
NCV	[MJ/m³]	33,989	10,235
GCV	[MJ/m³]	37,713	12,097
GCV/NCV	[-]	1,110	1,182
(superior) WI	[MJ/m³]	50,547	45,737
MN	[-]	100	0
O_{2min}	[mol/mol]	2	0,5
Air_{min}	[mol/mol]	9,524	2,381
CARI	[mol/mol]	12,76	9,013
T_{ad} (λ=1)	°C	1946	2101
mass-based NCV	[MJ/kg]	50	120

	Unit	CH_4	H_2
s_L (λ = 1)	[cm/s]	38,57	209,84
$s_{L\,max}$	[cm/s]	39,27	296,26
λ @ $s_{L\,max}$	[-]	0,9523	0,556
Lower explosion limit (LEL)	[vol.-%]	5	4
Upper explosion limit (UEL)	[vol.-%]	15	75
λ_{LEL}	[-]	2	10
λ_{UEL}	[-]	0,595	0,14

15 °C/ 15 °C

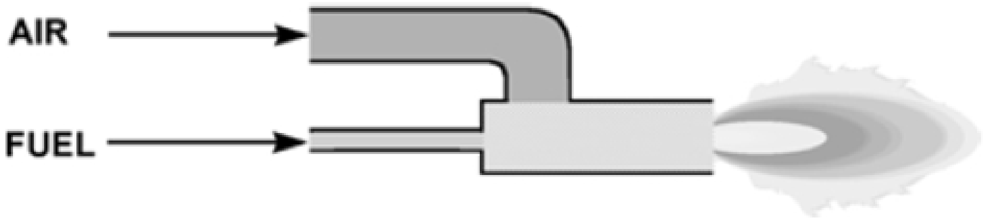
THE APPLIANCE SIDE

- How a combustion process responds to hydrogen admixture is not only dependent on the level of H_2, but also on the technology of the appliance itself. Different appliances will react differently.

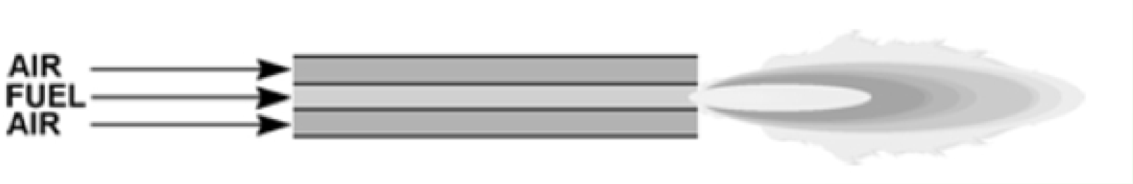
- Important aspects:
  - fully premixed systems vs. partially premixed systems vs. non-premixed systems
  - controlled vs. uncontrolled combustion systems
  - the initial adjustment of the appliance

FORMS OF COMBUSTION

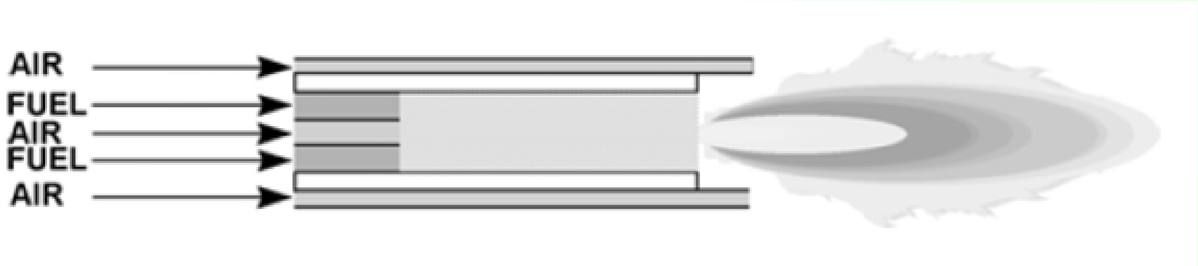
premixed combustion:



non-premixed combustion:

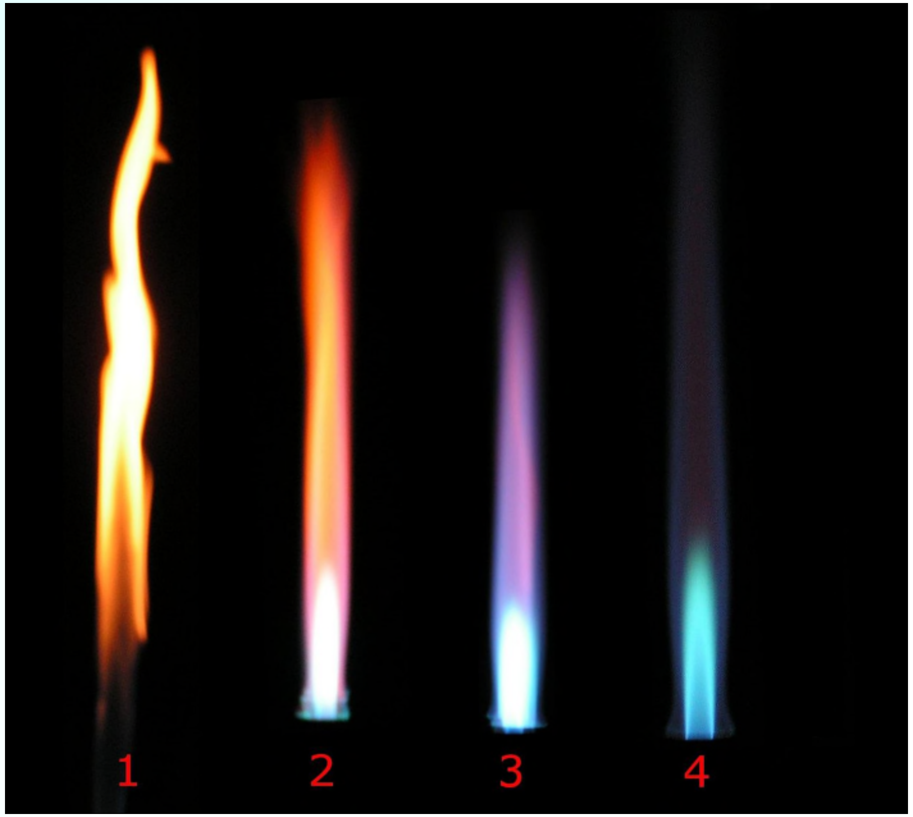


partially premixed combustion:



Images: C.E. Baukal Jr., Heat Transfer in Industrial Combustion, CRC Press, 2000

FORMS OF COMBUSTION

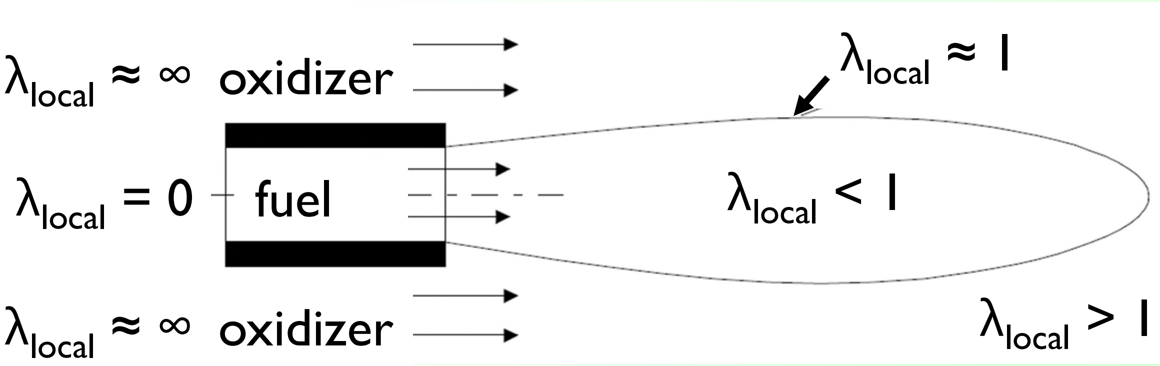


Source: Arthur Jan Fijałkowski / WikiCommons

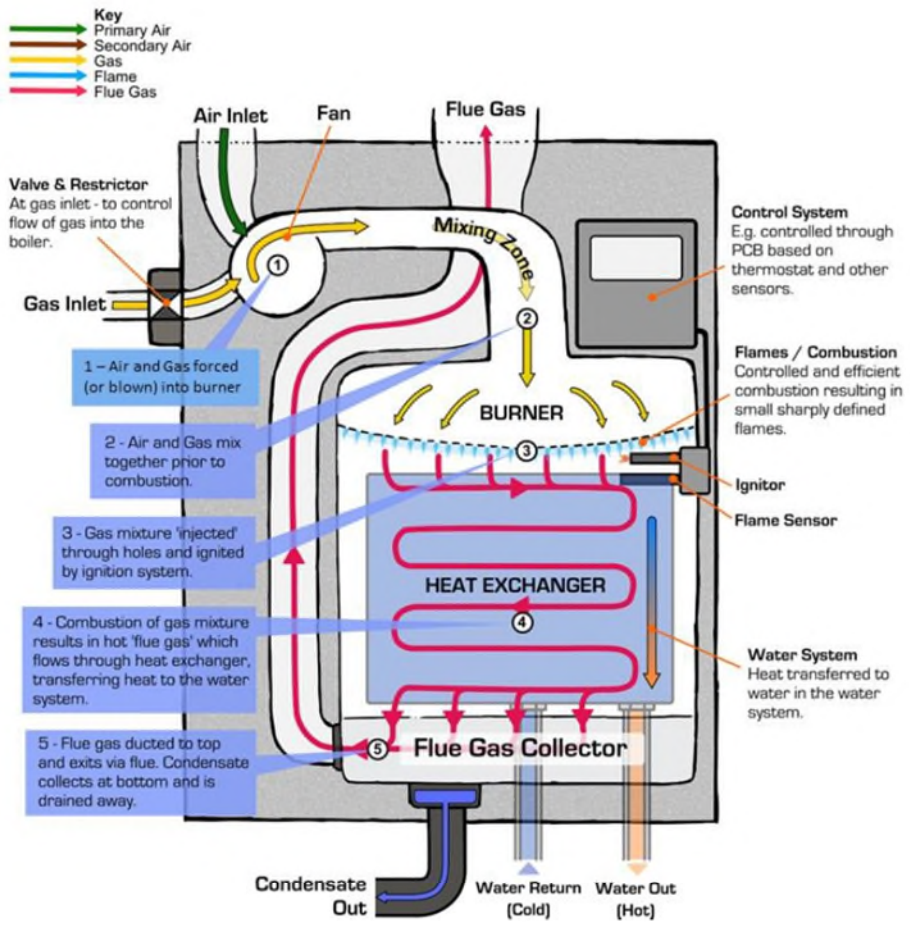
Non-premixed flame

premixed flame

- The form of combustion has a huge impact on the chemistry taking place in the flame, and hence flame shape, efficiency, pollutant emissions, ...



RESIDENTIAL HEATING – STOICHIOMETRY SHIFT



Source: Appraisal of Domestic Hydrogen Appliances, Frazer-Nash Consultancy, Glasgow, UK, 2018

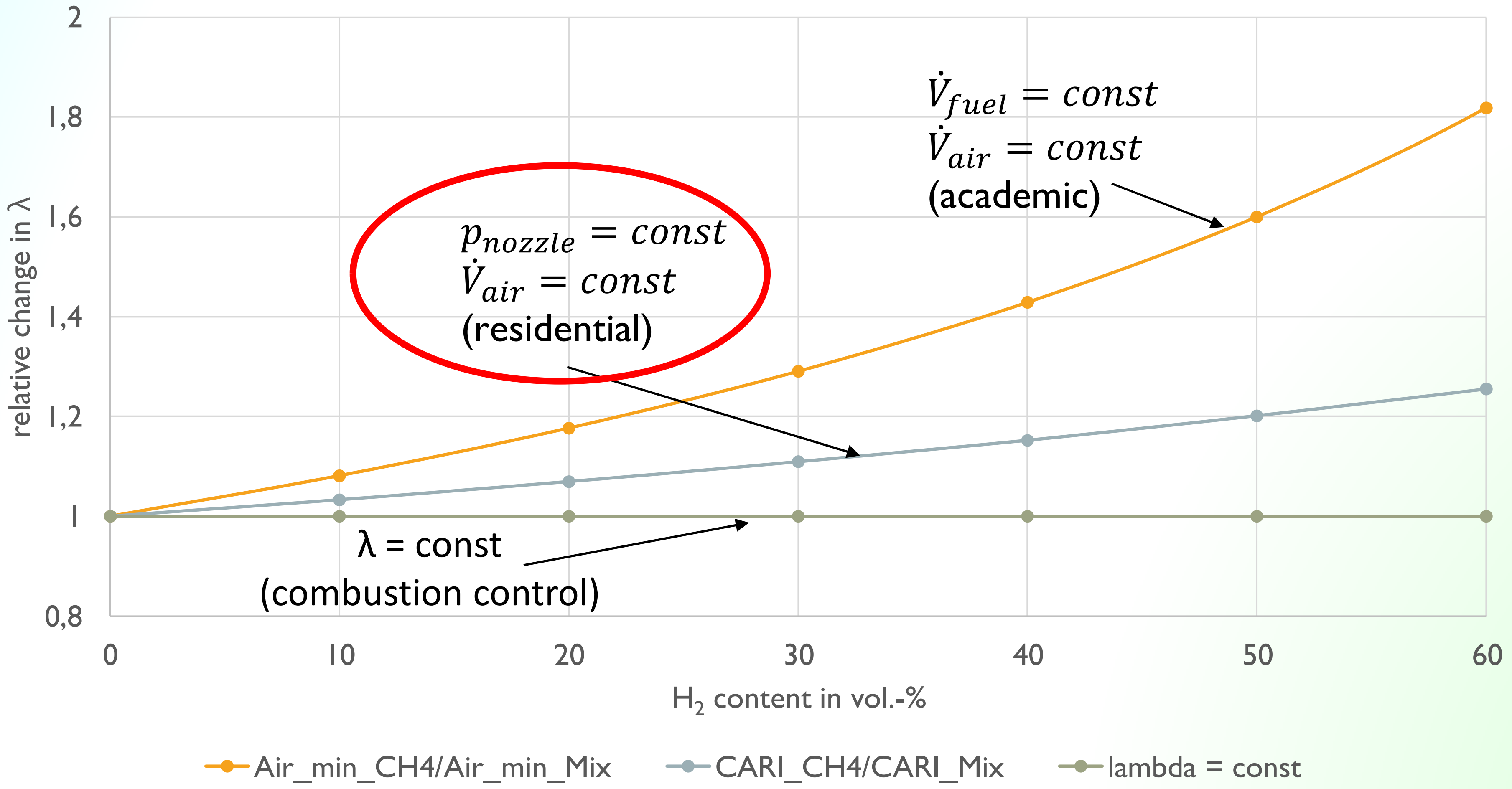
- Residential heating appliances generally use fully premixed burners and are designed to convey a certain amount of air (depending on fuel type and nominal firing rate). It can be assumed that nozzle pressure and diameter are constant.
- When switching to another fuel with a different minimum air requirement, the stoichiometry of the system may shift, assuming a **constant air flow**:

$$\frac{\lambda_2}{\lambda_1} = \frac{CARI_1}{CARI_2}.$$

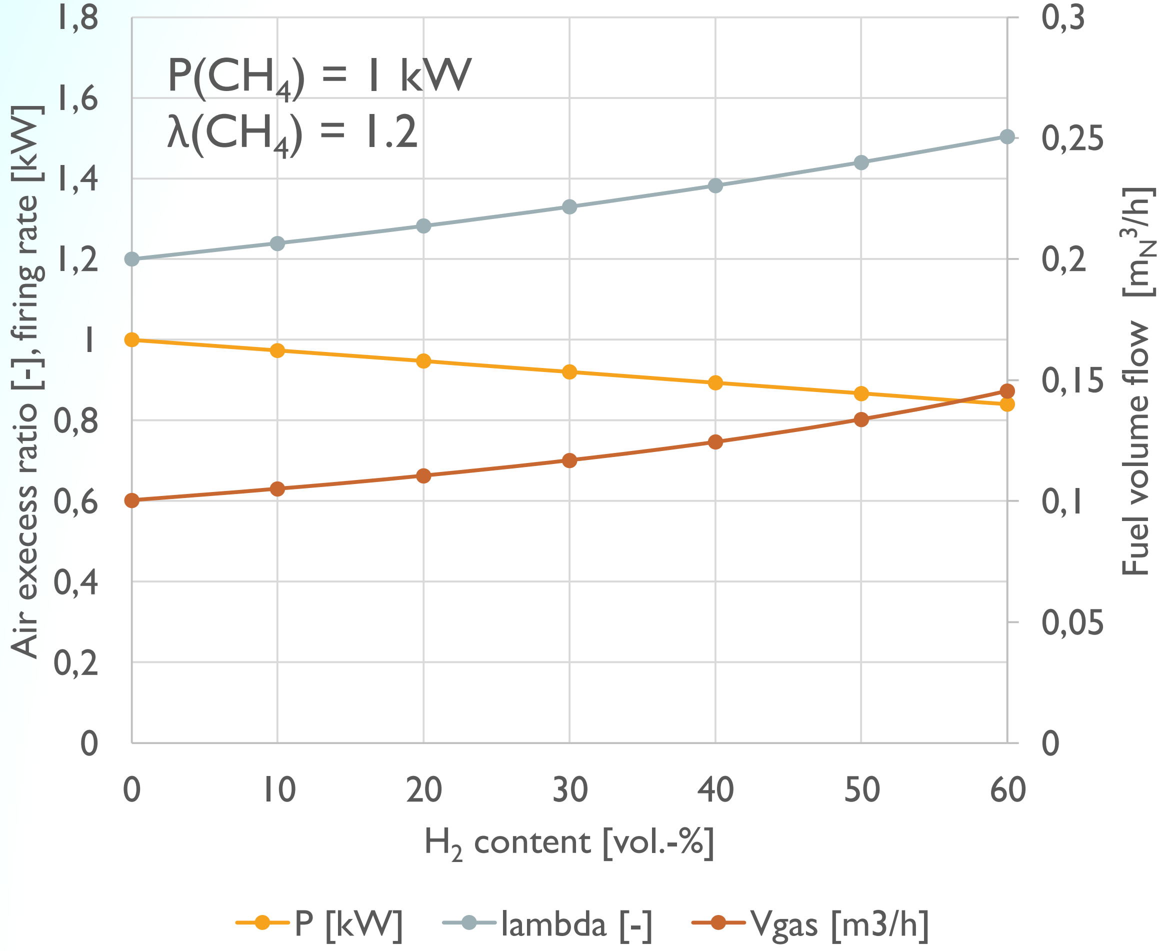
- In the case of an appliance **with combustion control**, the amount of air provided to the appliance can be changed to maintain a **constant air excess ratio** (depending on the fan):

$$\lambda_2 = \lambda_1$$

STOICHIOMETRY SHIFT



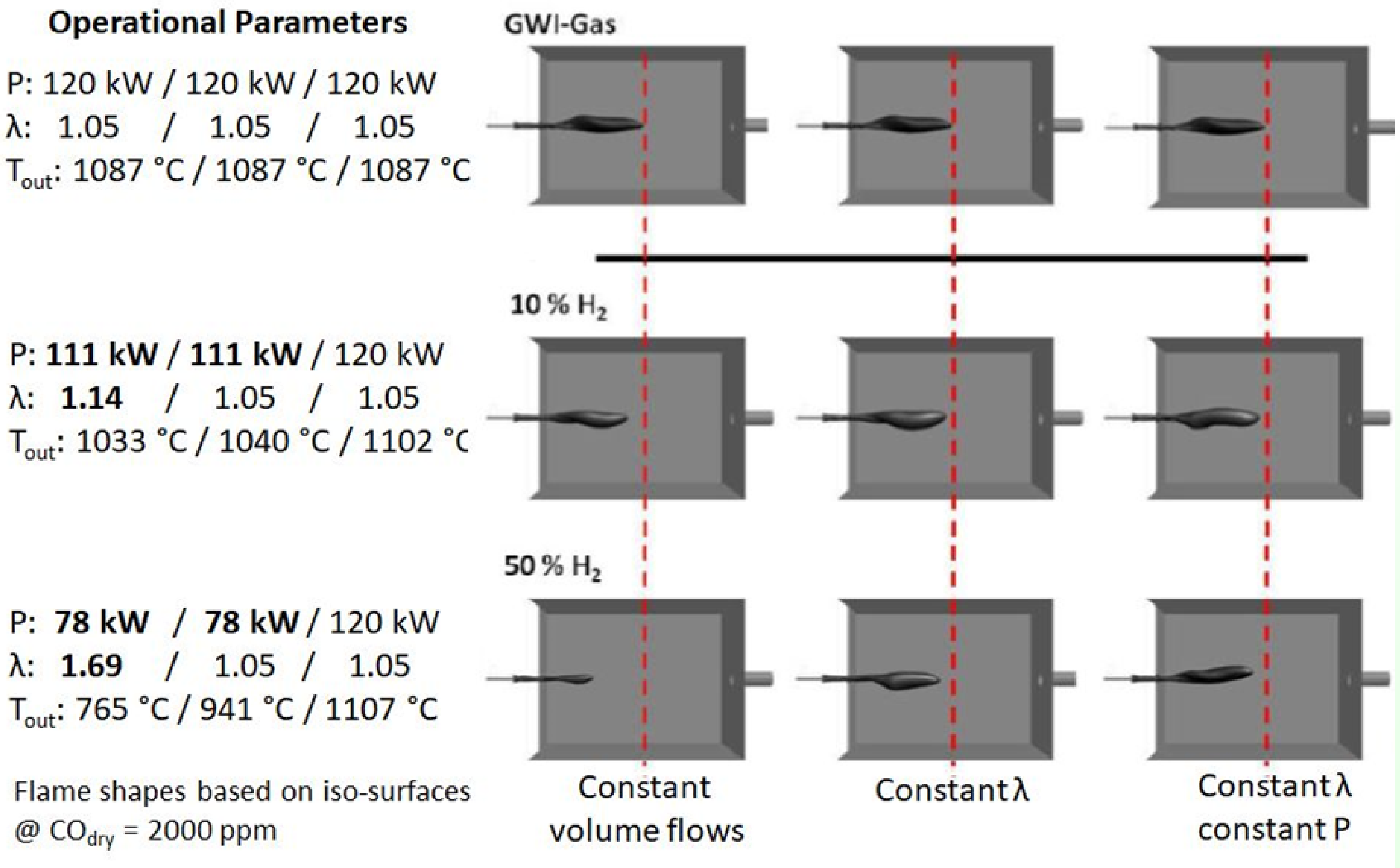
RESIDENTAL HEATING APPLIANCE – NO COMBUSTION CONTROL



- Firing rate: $\frac{P_2}{P_1} = \frac{W_{i,2}}{W_{i,1}}$
- Fuel volume flow: $\dot{V}_{Gas} = \frac{P}{H_i}$
- Air excess ratio: $\frac{\lambda_2}{\lambda_1} = \frac{CARI_1}{CARI_2}$

- In the case of H_2 admixture, the firing rate of the burner decreases with higher levels of H_2, while the fuel volume flow increases.
- At some point, the nozzle pressure will **not be high enough** to push sufficient amounts of fuel into the system, **no further increase** in fuel volume flow is possible then.

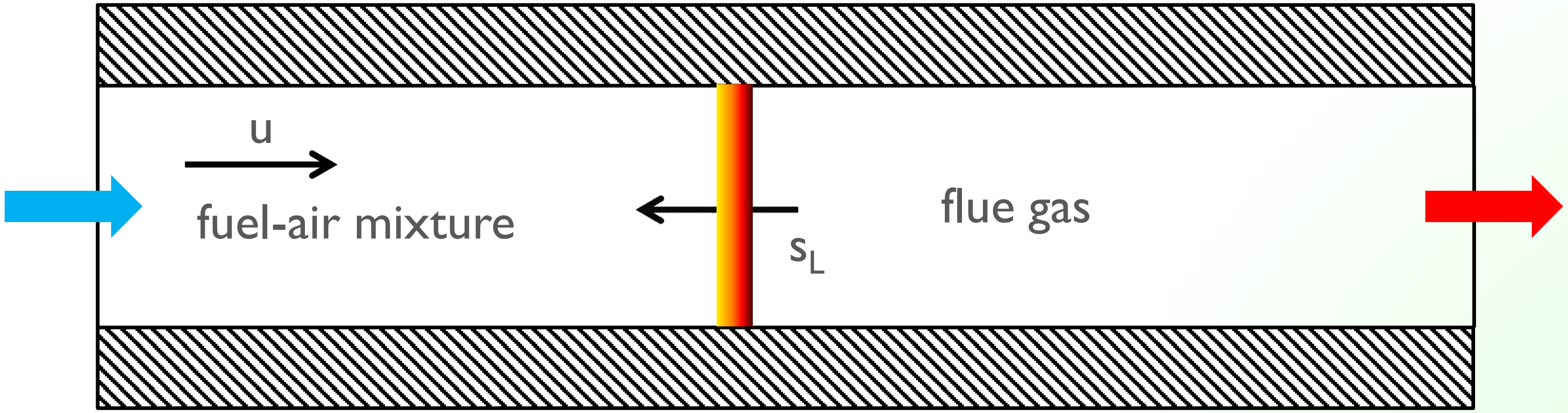
CFD STUDY: NON-PREMIXED INDUSTRIAL BURNER



Source: Leicher, J., Nowakowski, T., Giese, A., Görner, K., Hydrogen in natural gas: how does it impact industrial end users?, World Gas Conference 2018, Washington D.C., USA, 2018

LAMINAR COMBUSTION VELOCITIES AND FLAME STABILITY

- The combustion velocity is crucial for flame stabilization and phenomena like flash-backs or blow-outs. This is particularly relevant for premixed burner systems. As flows in residential appliances are usually **laminar**, only the **laminar combustion velocity** is considered here. For turbulent combustion systems, the physics is similar, but the **turbulent combustion velocity s_T** has to be considered.

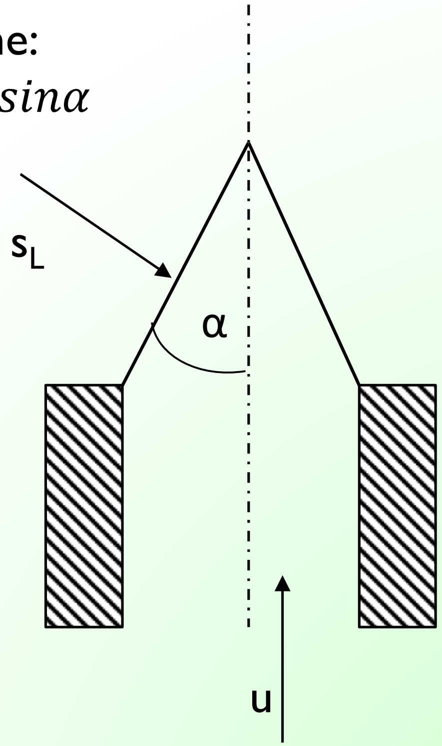


- A flame will **stabilize** where there is a **balance ($s_L = u$)** between the flow velocity u and the (laminar) combustion velocity s_L.
- **If $u < s_L$** the flame will move upstream, potentially leading to a **flash-back**.
  If **$u > s_L$**, the flame will move downstream, causing a **blow-out**.

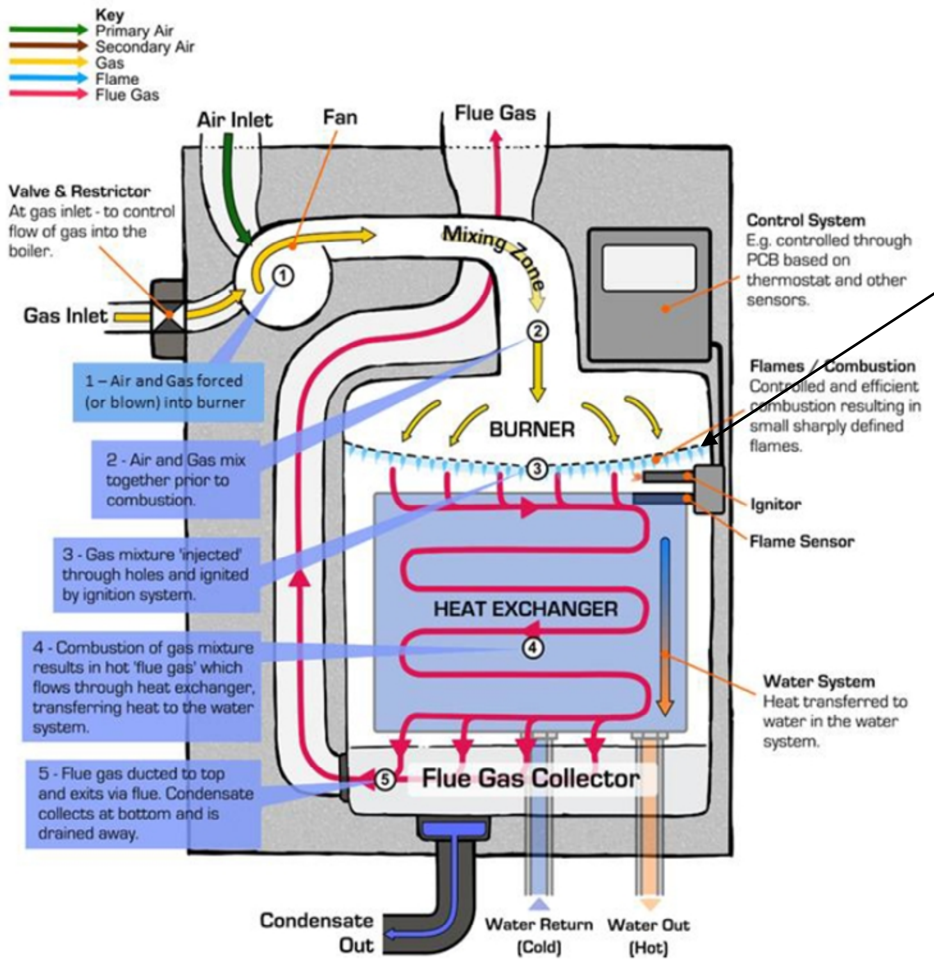
FLAME STABILIZATION

Source: www.firesciencetools.com

Stable flame:
$|u| = |s_L| \cdot sin\alpha$

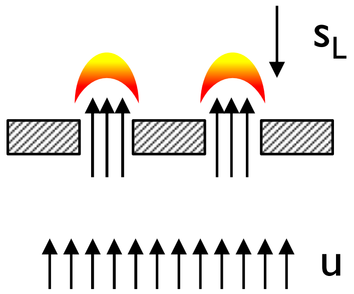


FLAME STABILIZATION

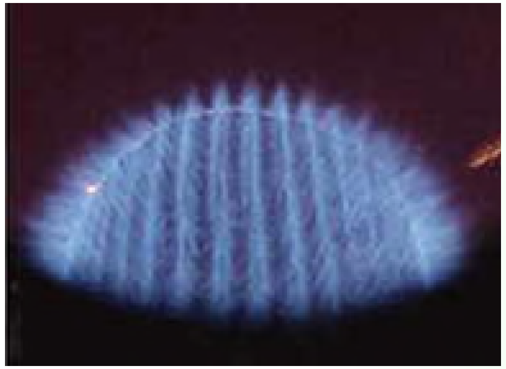


Quelle: Appraisal of Domestic Hydrogen Appliances, Frazer-Nash Consultancy, Glasgow, UK, 2018

Flame holder



fuel-air mixture



Source: Riello

- Flameholders are designed with typical laminar combustion velocities (s_L) and flow speeds (u) in mind.
- $s_L = f(\lambda, T, X_{i,fuel})$
- $u = f(\lambda, X_{i,\,fuel}, \textbf{load})$

IMPACT ON A HEATING APPLIANCE (**NO** COMBUSTION CONTROL)

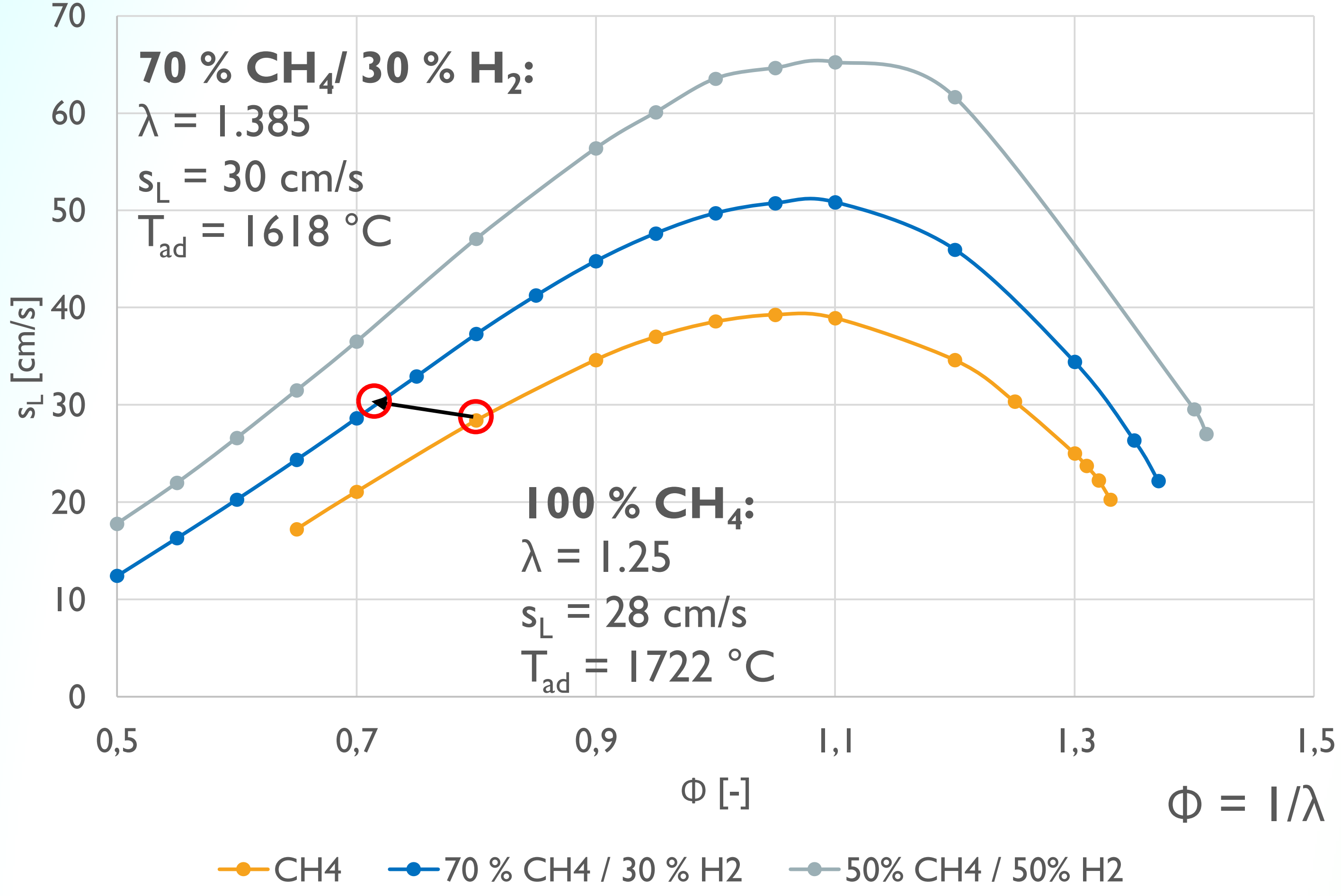
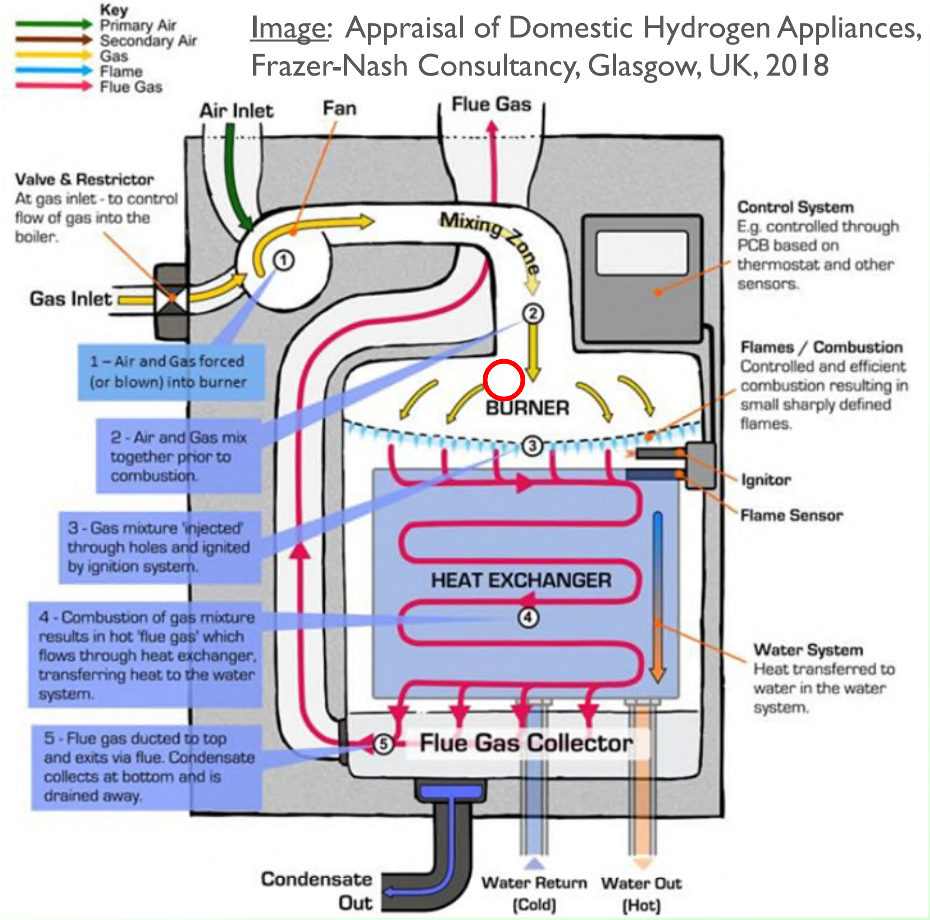
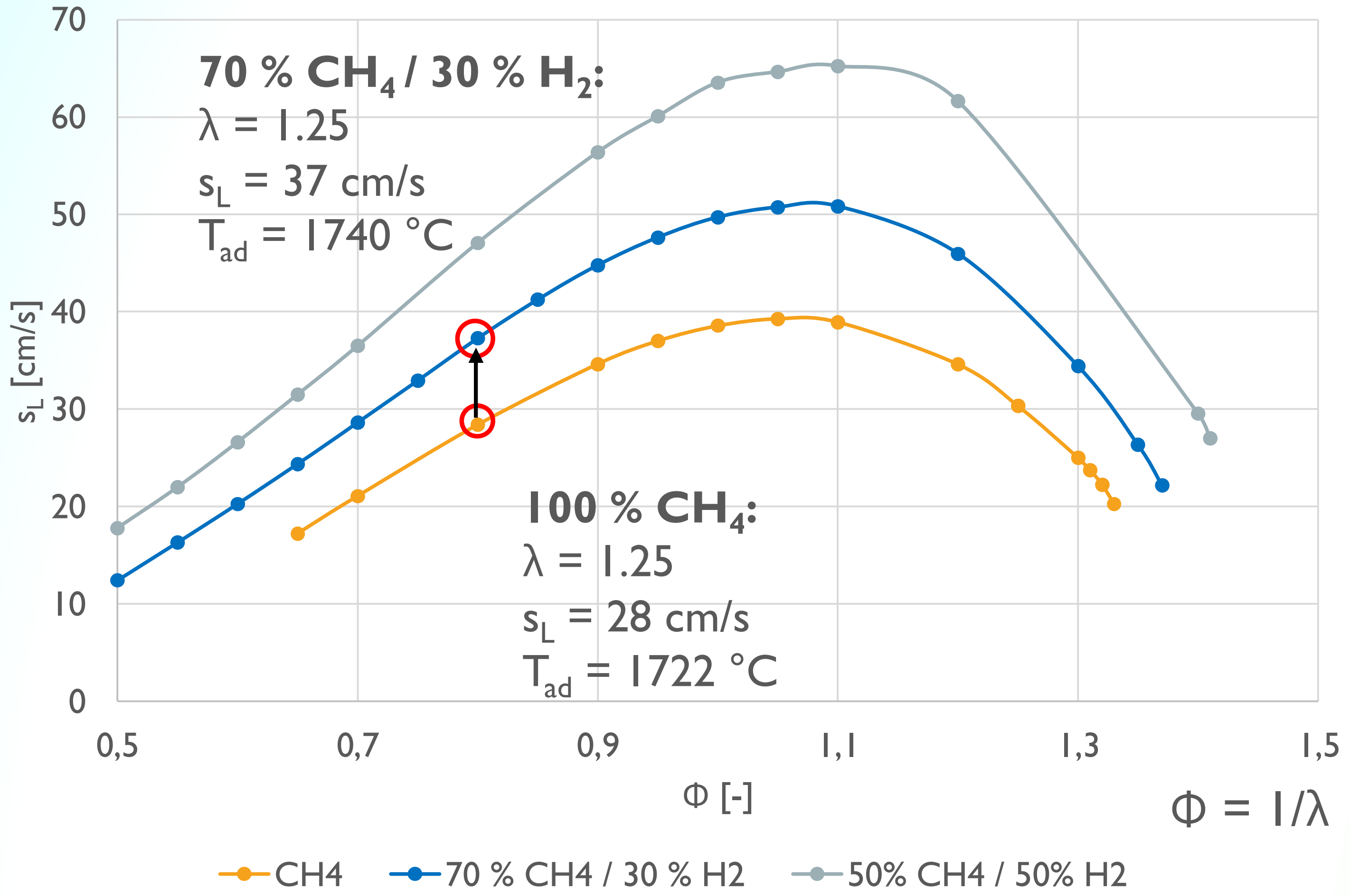


Image: Appraisal of Domestic Hydrogen Appliances, Frazer-Nash Consultancy, Glasgow, UK, 2018



IMPACT ON A HEATING APPLIANCE (**WITH** COMBUSTION CONTROL)



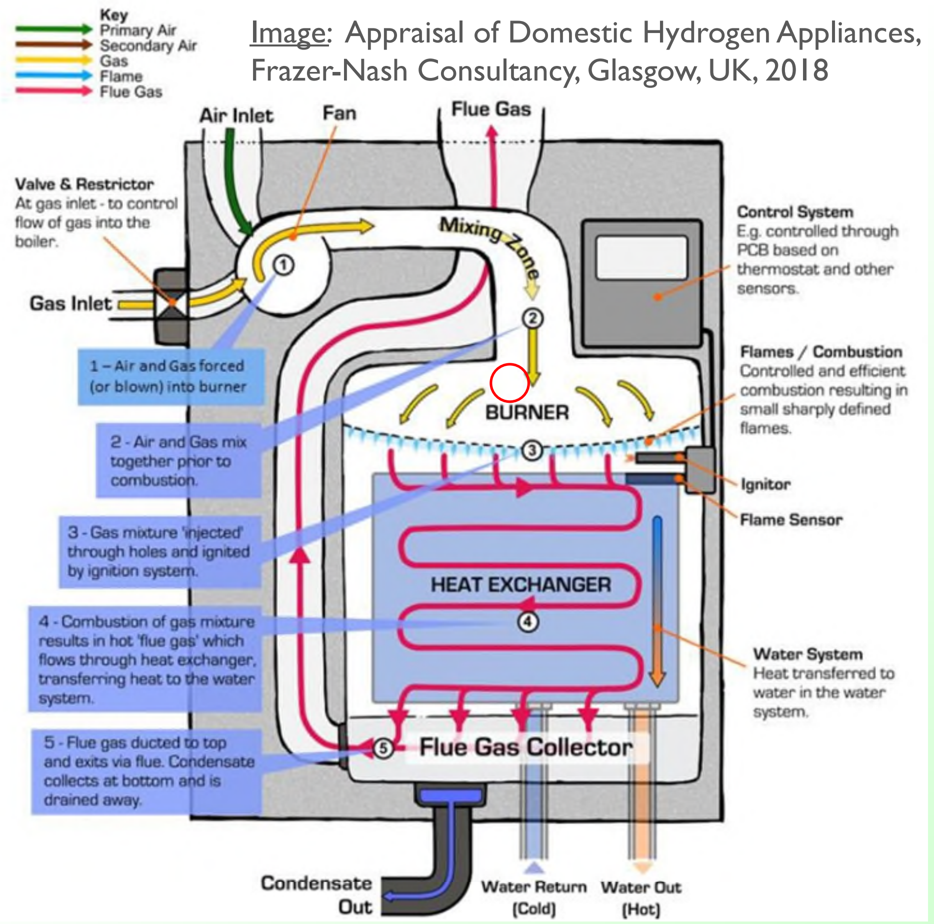
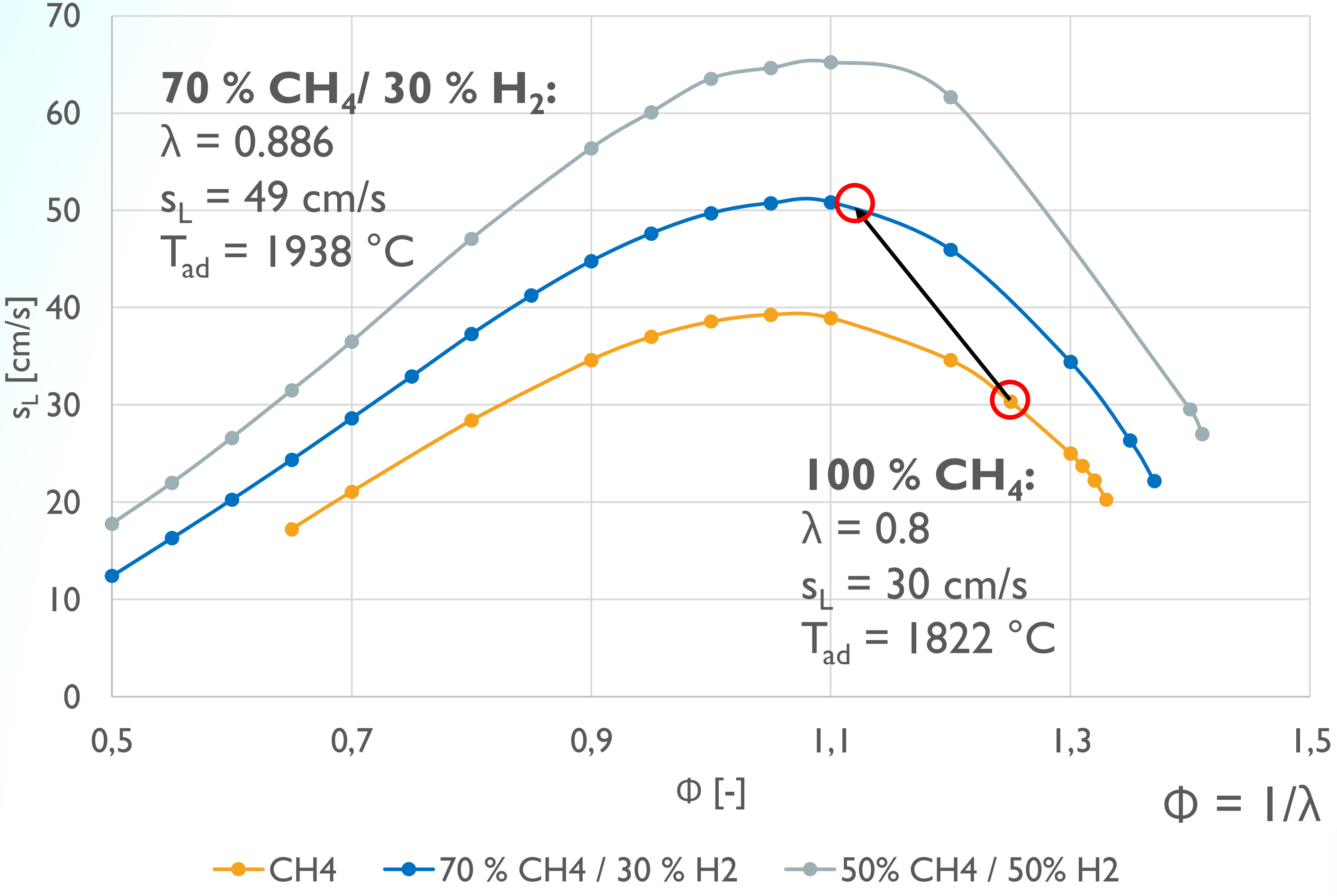


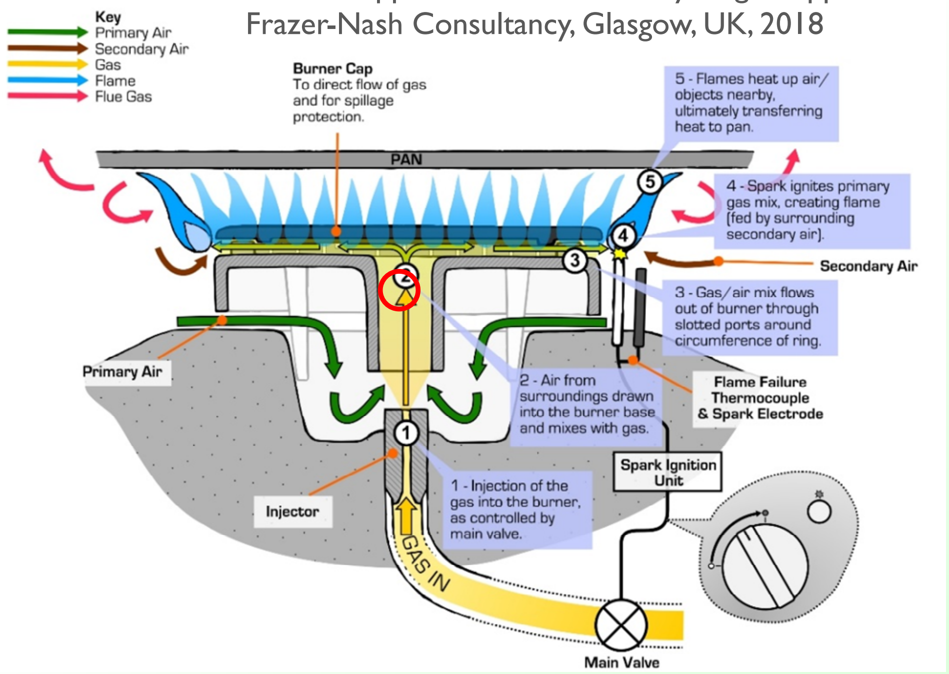
Image: Appraisal of Domestic Hydrogen Appliances, Frazer-Nash Consultancy, Glasgow, UK, 2018

IMPACT ON A PARTIALLY PREMIXED COOKING HOB

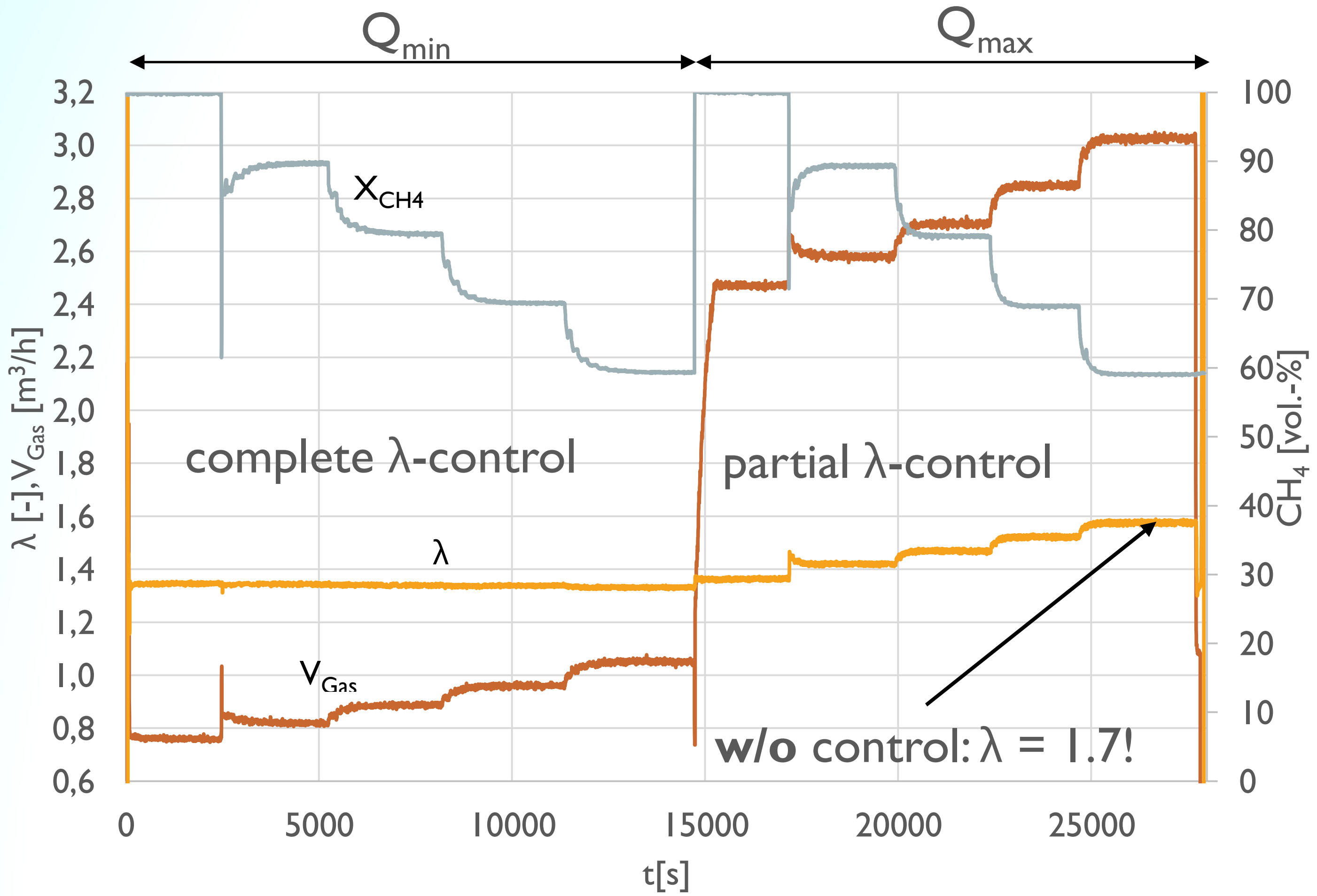


$\Phi = 1/\lambda$

Source: Appraisal of Domestic Hydrogen Appliances, Frazer-Nash Consultancy, Glasgow, UK, 2018



COMBUSTION CONTROL IN A HEATING APPLIANCE



- Combustion control systems are usually designed with certain fuel types in mind.
- If the fuel **changes too drastically**, they may respond in unexpected ways.
- These measurements show results for an appliance with combustion control, based on **flame ionization measurement**.
- It can be seen that the appliance manages to maintain a constant λ with varying levels of hydrogen at minimum load (Q_{min}), but **fails to do so** at maximum load (Q_{max}).

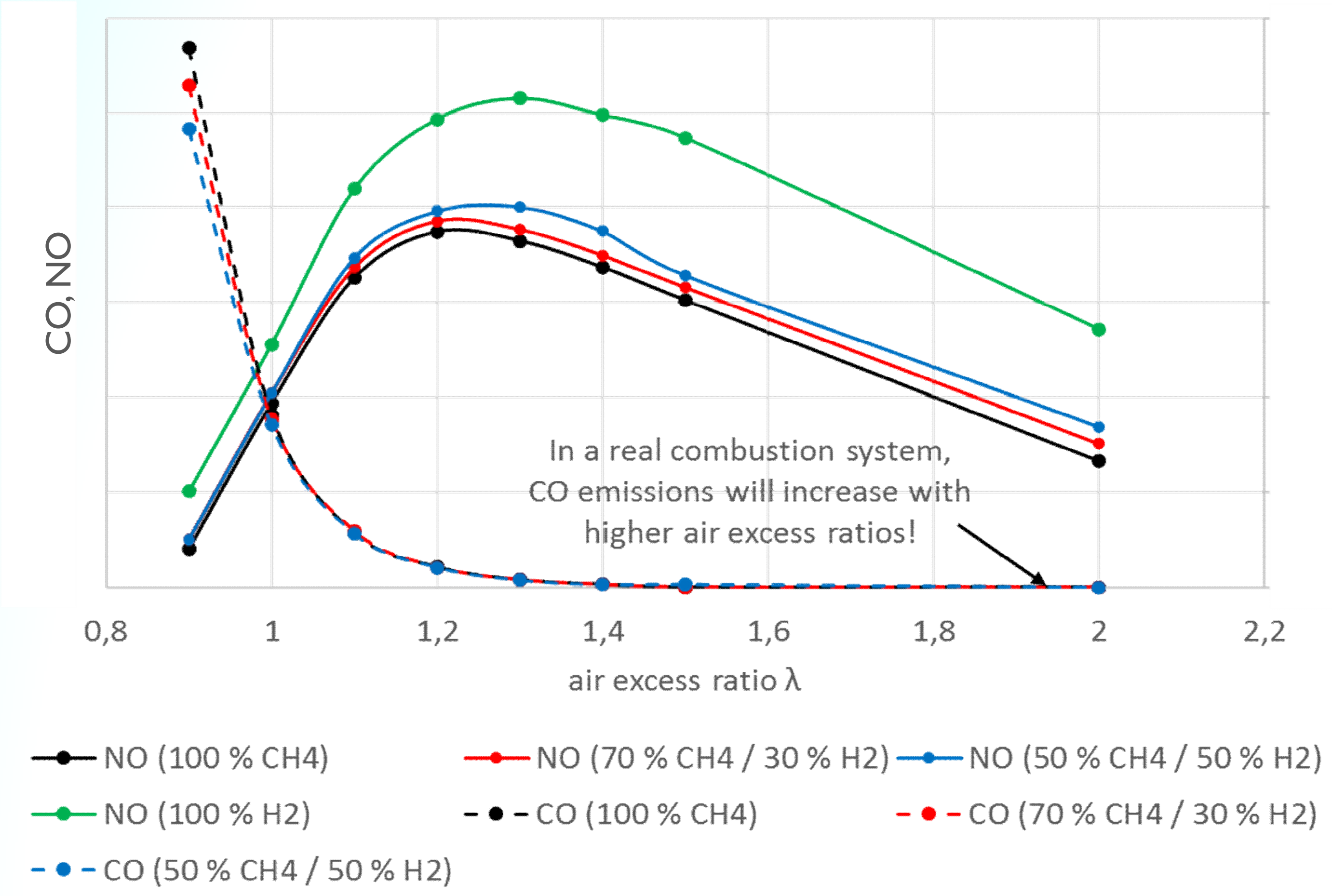
IMPACT OF H_2 ADMIXTURE ON FLAME STABILITY

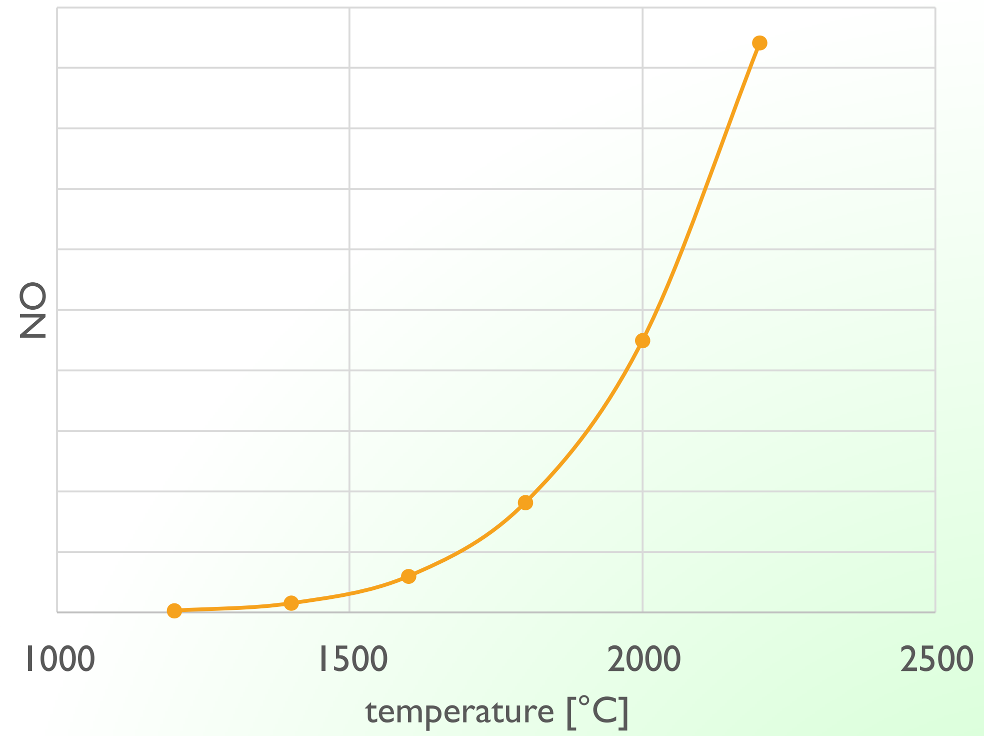
- Flame stability in residential combustion systems is not only dependent on the fuel gas composition (s_L), but also the appliance itself, its point of operation and the presence of a combustion control system.
- H_2 admixture generally leads to an **increase of the laminar combustion velocity**, but in **super-stoichiometric premixed** combustion systems **without combustion control**, this increase is **largely compensated** by the higher air excess ratio.
- In **partially premixed systems** where the primary zone is **sub-stoichiometric**, there is an overall **increase of s_L** as the effects of both H_2 admixture and stoichiometry shift add up, leading to an **increased risk of flash-backs**. This can be a concern for cooking hobs or other appliances with primary and secondary air intakes.
- In systems **with combustion air control** (or non-premixed systems), H_2 admixture will likely lead to higher laminar combustion velocities, **if the air excess ratio is kept constant**.
- There is also the question **how** the change in stoichiometry is **actually detected** in systems with combustion control. Systems based on ionization current may be more problematic here than systems based on O_2 measurements in the flue gas.

POLLUTANTS

- For the combustion of natural gas, the main pollutant species to be considered are **CO** and **NO_X**.
- CO_2 is usually **not considered a pollutant** as the formation of CO_2 is inevitable in the combustion of carbonaceous fuels. CO and NO_X formation, however, can be minimized by primary or secondary measures.
- **Carbon monoxide** (CO) is the result of an **incomplete carbon oxidization**, either due to a general lack of oxygen ($\lambda_{global} < 1$), poor mixing of fuel and oxidizer ($\lambda_{local} < 1$) or flame instabilities and excessive heat loss.
- **Nitrogen oxides** (NO_X) in gas combustion are usually formed via the **thermal NO_X** formation pathway, **primarily as NO**. Thermal NO_X formation is dependent on
    - local **temperatures** ($T_{local} > 1200$ °C)
    - local availability of **oxygen**
    - **residence times** in the hot zones
    - pressure (not relevant for residential appliances except maybe for ICE or MGT)

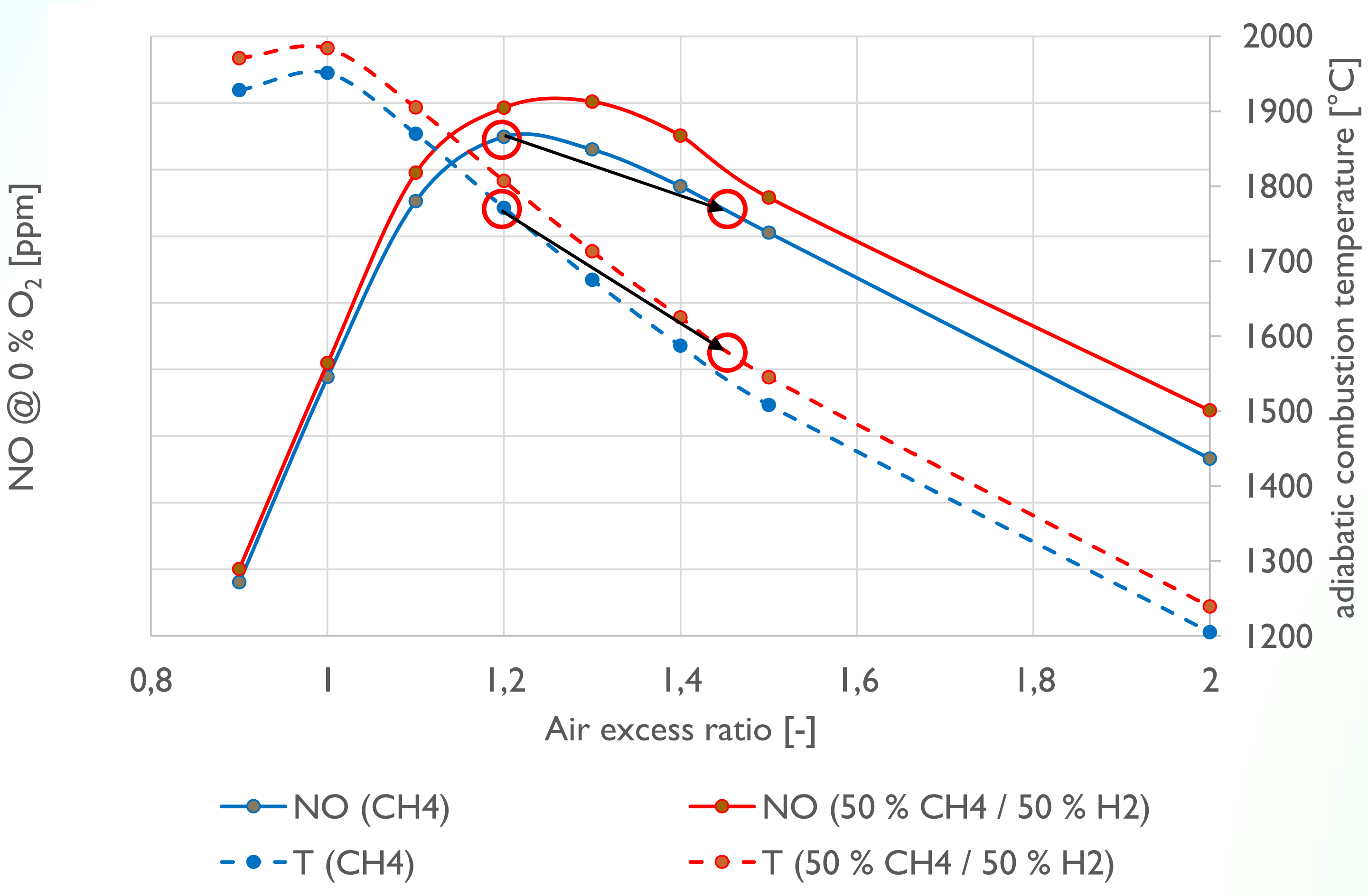
CO & NO VS. AIR EXCESS RATIO, H_2 & TEMPERATURE





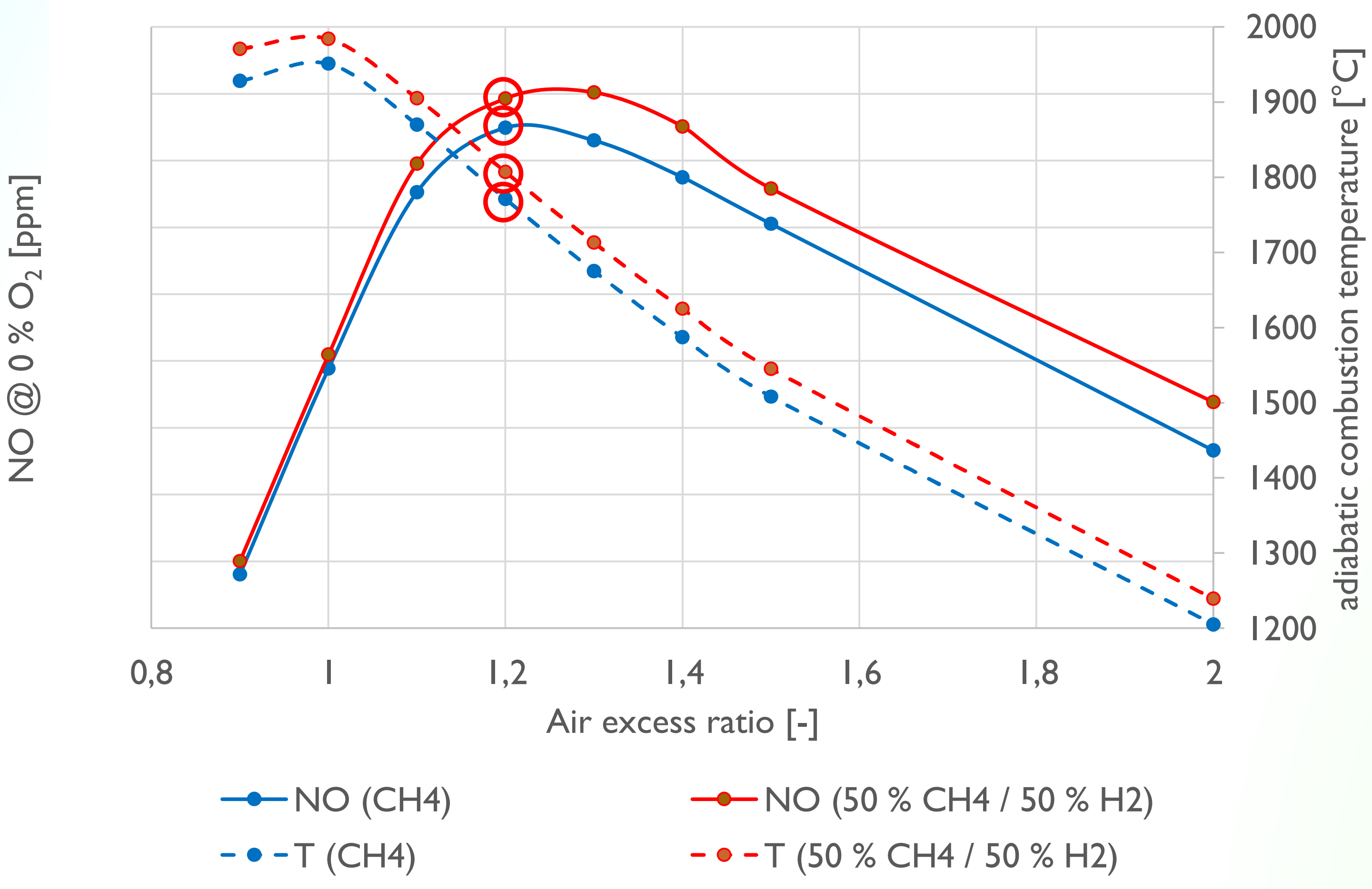
Calculations based adiabatic chemical equilibrium.

NO AND HYDROGEN ADMIXTURE (**NO** COMBUSTION CONTROL)



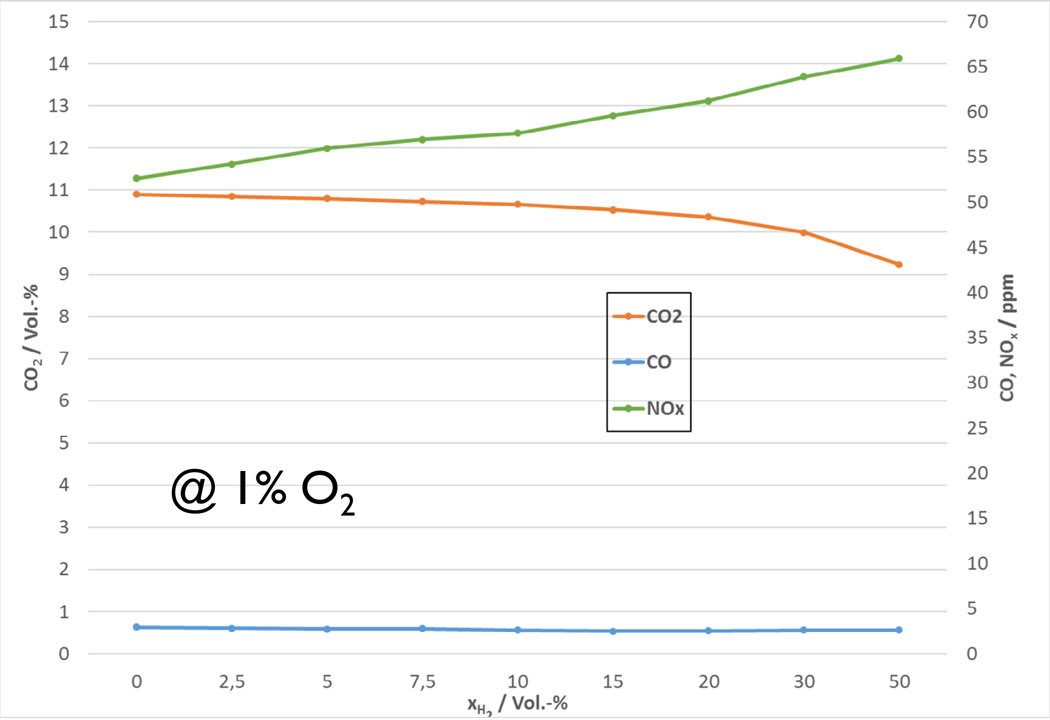
- In a premixed system **w/o combustion control**, there are **two competing phenomena**:
  - H_2 admixture leads to higher combustion temperatures and hence higher NO emissions
  - the stoichiometry shift towards higher air excess ratios reduces the temperature, and hence NO formation.
- If the initial air excess ratio is relatively high (> 1.2), the **net effect** is a decrease of NO concentrations in the flue gas.

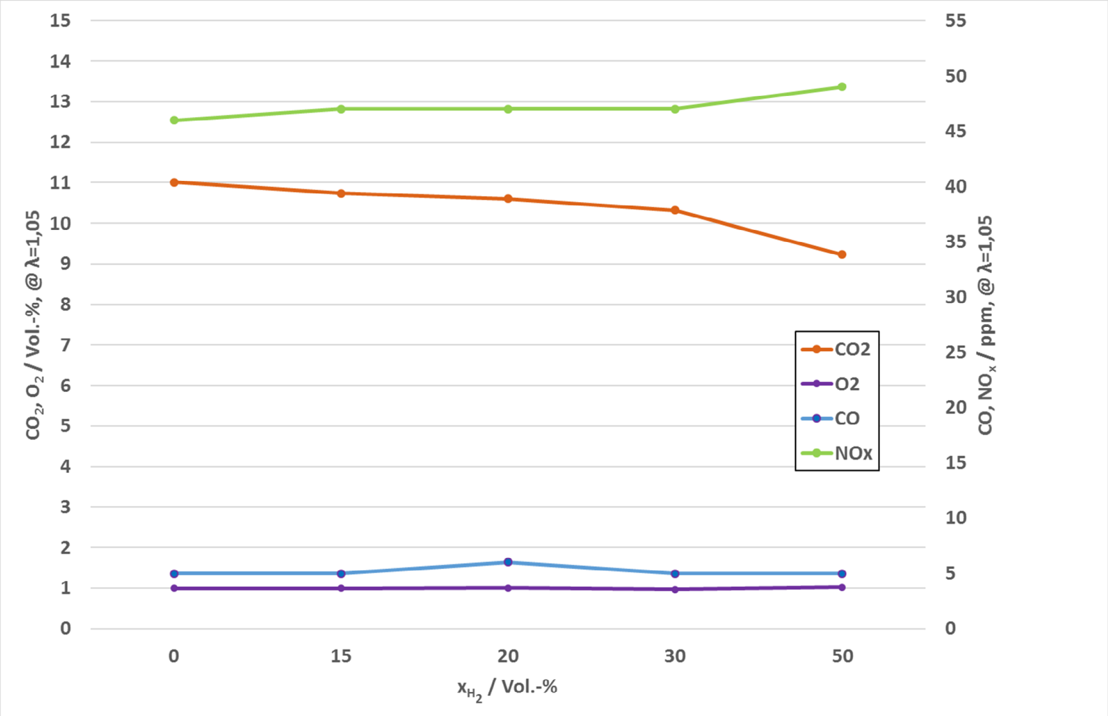
NO AND HYDROGEN ADMIXTURE (**WITH** COMBUSTION CONTROL)



- In systems with combustion control, a constant λ is enforced.
- Admixing H_2 will lead to higher temperatures in the reaction zone, and thus higher NO emissions.
- Non-premixed burners behave similarly (shown by experiments with industrial burners).
- **Other factors can interfere** with these trends. For example, increased heat loss (=> lower flame temperatures) due to the flame moving closer to the burner, can cause NO_X emissions to decrease, **despite constant λ**.

NO_X MEASUREMENTS FOR A NON-PREMIXED INDUSTRIAL BURNER (100 KW)





Scenario I:

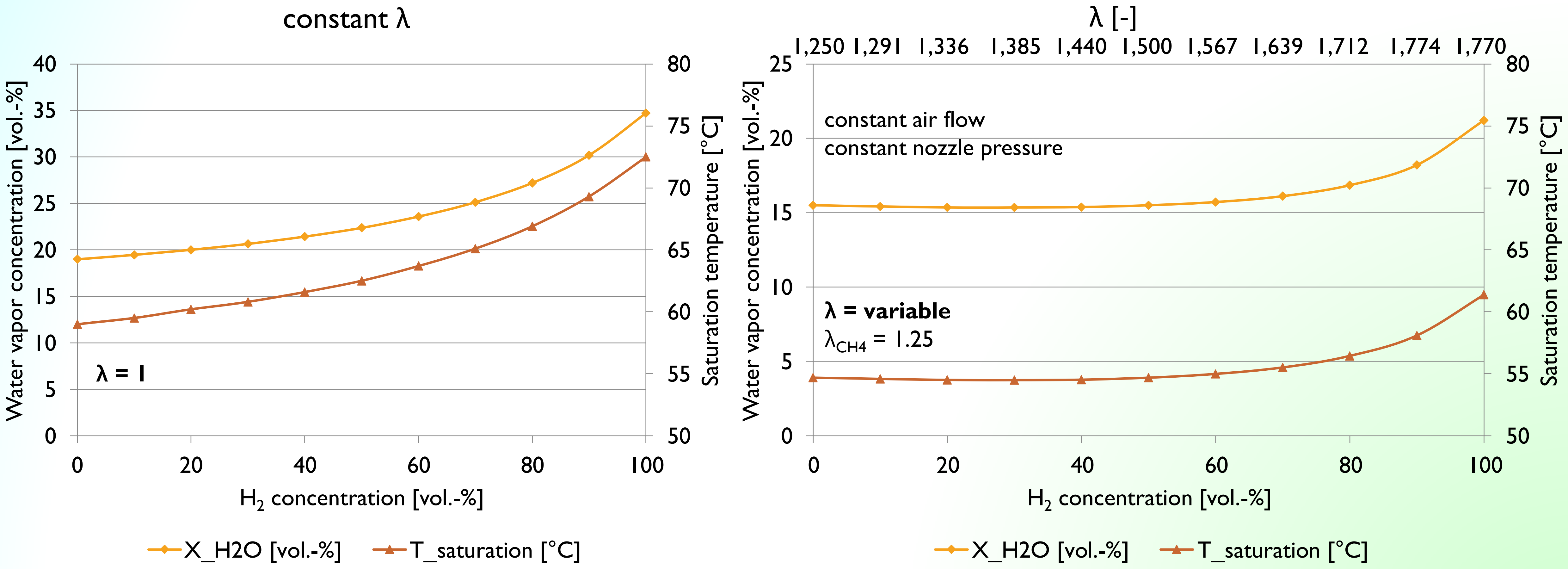
no control intervention at all, i. e. **volume flows** of **both fuel** and **air** remain **constant** (worst case).

Scenario III:

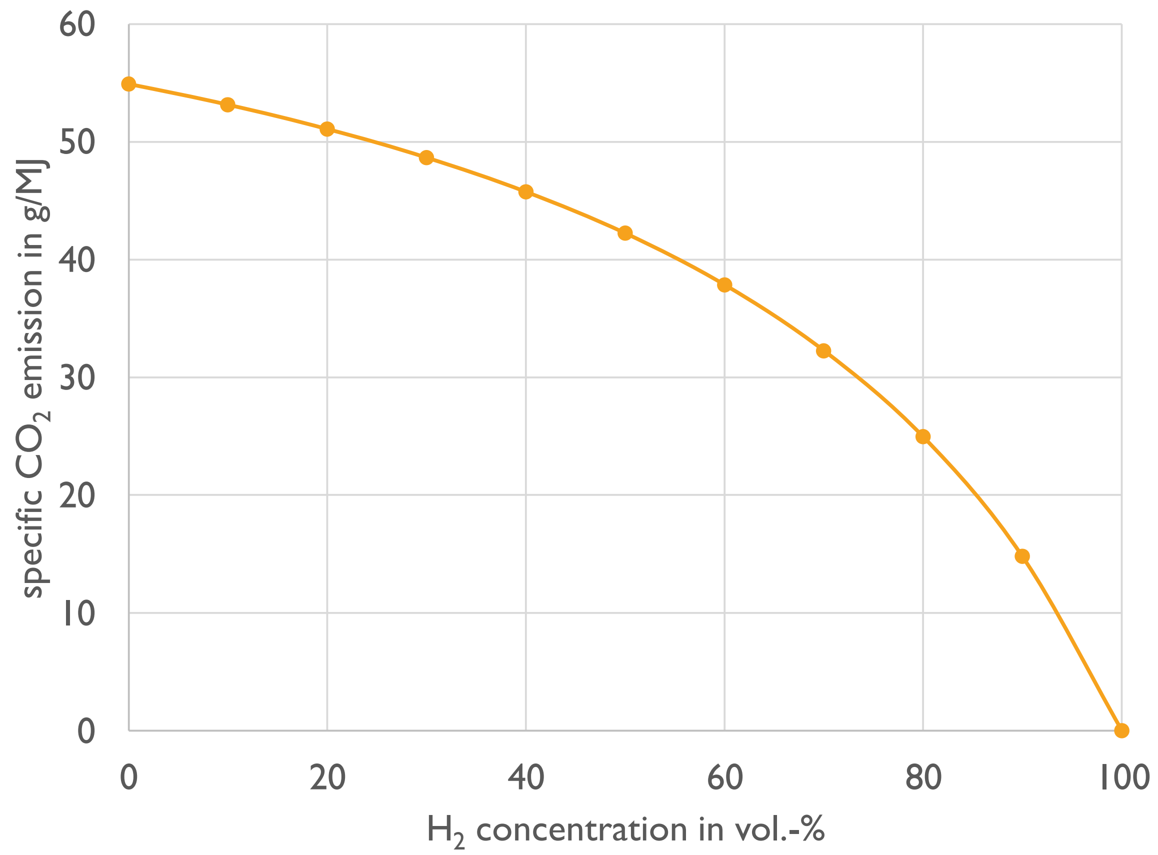
both burner firing rate and **air excess ratio** remain **constant**, based on advanced gas quality monitoring (best case).

Source: Leicher, J., Nowakowski, T., Giese, A., Görner, K., Hydrogen in natural gas: how does it impact industrial end users?, World Gas Conference 2018, Washington D.C., USA, 2018

CONDENSATION



CO_2 REDUCTION

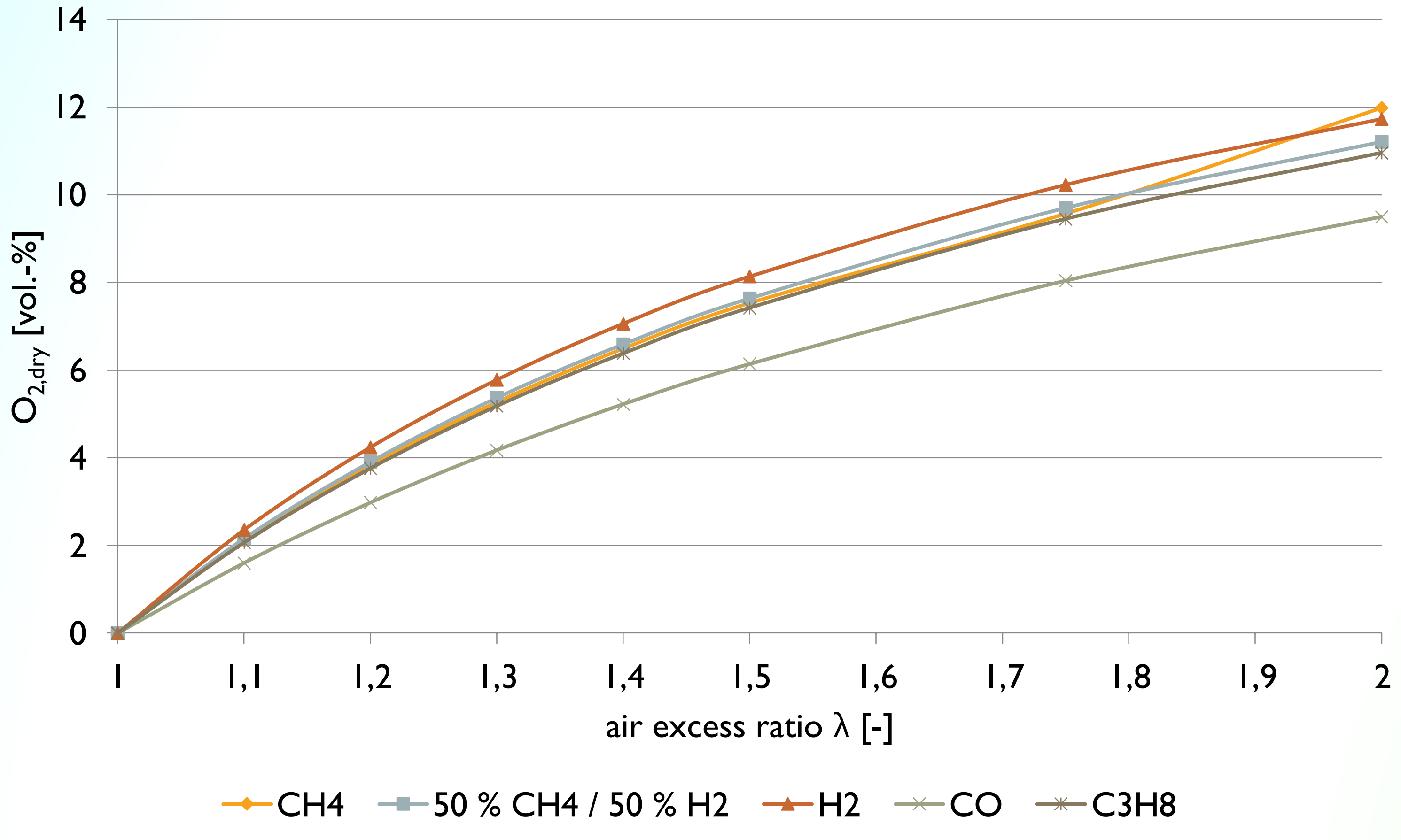


- The CO_2 reduction potential of hydrogen admixture (**per appliance**) in terms of combustion-related emissions is rather limited.
- **However:** if H_2 is injected into the gas grid in significant quantities, the **total CO_2 reduction** can be substantial, given the large amounts of natural gas being used in the EU.
  This is especially relevant if no or only minor changes are necessary to end-use equipment if H_2 is fed into the grid.
- The diagram only shows **direct CO_2 emissions** from the combustion of CH_4/H_2 blends. **Indirect CO_2 emissions** related to the production of H_2 are **not considered** here.

CONCLUSION

- From a combustion point-of-view, natural gas / methane and hydrogen are **very different fuels**. Therefore, blending natural gas with hydrogen will induce significant changes in the combustion characteristics of the fuel blend. The main differences are the reduced **densities**, **calorific values** and **minimum air requirements**, as well as increased **adiabatic combustion temperatures** and **laminar combustion velocities**.
- Combustion is a **complex phenomenon** that cannot be easily reduced to just a few characteristic properties. Instead, a **comprehensive analysis** is required that not only considers the **changes in the fuel** itself, but also the **combustion technologies** used in different appliances and equipment.
  Combustion control may add another layer of complexity, especially if the control system was not developed with hydrogen in mind.
- Many of the results presented here can be transferred to other end-use sectors, particularly those about the impact on gas quality criteria.
  However: it is crucial to **not only look at the fuel** itself, but also to see how these changes affect a combustion system. Here, significant **differences between the applications in different end-use sectors** can be expected, since the technologies and requirements involved are often very different.

BONUS: AIR EXCESS RATIO VS. O_2 IN THE FLUE GAS



QUESTIONS

Thank you for your attention

Link to THyGA project:

https://thyga-project.eu/

Link to the state of the art on the "Non-combustion impact of hydrogen admixture material compatibility":

https://thyga-project.eu/deliverable-d2-2-impact-of-hydrogen-admixture-on-combustion-processes-part-i-theory/