

For the attention of SFOE

P&D contract number SI/501002-01

Annual Report 2014

Future Mobility: hydrogen production from excess electricity with utilization in mobility and re-conversion in CHP-plants

WP1 H₂/HCNG demonstrator at Empa

WP2 Methanation plant at PSI

WP3 HCNG field testing at Empa (vehicles) and ETH (CHP)

5th of January 2015

1. Summary

The Future Mobility project is based on the new Swiss energy strategy with a strong development in renewable electricity production, whereby not the energy production is in the focus but the chemical storage of fluctuating renewable excess electricity and its use. The project is divided into three work packages:

- H₂/HCNG Demonstrator at Empa (WP1)
with design and realization of a H₂ production, HCNG blending and H₂/HCNG fueling station
- Methanation plant at PSI (WP2)
with research targets in the field of increasing the know-how on CO₂ methanation by modelling and pilot scale experiments that can be used for model validation
- HCNG field testing at Empa (vehicles) and ETH (CHP) (WP3)
with multi-month field testing of HCNG vehicles and a HCNG CHP-facility

Due to the temporal and spatial decoupling in production and use of renewable electricity, a significant part of the new renewable electricity production in summer ends up in excess electricity without storage¹. Simulations show, that the existing electricity storage capacity in Switzerland is too small for storing the whole excess electricity at an enhanced PV market development already in 2023, if no new storage systems are realized².

Stored renewable energy has significantly higher costs due to unavoidable losses and storage facility costs than renewable energy itself and therefore has to fight against a limited concern in the electricity market. However, mobility with a high statutory pressure on CO₂ reduction and taxed fossil fuels is expected to be a more suited market for stored renewable energy. Within the Future Mobility project, decentralized chemical storage of renewable excess electricity with transfer and use in the mobility sector is the focus, without neglecting other storage technologies as batteries, compressed air, etc.

Estimations on the potential for mobility show, that a CO₂ free operation of several 100'000 vehicles would be possible, if only half of the expected excess electricity could be used in 2050. On a long term view, a complete turnover from fossil to synthetic renewable fuels doesn't seem to be impossible, because there are no physical limits neither in renewable energy nor in CO₂. Furthermore, the storage of renewable energy would probably increase the acceptance of enhanced (subsidized) production of renewable energy by reducing the share of excess electricity.

¹ Prognos; Die Energieperspektiven für die Schweiz bis 2050, Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 – 2050, Ergebnisse der Modellrechnungen für das Energiesystem (2012)

² Prognos, Energieperspektiven 2050: Sensitivitätsanalysen Photovoltaik – Ergebnisse der Modellrechnungen; April 2013

WP 1 is focused on the design and realization of a Future Mobility demonstrator facility, consisting of a PV electricity production plant, a PEM electrolyzer system with 450 bar compression, 450 bar hydrogen storage and 350 bar hydrogen fueling station as well as a HCNG blending and fueling station. In parallel to the realization, a simulation of the facility will be developed for the investigation of operational aspects.

In **WP2**, the goal of the activities is to increase know-how on CO₂ methanation (converting biogas and pure CO₂, e.g. from industrial sources) and hydrogen-rich methanation of gasification derived producer gas by modelling and (dynamic) pilot scale experiments that can be used for model validation. In the pilot scale experiments the focus will lie on investigating dynamic load changes and feed gas variation for combining Power-to-Gas and polygeneration of fuel, heat and electricity. The pilot scale set-up "GanyMeth" that shall be used for the experimental part is still under construction; the erection of the set-up however is funded by another project. Delivery of the complete set-up is expected for early 2015 and the reactive runs could start after summer break 2015. The time was therefore used to set up a computer model of a cooled fluidized bed methanation reactor fed with a slightly over-stoichiometric CO₂/H₂ mixture. It could be shown that pressures of about 10 bar allow reaching sufficiently high CO₂ conversion, such that downstream separation of CO₂ can be avoided while still reaching the specifications for injection of the SNG into the natural gas grid. The simulations indicate that in isothermal fluidized beds, the low temperature level is very favorable for the conditions of intermittent operation with frequent start-up and shut-down.

In **WP3**, a hydrogen blending facility at Empa's CNG fueling station was designed for blending rates up to 25 vol%. An ad interim solution for refueling CNG with low hydrogen blending of 2 vol% was realized for a field testing of three CNG delivery vehicles. The monitoring of these vehicles shows a measurable efficiency increase of nearly 1% as well as slightly reduced engine crank-times in practice. A vehicle for higher H₂ blending is in preparation.

Acknowledgements

The Future Mobility project team would like to express special thanks of gratitude to the funding agencies: the Swiss Federal Office for Energy (SFOE) and the Swiss Gas Association (VSG/SVGW) as well as to the industrial partner within the work packages.

2. Electrolysis (WP1)

*Empa, Internal Combustion Engines Laboratory: **Urs Cabalzar, Marco Brügger, Brigitte Buchmann, Christian Bach***

2.1 General targets and state of WP1 compared to the proposal aims/milestones

The general target of WP1 is the design, realization and simulation of the H₂/HCNG demonstration facility, including following main issues:

- Building: finished end 5014 (on track)
- Installations:
 - a) PV will be realized within the context of the Empa campus energy strategy
 - b) The electrolyzer unit is installed and in operation
 - c) H₂ compressor unit, storage cylinders and fueling station will be delivered in Spring 2015
 - d) The HCNG-blending system is under construction (intermediate system in operation)
 - e) Fueling dispenser are partly in operation (HCNG) while H₂ dispenser will be delivered in Spring 2015
- Simulations:
 - a) HCNG blending system is in development
 - b) Facility Simulation not yet started

2.2 Main Achievements of WP1 in 2014

After the building application for the H₂/HCNG-Demonstrator hall was approved the renovation of the building started in the beginning of July 2014 and was completed by end of November 2014. Employing an aluminum rib mesh the façade was designed to be both optically appealing and according to safety regulations which require sufficient natural ventilation.

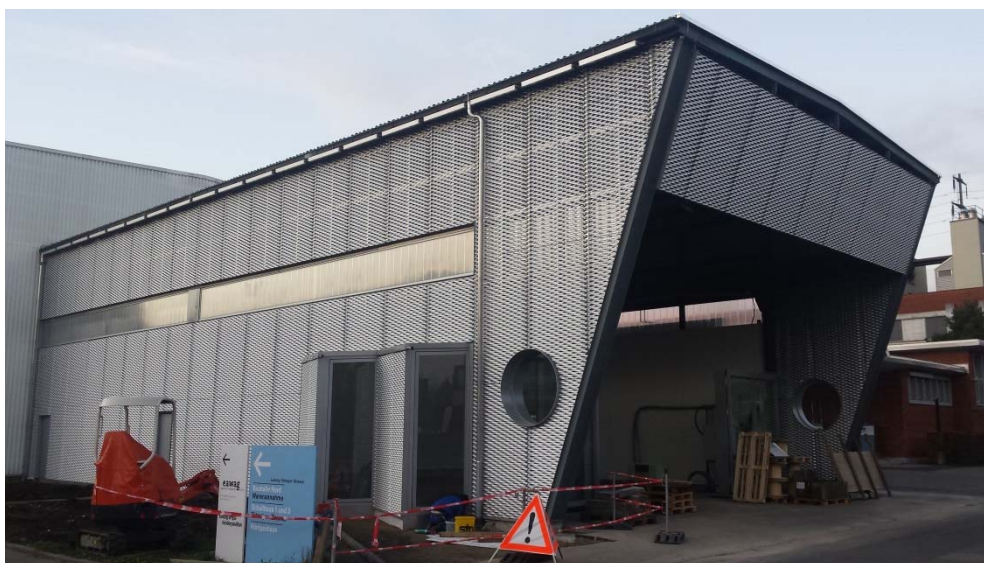


Fig. 1 H₂/HCNG-Demonstrator building (picture taken 28 Nov. 2014)

On the basis of a plant model, hydrogen production and demand was simulated to determine size and specifications of the components needed for the Demonstrator. Regarding the electrolyzer the required specifications were published through a WTO tender by the end of March 2014. In June 2014 the order was placed with Diamond Lite (Proton OnSite) comprising of a PEM-type electrolyzer capable of producing 30 Nm³ of hydrogen per hour at the nominal power of 180 kW. The electrolyzer was installed and commissioned using tentative connections in the beginning of December 2014.

The hydrogen compressor will be provided according to the terms of the collaboration agreement between Empa and the industrial project partner Atlas Copco concluded by the end of 2013. Regarding its main specifications, the flow rate of the compressor ranges from 30 Nm³/h to 65 Nm³/h at a power consumption of 15 kW to 30 kW. Along with the fuel dispensers, the storage cylinders and the piping material, the compressor is planned to arrive at Empa in spring 2015.

2.3 Dissemination activities within WP1

Poster Presentations:

- 1st Annual meeting SCCER Mobility (11.09.2014) at ETH Zurich
- Tage der Technik-Veranstaltung (02.10.2014) at Empa Dübendorf

Talks:

- HSR Expertengesprächen Power-to-Gas (13.05.2013) at HSR Rapperswil
- Parlamentariergruppe "Erneuerbare Energie" (19.09.2014) in Bern
- Jahreskonferenz der Agentur Erneuerbare Energie (11.11.2014) in Luzern

2.4 Publications / patents

None

2.5 Industrial and institutional WP1 partners

Industrial Partner:

- Atlas Copco
- Endress&Hauser

Funding Partner:

- Swiss Federal Office for Energy (SFOE)
- Glattwerk Dübendorf
- Stadt Dübendorf

2.6 Project risks in WP1

At present, we do not see any risks to the outcome of the project.

3. Methanation (WP2)

PSI, Combustion Research Laboratory: **Tilman Schildhauer, Jessica Settino, Sinan Teske**

3.1 General targets and state of WP2 compared to the proposal aims/milestones

a) Hydrogen addition to hydrothermal gasification/methanation

The activities have not yet started.

b) Hydrogen-rich methanation of CO₂-containing gases

The goal of the activities is to increase know-how on CO₂ methanation (converting biogas and pure CO₂, e.g. from industrial sources) and hydrogen-rich methanation of gasification derived producer gas by modelling and (dynamic) pilot scale experiments that can be used for model validation.

In the pilot scale experiments the focus lies on investigating dynamic load changes and feed gas variation for combining Power to Gas and polygeneration of fuel, heat and electricity.

3.2 Main Achievements of WP2 in 2014

The pilot scale set-up "GanyMeth" that shall be used for the experimental part is still under construction; the erection of the set-up however is funded by another project. Several necessary technical clarifications and adaptations delayed the delivery by a couple of months compared to the plan. Still, the main equipment (reactor, filter, activation reactor) is built and approved. Delivery of the complete set-up is expected for early 2015, commissioning and cold test (hydrodynamic measurements) should be finished in summer 2015. Therefore, the reactive runs could start after summer break 2015.

To prepare the reactive experimental campaign, especially to secure the gas supply, the integration of the GanyMeth into the Energy System Integration platform (ESI) has been supported. The ESI will be built at PSI as Research and Technology Transfer Platform (RTTP) of the two SCCERs (Swiss Competence Centers of Energy Research) on biomass and energy storage. It will comprise an electrolyser, a hydrogen tank and a CO₂ tank that will be used for the experimental campaigns with GanyMeth. The support of integrating GanyMeth into ESI comprised many technical specifications and detail discussion such as on safety and control systems etc.

Preliminary lab-scale experiments and modelling study

The time was therefore used to set up a computer model of a fluidized bed methanation reactor. Preliminary laboratory experiments showed that the applied commercial nickel based catalyst is active for CO₂ methanation also at temperatures below 300°C, see figure 2.1. This can be advantageous, as thermodynamic equilibrium calculations show that lower temperatures favor complete conversion of CO₂ which would allow omitting a downstream CO₂-separation in the gas up-grading section.

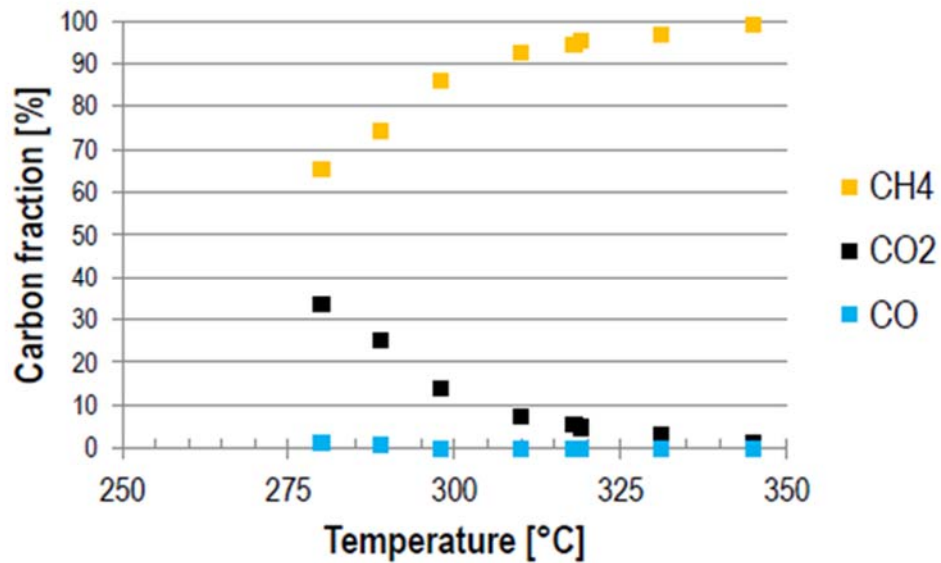


Fig 2.1. Laboratory experiments with hydrogen/CO₂ mixture using a commercial nickel based catalysts: distribution of the carbon containing species

In cooled fixed bed reactors which are used in the Power-to-Gas plant in Werlte/Germany^{3,4}, the axial transport of heat is quite limited and therefore, all heat has to be removed locally by radial transport to the cooling wall. In consequence local hot-spots are difficult to avoid^{5,6}. On the other hand, fluidized bed reactors allow for efficient axial and radial dispersion of the heat, because the catalyst particles, on which the heat by the exothermic reactions is released, are transported throughout the reactor. Due to their movement that disturbs laminar films, heat transfer to immersed cooling coils is relatively high. Therefore, under assumption of sufficient high bubbling fluidization, fluidized bed reactors can be considered as thermally well mixed which allows the simultaneous use of the complete immersed heat exchanger surfaces in the reactor.

³ M. Specht, F. Baumgart, B. Feigl, V. Frick, B. Stürmer, U. Zuberbühler, M. Sterner, G. Waldstein, Storing bioenergy and renewable electricity in the natural gas grid, in: G. Stadermann, P. Szczepanski (Eds.), FVEE-AEE Topics 2009, Renewable Energy Research Association, Berlin, 2011, 69–78

⁴ Company presentation Etogas GmbH, <http://oesterreichsenergie.at/files/oesterreichsenergie.at/Downloads%20Veranstaltungen/Victor-Kaplan-Lectures/VKL1-Okt-2013/Power%20to%20Gas-ETOGAS.pdf>

⁵ T. Schaaf, J. Grünig, M. Schuster, A. Orth, Speicherung von elektrischer Energie im Erdgasnetz – Methanisierung von CO₂-haltigen Gasen, CHEMIE INGENIEUR TECHNIK 86 (4), 476–485 (2014)

⁶ M.A. Schöb, A. Redenius, T. Turek, R. Güttel, Chemische Speicherung regenerativer elektrischer Energie durch Methanisierung von Prozessgasen aus der Stahlindustrie, CHEMIE INGENIEUR TECHNIK 86 (5), 734–739 (2014)

The performance of fluidized beds for heat removal in methanation has been demonstrated successfully in pilot and demonstration scale for both methanation of coal gasification derived CO/H₂ mixtures (Comflux project^{7,8}) and conversion of biomass gasification derived producer gas (EU project BioSNG⁹). For the latter case, it could be shown that fluidized bed methanation reactors even allow the conversion of unsaturated hydrocarbons such as acetylene, ethylene and benzene without significant catalyst deactivation by carbon deposition^{10,11}. As fixed bed methanation reactors suffer from severe carbon deposition in the presence of unsaturated hydrocarbons¹², the ability of fluidized beds to convert these unsaturated species opens a unique pathway to use biomass gasification derived producer gas or coke oven gas as carbon source for Power-to-Gas applications. The stronger robustness of fluidized bed methanation reactors with respect to avoidance of carbon deposition also facilitates the recirculation of methane, i.e. lower deactivation rates at similar steam addition or same deactivation rate at (economically favorable) lower steam addition can be expected.

One challenge in bubbling fluidized beds, however, is the mass transfer between the rising voidages containing only little catalyst particles (so-called bubble phase) and the gas surrounding the catalyst particles (the so-called dense phase). This mass transfer is a function of the concentration difference and the bubble diameter and therefore is influenced by reaction rates, pressure and fluidization number, i.e. the ratio between linear gas velocity in the reactor and the minimum velocity necessary to fluidize the catalyst particles. In the following, therefore the two-phase model by¹³ is used to predict the conversion of a fluidized bed methanation reactor at the same WHSV as the fixed bed reactor with catalyst particles.

For the modelling study, only the two main reactions CO methanation eq. 1, and Water gas shift, eq. 2 (combined giving CO₂ methanation, eq. 3) are considered, while carbon deposition by Boudouard reaction and similar are neglected.



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- ⁷ K. Hedden, A. Anderlohr, J. Becker, H.-P. Zeeb, Y-H. Cheng, Gleichzeitige Konvertierung und Methanisierung CO-reicher Gase, BMFT-FB- T 86-044 (1986)
- ⁸ G. Friedrichs, P. Proplesch, G. Wisman, W. Lommerzheim, Methanisierung von Kohlevergasungsgasen im Wirbelbett, BMFT-FB- T 85-106 (1985)
- ⁹ Kopyscinski, J., Schildhauer, T.J., Biollaz, S. (2010), Fuel 89 (8), 1763 - 1783
- ¹⁰ M.C. Seemann, T.J. Schildhauer, S.M.A. Biollaz, Industrial & Engineering Chemistry Research 49 (15), 7034–7038 (2010)
- ¹¹ J. Kopyscinski, M.C. Seemann, R. Moergeli, S.M.A. Biollaz, T.J. Schildhauer, Applied Catalysis A: General 462–463, 150-156 (2013)
- ¹² Struis, R.P.W.J., Schildhauer, T.J., Czekaj, I., Janousch, M., Ludwig, C. Biollaz, S. (2009), Applied Catalysis A: General 362, 121-128
- ¹³ J. Kopyscinski, T.J. Schildhauer, S.M.A. Biollaz, Methanation in a fluidized bed reactor with high initial CO partial pressure: Part II - Modeling and sensitivity study, Chemical Engineering Science 66, 1612 - 1621 (2011)

The cooled fluidized bed reactor is modelled according to the pseudo-homogeneous two phase approach of Kopyscinski et al.¹³ where hydrodynamic correlations for freely bubbling fluidized beds are applied. From this simulation study, it is known that the mass transfer between the voids ("bubbles" containing no catalyst particles) and the so called dense phase (which contains the catalyst particles suspended in the dense phase gas flow) is limiting the overall reactor performance. Recent studies showed that immersed vertical heat transfer tubes lead to even smaller bubbles than in fluidized beds without internals^{14,15,16}; therefore, the choice of this model can be considered a conservative assumption. For the kinetics of the isothermal methanation and the water gas shift reaction, the model 14b from¹⁷ is used.

Briefly, the two phases are the bubble phase and the dense phase (i.e., fluidized catalyst particles and the surrounding gas) connected via two mass transfer terms. One represents the mass transfer due to the concentration difference and the other – called bulk flow – represents a volume flow from the bubble to the dense phase induced due to the volume contraction occurring in the dense phase. The mole balance for the bubble and dense phase are shown in eqs. (4) and (5), respectively.

$$0 = -\frac{d\dot{n}_{b,i}}{dh} - K_{G,i} \cdot a \cdot A \cdot (c_{b,i} - c_{e,i}) - \dot{N}_{vc} \cdot x_{b,i} \quad (4)$$

$$0 = -\frac{d\dot{n}_{e,i}}{dh} + K_{G,i} \cdot a \cdot A \cdot (c_{b,i} - c_{e,i}) + \dot{N}_{vc} \cdot x_{b,i} + (1 - \varepsilon_b) \cdot (1 - \varepsilon_{mf}) \cdot \rho_p \cdot A \cdot R_i \quad (5)$$

Here, a is the specific mass transfer area, A is the cross sectional area of the reactor, $K_{G,i}$ is the mass transfer coefficient, $x_{b,i}$ is the mole fraction of species i in the bubble phase, ρ_p is the particle density, $(1 - \varepsilon_b)$ is the volume fraction of the dense phase, and $(1 - \varepsilon_{mf})$ is the volume fraction of the particles. The total bulk flow from the bubble to the dense phase \dot{N}_{vc} is described as the sum of the molar losses due to the reaction and mass transfer in the dense phase, see eq. (6).

$$\dot{N}_{vc} = \frac{\dot{n}_{vc}}{dh} = \sum_i K_{G,i} \cdot a \cdot A \cdot (c_{b,i} - c_{e,i}) + (1 - \varepsilon_b) \cdot (1 - \varepsilon_{mf}) \cdot \rho_p \cdot A \cdot \sum_i R_i \quad (6)$$

¹⁴ M. Rüdissülli, T.J. Schildhauer, S.M.A. Biollaz, J.R. van Ommen, Radial Bubble Distribution in a Fluidized Bed with Vertical Tubes, *Industrial & Engineering Chemistry Research* 51, 13815 - 13824 (2012)

¹⁵ M. Rüdissülli, T.J. Schildhauer, S.M.A. Biollaz, J.R. van Ommen, Bubble characterization in a fluidized bed with vertical tubes, *Industrial & Engineering Chemistry Research* 51, 4748 - 4758 (2012)

¹⁶ S. Maurer, E.C. Wagner, T.J. Schildhauer, J.R. van Ommen, S.M.A. Biollaz, R.F. Mudde, Proceedings of the 11th International Conference on Fluidized bed Technology, 14-17 May, 2014

¹⁷ J. Kopyscinski, T.J. Schildhauer, F. Vogel, S. Biollaz, A. Wokaun, Applying spatially resolved concentration and temperature measurements in a catalytic plate reactor for the kinetic study of CO methanation, *Journal of Catalysis* 271 (2), 262 - 279 (2010)

The numerical model describes the hydrodynamic parameters by applying correlations from literature on the height dependent mean bubble size d_b^{13} . The bubble velocity u_b , the bubble gas hold-up ϵ_b , and the specific surface area a are calculated using the mean bubble size d_b . Although these values are correlated with the bubble size distribution, using the height dependent mean bubble size is the best assumption at present. Another parameter is the mass transfer coefficient $K_{G,i}$, also taken from hydrodynamic correlations.

Results:

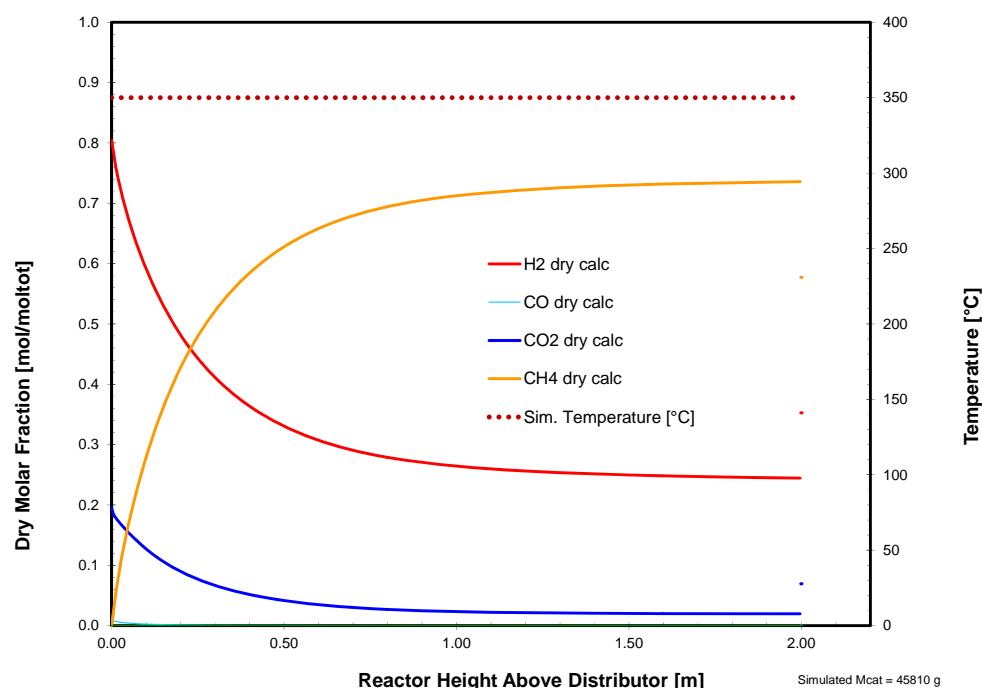


Fig. 2.2: Dry molar fractions (i.e. after water removal) of the gas flowing between the catalyst particles in the so-called dense phase (full lines) at an isothermal temperature of 350°C and 3 bara pressure, when feeding a slightly over-stoichiometric mixture of $H_2/CO_2 = 4.1/1$. The points at 2 m reactor length indicate the outlet gas composition after mixing of bubble and dense phase.

Figure 2.2 shows the “dry” molar fractions (i.e. after water removal) of the gas flowing between the catalyst particles in the so-called dense phase at an isothermal temperature of 350°C and 3 bara pressure, when feeding a slightly over-stoichiometric mixture of $H_2/CO_2 = 4.1/1$.

It can be observed that the conversion to methane is fast at the beginning and apparently very slow at the second half of the reactor. Still, the concentrations in the bubble phase differ significantly. The points at 2 m reactor height indicate the gas after mixing of bubble and dense phase, i.e. the outlet gas composition. With a methane fraction of only 58%, a H_2 fraction of 35% and about 7% CO_2 fraction, the gas would lead even after hydrogen removal

to a SNG with more than 10% CO₂ which does not fulfill the H-gas specifications^{18,19}. Due to better mass transfer, the situation is strongly improved at 10 bara (see figure 3.2) where high methane yields are reached, and the SNG after the hydrogen removal would contain only 2.4% CO₂. Pressures between 3 bara and 10 bara would lead to remaining CO₂ fractions between 2.4% and 10%. The CO₂ and H₂ concentrations could be further decreased by recirculation or feeding of methane rich gas, e.g. biogas.

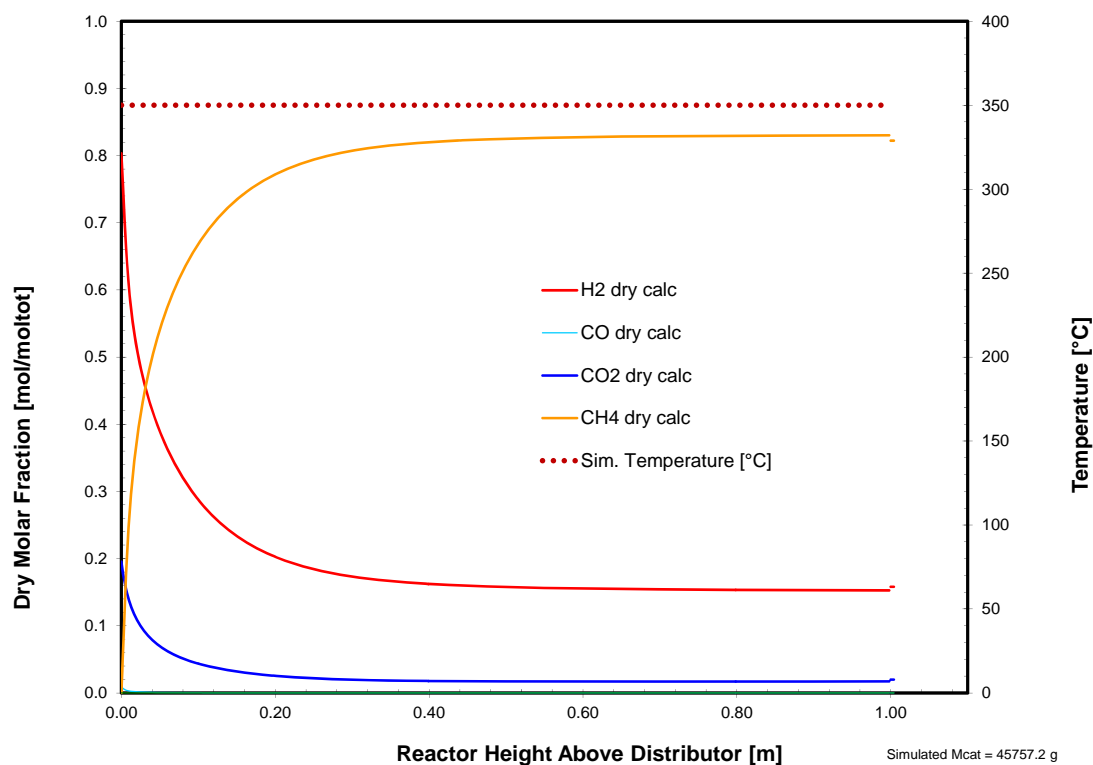


Fig. 2.3: Dry molar fractions (i.e. after water removal) of the gas flowing between the catalyst particles in the so-called dense phase (full lines) at an isothermal temperature of 350°C and 10 bara pressure, when feeding a slightly over-stoichiometric mixture of H₂/CO₂= 4.1/1. The points at 2 m reactor length indicate the outlet gas composition after mixing of bubble and dense phase.

¹⁸ DVGW-Arbeitsblatt G 262 - Nutzung von Gasen aus regenerativen Quellen in der öffentlichen Gasversorgung, (German technical guideline), 2011

¹⁹ DVGW-Arbeitsblatt G 260 - Gasbeschaffenheit, (German technical guideline), 2013

Conclusions:

This study on cooled fluidized bed methanation reactor configurations fed with a slightly over-stoichiometric CO₂/H₂ mixture at the reactor inlet showed that pressures of about 10 bar allow reaching sufficiently high CO₂ conversion, such that downstream separation of CO₂ can be avoided while still reaching the specifications for injection of the SNG into the natural gas grid. Applying a reactor type with high heat removal performance (fluidized bed, in which the heat is dispersed through the complete reactor by moving the hot catalyst particles) allows controlling the temperature. Temperature run-away and the resulting peak temperature (which are typical for fixed bed reactors) are avoided and therefore, very active catalysts can be used.

The simulations indicate that in fluidized beds, the low temperature level is very favorable for the conditions of intermittent operation with frequent start-up and shut-down. Still, the mass transfer between bubble and dense phase suggests around 10 bar operation pressure, unless significant amounts of methane can be fed or recirculated. For deeper understanding of the limitations by mass and heat transfer, pilot scale experiments are necessary for both reactor types.

3.3 Dissemination activities within the WP2

The activities on applying fluidized bed methanation for different Power-to-Gas process concepts, i.e. using biogas, gasification derived producer gas and CO from industrial sources, are integrated into the Energy System Integration platform (ESI) built at PSI and the communication of that platform. Therefore, presentations at the Future Energy Conference at CSEM in Neuchâtel (27.11.2014) and at the Biomass for Swiss Energy Future Conference 02.12.2014 at PSI, Villigen covered also the investigations conducted within Renerg².

3.4 Publications / patents

A comparative simulation of fluidized bed methanation and cooled fixed bed reactors containing the above shown results has been written and submitted in September 2014 to "Fuel": T.J. Schildhauer, J. Settino, S.L. Teske, *Modelling study of fixed and fluidized bed reactors for CO₂ methanation in Power-to-Gas applications*.

3.5 Industrial and institutional WP2 partners

Due to the integration into the Energy System Integration platform (ESI) built at PSI, the investigated catalytic methanation based process concepts for Power-to-Gas applications will be presented to several potential industrial partners in the first half of 2015.

3.6 Project risks in WP2

The erection and commissioning of the pilot scale set-up GanyMeth id delayed by a couple of months. This however does not represent any risk to the planned activities, as the time is used for further modelling work. Based on the modelling results, improved experimental campaigns can be conducted which can be focused on promising operation conditions identified by the modelling.

4. HCNG field testing (WP3)

*Empa, Internal Combustion Engines: **Urs Cabalzar, Thomas Bütler, Mathias Huber**
ETH, Aerothermochemistry and Combustions Laboratory: **Christian Schürch,***

4.1 General targets and state of WP3 compared to the proposal aims/milestones

a) HCNG blending station (WP 3.1)

.1 Ad interims solution for HCNG refueling

The work sub-package 3.1 contains the development of an ad interims fuel dispensing solution for vehicles running on a mixture of natural gas and hydrogen (2 vol%) in a first step (Figure 3.1). Subsequently a permanent fuel dispenser is to be developed allowing convenient refueling of natural gas/hydrogen-mixtures with hydrogen volume fractions within the region of 2...30 vol%.

The processes of planning, development and realization of the ad interims fuel dispensing solution were completed in the course of the year 2014 as projected. Hence, the field testing scheduled in WP 3.2 with test vehicles running on CNG with slight hydrogen addition (2 vol%) was able to commence at the end of 09/2014. The ad interims solution consists of a H₂-dispenser developed in collaboration with Apex AG and Endress&Hauser (white dispenser) and the existing CNG-dispenser of Empa. As shown in the picture below, hydrogen is supplied from a gas cylinder bundle behind the dispenser.



Fig. 3.1: Ad interim solution for refueling CNG with slight hydrogen addition (2 vol%)

During a refueling process both car tank pressure as well as ambient temperature have to be identified to determine the amount of hydrogen to be refueled based on a table at hand. After refueling hydrogen, the CNG-dispenser is connected to the vehicle and the tank is filled with CNG until the dispenser stops automatically. Besides its inconvenience with respect to handling, this process allows a safe and rather accurate way of refueling CNG/hydrogen mixtures which were the priority objectives of this subproject.

.2 Permanent HCNG-dispenser

For the permanent HCNG-dispenser the level of convenience is targeted to be in accordance with conventional dispensers for gaseous fuels. Particularly, refueling should be possible through one dispenser nozzle and relevant parameters are measured by the dispenser automatically. The person refueling will only have to preselect the required hydrogen fraction (2...30 vol%) and start the refueling process.

To achieve the dispensing of the required mixing ratio various approaches exist. To find an optimal solution in terms of functionality, safety as well as regarding economic aspects the refueling process is simulated using the multi-physics software AMESim. To validate the model, relevant operating parameters (particularly pressures at various positions) are to be measured on the existing CNG-station. On that basis the model is extended by different hydrogen addition systems, each of them yielding results that help defining a suitable mixing process.

b) *HCNG vehicle field testing (WP 3.2)*

.1 Field testing with 3 standard CNG vehicles

Three vehicles of the fleet operator company Mobility Solutions AG were selected as field testing vehicles and were equipped with data loggers to record various engine parameters. With each vehicle, baseline measurements were carried out on the chassis dynamometer at Empa focusing on emissions and fuel consumption (efficiency).

Thereafter, the vehicles were in use about 3 months in normal operating with CNG. After this phase, the vehicles were successively switched to HCNG operation (2 vol% H₂) and measured again on the dynamometer after some run in time (Figure 3.2). Currently, all vehicles are still in the long-term field test.



Fig. 3.2: Fiat Ducato from Mobility Solutions AG on the chassis dyno at Empa

.2 Field testing with special HCNG vehicle

The vehicle procurement and part provision process is currently running and clarifications for the modification and approval for the vehicle is in progress. As soon as the HCNG fuelling station is fully operational (different blending ratios with 2, 15, 25 vol% H₂) the vehicle is put into operation and a base measurements will be carried out on the chassis dynamometer at Empa.

c) *HCNG decentralized power (co-)generation (WP 3.3)*

WP3.3 requires the testing on three different types of test carriers. For the fundamental combustion research an engine on an engine test bench will be used. This set-up will be installed in the ETH/LAV laboratory and is described in more detail below. For thermal investigations of the whole CHP set-up an already existing CHP set-up will be used²⁰. This set-up is also installed in the ETH/LAV laboratory. The field testing will be made together with partners in the industry. These partners are still to be found.

A 250 cm³ 1-cylinder 4-stroke engine by Swiss Auto will be used as the test carrier for the fundamental combustion research. This engine is originally designed for the application in karts. The design constrains were a cheap production and high power. Efficiencies and emissions were of secondary interest. The valve timing is far from optimal for the target rotational speed of 3'000 rpm for a CHP application. Also the valves and valve seats are not designed for the combustion of natural gas. Experiments on a similar engine have shown that the valve play will decrease quickly when operated with natural gas²⁰.

4.2 **Main achievements of WP3 in 2014**

a) *HCNG blending station (WP 3.1)*

.1 Main achievements

The following listing contains the main achievements of this work sub-package so far:

- Planning and developing of the ad interims fuel dispensing solution finalized (for 2 vol-% H₂)
- Commissioning of the ad interims solution at the end of 09/2014
- Implementation of the AMESim model for the existing CNG refueling station completed
- Measurements on CNG station conducted and model validated
- AMESim model extended by different hydrogen addition systems

With the commissioning of the ad interims solution the sub-task of WP 3.1 regarding 2 vol% hydrogen refueling is completed. Solely monitoring, maintenance and support is conducted further on.

²⁰ Auslegung und Realisierung von WKK-Anlagen mit „Null“ – Schadstoffpotential unter besonderer Berücksichtigung biogener Energieträger, Schlussbericht, Bundesamt für Energie BFE, 30.06.2014

Concerning the permanent HCNG dispenser the main part of the modelling is finalized. Valuable insights about different hydrogen addition systems have already been gained steering further efforts towards a selected HCNG dispensing approach. Figure 3.3 serves as an example of what parameters are analyzed during the simulation of an HCNG refueling process employing an intermittent-type hydrogen addition system.

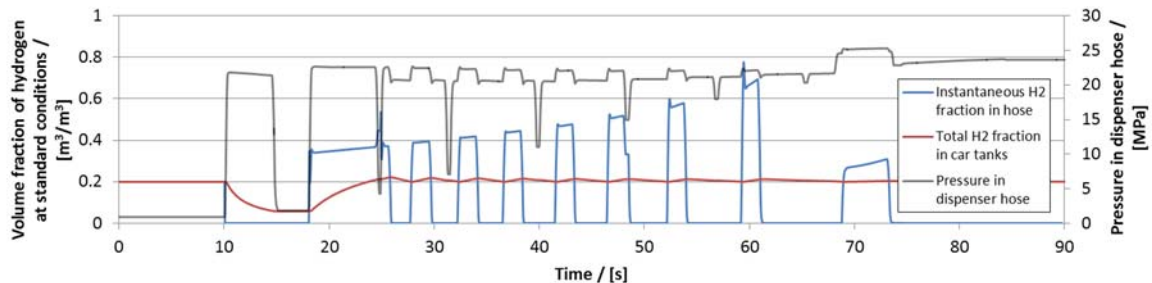


Fig. 3.3: Simulation result for 3 exemplary parameters (see legend) during an HCNG refueling process

.2 Outreach

Further work will include the final definition of the hydrogen addition system to be designed. For this purpose additional simulation runs and simulation data analysis will be carried out that may lead to small model adaptations based on the findings.

As the final HCNG dispensing concept is fixed a refueling control system has to be developed that governs the refueling process as well as the gas mixing. Due to the fact that natural gas is supplied from the existing CNG-station this task will be accomplished in collaboration with the project partner Atlas Copco AG (Greenfield) who provided the CNG-station.

In further steps the physical HCNG dispenser is constructed and integrated in the current fueling station. Tests during the construction process and after integration will be conducted to confirm that the refueling process is safe and accurate regarding the preselected gas mixture.

b) *HCNG vehicle field testing (WP 3.2)*

.1 HCNG field testing (Phase 1 with 2 vol% H₂-blending)

The CNG vehicles with 2 vol% hydrogen blending are mainly used in the parcel distribution service and therefore have a high number of motor starts per day. The data from the field test shows an average of over 30 starts a day. One day, one of the test vehicles was started 87 times. Currently we evaluated 2'430 engine starts with CNG and 1'807 engine starts with HCNG (2 vol% H₂). On average, 95% of the engine starts are carried out at an engine coolant temperature higher than 80°C.

The evaluation also included an analysis of engine start times. One of the results of this analysis was the time delay from the first turn of the engine starter and the first firing of the first cylinder. Four different delays were distinguished:

- very short; time from crank to first fire smaller than 100 ms
- short; time from crank to first fire between 100ms and 200 ms
- normal; time from crank to first fire between 200ms and 400 ms
- long; time from crank to first fire bigger than 400 ms

HCNG compared to CNG operation shows a shift to shorter crank to first fire times (Figure 3.4). This can be explained with the higher ignition quality caused by the hydrogen in the HCNG blend. Even small amounts of hydrogen seem to have an impact on start quality.

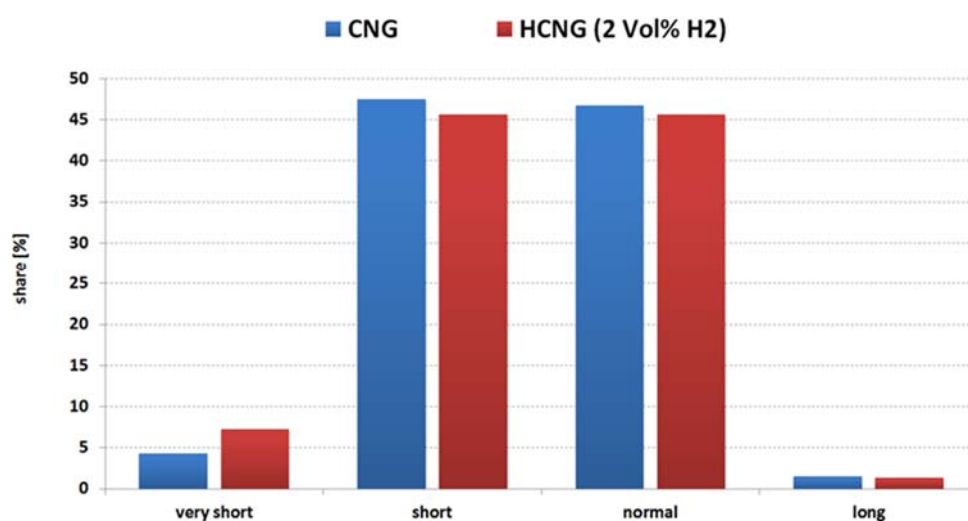


Fig. 3.4: Delay from crank to first fire for CNG and HCNG (data from field test; 2'430 starts with CNG, 1807 starts with HCNG (2 vol% H₂))

.2 Chassis dyno measurements with standard CNG vehicles

With each vehicle base measurements were carried out on the chassis dynamometer with CNG and also with HCNG (2 vol% H₂) as fuel. As driving cycle for these measurements, the CADC cycle from the Artemis program has been used. This cycle corresponds to a real world driving cycles with three phases (urban, rural, highway) (Figure 3.5)

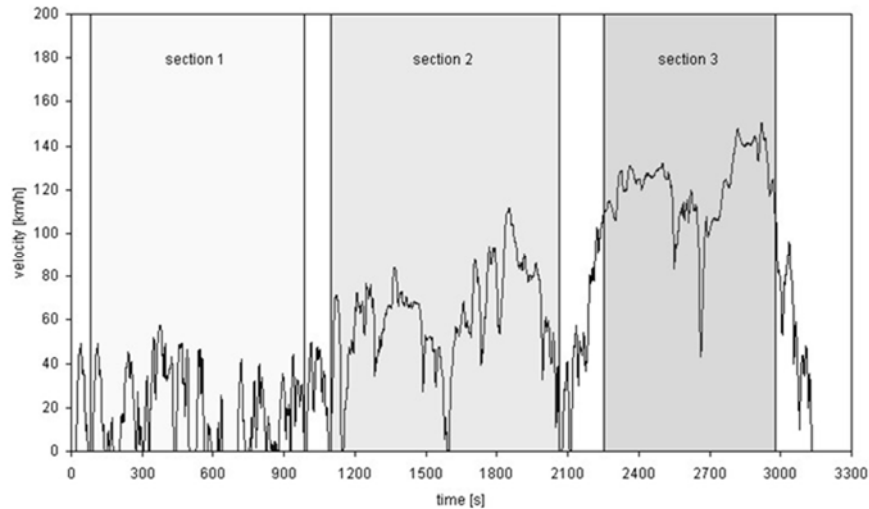


Fig. 3.5: Artemis CADC speed profile; section1 = urban, section 2 = rural, section 3 = highway

The emission values for carbon monoxide (CO), nitrogen oxides (NOx) and unburned hydrocarbons (T.HC) show no significant differences between the two types of fuel. However, the 2 vol% H₂ blending shows a slight reduction of CO₂ emissions of 1 – 1.5%, which can be explained by the reduced C-content of the fuel as well as a slight improvement of engine efficiency (Figure 3.6).

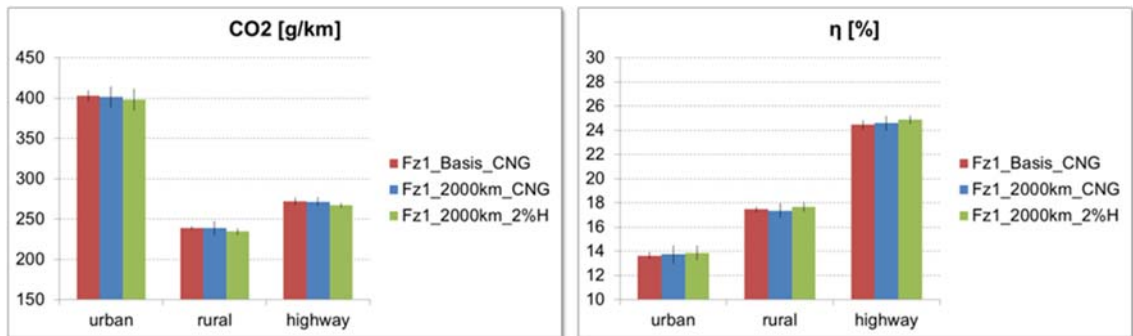


Fig. 3.6: CO₂ [g/km] and vehicle efficiency [%] with 95% confidence interval (black bars)

The slight efficiency increase can be explained by the improved ignition phase. Such effects have already been observed at Empa in other HCNG projects. In the current case, however, they are very faint due to the low blending of hydrogen.

.3 Outreach

The three field testing vehicles of Mobility Solutions AG remain in the field test and are fuelled with HCNG (2 vol% H₂). The data loggers of the vehicles stay active to collect more measurement data for a more accurate comparison of the start-up behavior with the different fuels. At regular intervals, oil samples are taken to investigate the effects of HCNG operation on oil aging. At the end of the field test, one vehicle is measured again on the chassis dyno to analyse the aging behavior of the exhaust after treatment system.

Once the HCNG vehicle for higher H₂ blending is prepared and approved for the operation with HCNG (different H₂-blending ratios of 15, 25 vol%) and the HCNG filling station is put into operation, it will run a long term field test. For this field test, the vehicle will be equipped with an enhanced data logging system. At regular intervals, oil samples are taken to investigate the effects of HCNG operation on oil aging. During the field test, the vehicle will be measured within certain intervals on the chassis dyno to analyse the fuel consumption behavior as well as the aging behavior of the exhaust after treatment system.

c) *HCNG decentralized power (co-)generation (WP 3.3)*

.1 Planned modifications

The gas exchange process will be optimized for the low rotational speed of 3'000 rpm. This includes a redesign of the camshaft and adjustment of intake and exhaust runner length. This optimization and the check of the Hertzian pressure between cams and valves will be made in GT-Power. The goal is to use the original cam shaft and grind the cams down at Swiss Auto such that the optimal timing found in GT-Power results.

The valves as well as the valve seats will have to be replaced by harder material. A supplier for the valves is already known (Intervals Technologies AG). The valve seats are standard parts and can be ordered anywhere.

.2 Test bench

After modifying the engine it will be mounted together with an Apicom eddy current break. This will allow for torque and power measurements. The engine will be equipped with pressure indicators at the intake- and exhaust runner as well as in the combustion chamber. Temperatures will be measured in the gas path as well as in the coolant circuit. A WOODWARD MotoTron Controller will be used for the engine control. A Fiat 500 twin air catalytic converter for natural gas will be used to treat the exhaust gas.

3 Outreach

The main issue with natural gas engines is the ignition. Due to the chemical stability of the CH₄ molecule the minimum ignition energy is 17.5 times higher than for H₂. Also the laminar flame speed of H₂ is about 8 times higher than the one of pure methane. Up to now the normal open-chamber spark plugs were replaced by the more expensive pre-chamber sparkplugs to compensate these effects. By studying the combustion process with pre-chamber and open-chamber spark plugs as well as different portions of H₂ in the H₂ / CH₄ fuel mixture a statement about the benefit of a H₂ enriched fuel should be made. Also the effects on break power, emissions and efficiencies will be investigated.

In contrast to mobile applications a stationary CHP will not be supplied with compressed natural gas. Also in future the existing natural gas grid will be used for the CH₄ supply and H₂ will most probably have to be introduced separately. From earlier research on the same engine²¹ it was recommended that a direct injection of H₂ should not be implemented due to the short penetration length of H₂, low turbulence inside the engine in general and unknown flow fields. The following three concepts of introducing H₂ and CH₄ into the combustion chamber are therefore going to be investigated:

- Introduction of a pre-mixed H₂ / CH₄ mixture via a venturi mixer into the intake air stream
- Port fuel injection of pre- mixed H₂ / CH₄
- Port fuel injection of H₂ into the premixed CH₄ / air mixture

In a next step the influence of EGR on performance and emissions shall be investigated. The question to be answered is whether a catalytic converter becomes redundant with the use of EGR. At first only low pressure EGR will be implemented. For high pressure EGR an external device for supplying the pressure would have to be installed because turbo chargers for such small engines do not exist on the automotive market. At this stage it is however not planned to install an external boost device.

The best strategies regarding the use of H₂ and EGR will then be implemented on the CHP test bench and in the industry.

5.3 Dissemination activities within the WP3

Power-to-Gas conference on 25th of February 2015 is planned at the Empa-Academy. At this conference, the H₂ production and HCNG blending/fueling facility will be demonstrated.

5.4 Publications / patents

None

²¹ Customized Hybrid Powertrains – Cohyb, Final Report, CCEM, 27.01.2014

5.5 Industrial and institutional WP3 partners

- SFOE (BFE) Swiss federal office of energy
- FOGA Research, development and promotion fund of the Swiss gas industry
- Mobility Solutions AG Corporate fleet manager (fleet of Post AG)
Providing and operating of test vehicles for field testing
- Iveco / FPT Motorenforschung AG Powertrain technologies company
Collaboration regarding the adaption of CNG-vehicles for HCNG use
- SwissAuto Engine company
Support on CHP test engine
- Motorex Lubricant company
Information exchange with respect to permissible engine lubricants for hydrogen enriched fuels

5.6 Project risks in WP3

None