Alternative fuels for mobility and transport: Harnessing excess electricity from renewable power sources with power-to-gas

Gerda Gahleitner
Energy Institute at the Johannes Kepler University Linz
Altenberger Straße 69
4040 Linz
Austria
gahleitner@energieinstitut-linz.at

Johannes Lindorfer
Energy Institute at the Johannes Kepler University Linz
Altenberger Straße 69
4040 Linz
Austria
lindorfer@energieinstitut-linz.at

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Abstract
This article presents the analysis of economic, technical and ecological aspects of alternative gaseous fuel production from renewable excess electricity. Besides improvements in energy efficiency, renewable fuels will be required for the reduction of overall greenhouse gas emissions in the transport and mobility sector. The 'power-to-gas' technology provides hydrogen by splitting water with excess electricity from renewable power sources or further synthesizes methane by using carbon dioxide. Thereby both, the increasing demand for energy storage due to fluctuating renewable power sources and the demand of alternative fuels for mobility, are addressed.

The article provides a short review of realized power-to-gas demonstrations for transport applications and discusses occurring problems as well as topics for further development. In terms of ecological aspects it can be shown that if electricity and carbon dioxide origin from renewable sources, a substantial reduction in greenhouse gas emissions can be reached for synthetic methane compared to conventional diesel.

The presented case study for the supply of an Austrian public bus fleet with synthetic methane indicates that production costs are mainly influenced by the electricity price and the investment costs. They also strongly depend on the amount of full load hours per year of the power-to-gas facility. Currently, the synthetic methane production costs of 0.41 Euro/kWh are considerably higher than diesel prices. For the future utilization of expected excess electricity from renewable power sources and a possible adaptation of the legal framework in the electricity sector the costs of synthetic methane production can possibly be reduced to approximately 0.13 Euro/kWh. Future research should focus on improving the efficiency, reliability, costs and lifetime of the components, and optimum system configurations should be determined to improve the integration into the overall energy system.

Introduction
For mitigating climate change, the reduction of global greenhouse gas (GHG) emissions is essential and can be realized on the one hand with improvements in energy efficiency and on the other hand with the development of renewable technologies. Regarding the reduction of overall greenhouse gas emissions, not only the electricity but also the transportation, heating and industry sectors have to be addressed. In the year 2011, 20.3 % of global electricity has been produced from renewable power sources.[1] Wind and solar power actually account for a small fraction as the greatest amount (15.3 %) has been produced by hydropower, but these technologies show high potentials for the future. Nevertheless, wind and solar power show strongly fluctuating characteristics and require load levelling and energy storage.

Especially in the transportation sector, the development of renewable fuels is a big challenge as currently the vast majority is derived from fossil feedstock. Currently liquid biofuels account for only 3 % of global fuel production[2] and other renewable transport technologies play an insignificant role.

1. REN21, Renewables 2012 Global Status Report. Paris, 2012, REN21 Secretariat. http://www.map.ren21.net/GSR/GSR2012.pdf, accessed 17.12.2012.
2. REN21, 2012

Several problems are accompanied with biofuels as arable land is needed for growing feedstock, and competition with food production is an issue.[3, 4] Direct utilization of renewable electricity in electric vehicles represents an efficient transport technology without emissions but faces challenges such as small driving range, heavy and expensive batteries with short lifetimes or extra burden of the public electricity grid. Power-to-gas technology for hydrogen or synthetic methane production out of renewable electricity represents another option for renewable fuel production. Additionally, it addresses the increasing demand for energy storage due to fluctuating renewable power sources when utilizing excess electricity. 'Excess electricity' could be specified as the electricity that cannot be fed into the public electricity grid or be utilized otherwise. Reasons for that could be a lower electricity demand than the actual generation or that in local grids the electricity network may be too weak to transport peak production from renewables.

With power-to-gas, electricity from renewable power sources splits water via an electrolyzer. The produced hydrogen can be either directly utilized or further synthesized to methane with carbon dioxide. Depending on the integration into the energy infrastructure, various applications can be realized. The produced hydrogen or methane can be directly utilized in refuelling stations for transportation purposes. Another possibility is to feed them into the gas distribution system and therefore provide energy for the electricity, heating and transportation sector. Further applications could be the utilization of hydrogen in industry or the reconversion into electricity via fuel cells. These applications are not considered in this article as only pathways for providing alternative fuels are evaluated.

The information for the review of realized power-to-gas pilot plants for transportation purposes is mainly gathered from www.h2stations.org[5] and Gahleitner, 2013[6]. The environmental impacts of various transportation fuels are evaluated with data from a well-to-wheel (WTW) analysis performed by Edwards et al., 2011[7]. The calculations for the Austrian case study are based on data from peer-reviewed literature and component manufacturers. Since power-to-gas is not a fully developed technology, well-defined cost values are not always available. The cost estimation of fuels from power-to-gas is therefore performed for the mid-term and the long-term perspective.

The article presents various applications of the power-to-gas technology for mobility purposes with information about the main components of the system. A short review of realized demonstration plants is provided, and occurring problems, future research demand and potential of the technology is discussed. Fuels produced via power-to-gas technology are compared to other transportation fuels in terms of environmental impacts such as greenhouse gas emissions. The presented case study for Austria deals with the system design for a bus fleet and economic evaluation of power-to-gas for sustainable mobility. SNG (synthetic natural gas) fuel production costs and total costs for the bus fleet are calculated for the mid-term and the long-term perspective and the required modification of regulations is discussed. Power-to-gas technology for alternative fuel production is evaluated with regard to economic and ecological aspects and future research demand is deduced.

Power-to-gas for transport applications

The power-to-gas technology utilizes electricity from fluctuating renewable power sources for splitting water into hydrogen and oxygen in an electrolyzer. The produced hydrogen can be utilized as fuel for transportation purposes, can be fed into the gas distribution system, utilized directly in the chemical industry or can be reconverted into electricity with a fuel cell. Another possibility is to further synthesize hydrogen to methane with carbon dioxide in the so-called Sabatier process.[8] Although this pathway has a lower efficiency, synthetically produced methane has the advantage that it can be utilized in the same way as natural gas and therefore no additional infrastructure is required. As this article focuses on alternative fuels for transportation purposes, only the pathways for fuel production via power-to-gas are illustrated in Figure 1.

Renewable electricity for operation of the water electrolyzer can be obtained directly from renewable power sources or indirectly over the public electricity grid. For every pathway there are different operating modes which determine the electricity costs as well as the operating hours. Grid-connected systems could obtain electricity with the conventional EU-mix or certified green electricity. Depending on the desired amount of full load hours excess electricity or base electricity has to be utilized.

There are several possible pathways to provide fuel from power-to-gas. The first option is to directly provide hydrogen as fuel for vehicles with a fuel cell or an internal combustion engine. The produced hydrogen can be distributed to the refuelling station with a hydrogen pipeline or in pressure vessels, depending on the distance and amount of hydrogen. If the refuelling station is on-site, there is no need for hydrogen distribution.

Hydrogen could also be directly fed into the gas infrastructure but the restrictions on the allowed volumetric fraction have to be considered.[9] In this option, the gas distribution system serves for energy transport and the fuel can be utilized in a CNG (compressed natural gas) refuelling station, independent from the site of production.

3. Ajanovic A, Biofuels versus food production: does biofuels production increase food prices?, Energy 2011, 36 pp. 2070–2076. DOI 10.1016/j.energy.2010.05.019.

4. Söderberg C, Eckerberg K, 2012, Rising policy conflicts in Europe over bioenergy and forestry, Forest Policy and Economics 2012. DOI 10.1016/j.forpol.2012.09.015.

5. http://www.h2stations.org, accessed January 04, 2013.

6. Gahleitner G, Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications, International Journal of Hydrogen Energy 2013, DOI 10.1016/j.ijhydene.2012.12.010.

7. Edwards R, Larivé J-F, Beziat J-C, Well-to-wheel analysis of future automotive fuels and power trains in the European context. Report Version 3c. European Commission, Joint Research Center, Institute for Energy and Transport, Luxembourg, 2011. doi:10.2788/79018.

8. Müller B, Müller K, Teichmann D, Arlt W, Energiespeicherung mittels Methan und energietragenden Stoffen – ein thermodynamischer Vergleich. Chemie Ingenieur Technik 2011, 83, No. II, 2002-2013. DOI 10.1002/cite.201100113.

9. Mueller-Syring G, Henel M, Power-to-Gas: Konzepte, Kosten, Potenziale. DBI Fachforum: Energiespeicherkonzepte und Wasserstoff, 2011. http://www.dbi-gti.de/fileadmin/downloads/5_Veroeffentlichungen/Tagungen_Workshops/2011/H2-FF/07_Mueller-Syring_DBI_GUT.pdf, accessed 17.12.2012.

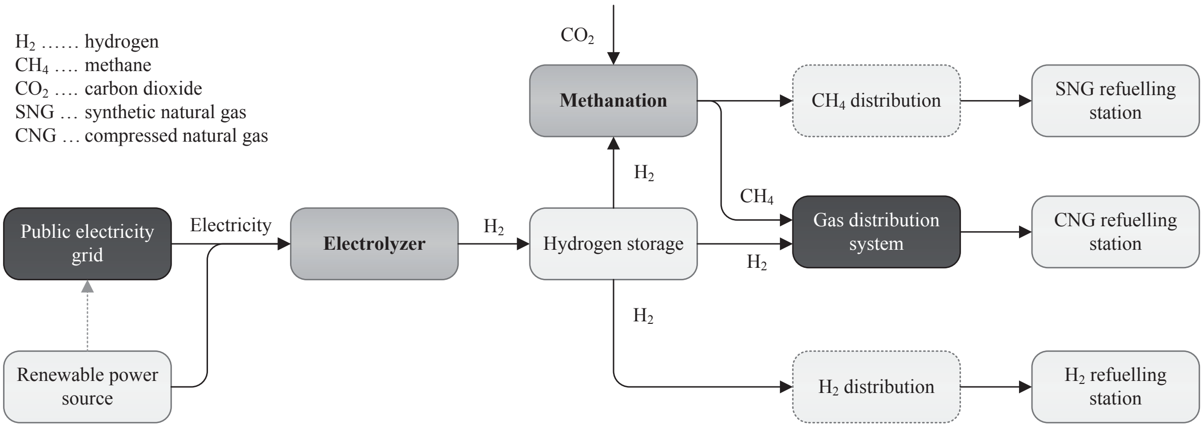

Figure 1. Pathways for application of power-to-gas for alternative fuel production.

If the produced hydrogen is further synthesized to methane, carbon dioxide has to be available. There are numerous potential CO_2 sources such as flue gas from fossil power plants, industrial processes in lime and cement industry, biotechnological processes or even extraction from the ambient air.[10, 11] The produced synthetic methane could also be fed into the gas distribution system with the advantage that there are no restrictions on the allowed amount since it is nearly identical to natural gas. The advantage of employing the gas distribution system for energy transport is that production and consumption are decoupled. Therefore both an optimum site for production with availability of renewable resources and carbon dioxide and an optimum site for consumption with storage infrastructure, refuelling station and fuel demand can be chosen.

Another option is to provide the SNG directly at a refuelling station. It can be applied in conventional CNG refuelling stations and CNG cars where natural gas is currently used and which are state-of-the-art technologies. If the refuelling station is not on-site, the synthetic methane could also be transported to the site of application.

MAIN COMPONENTS

The two main components of a power-to-gas system are the water electrolyzer and the methanation reactor in case that synthetic methane is produced.

There are various types of water electrolyzers that are characterized by the applied electrolyte. A detailed evaluation of electrolyzer technologies is provided by Ursua et al., 2012[12] and by Smolinka et al., 2011[13]. Here only the main characteristics of the alkaline (AEC), proton exchange membrane (PEMEC) and the solid oxide electrolysis cell (SOEC) are described. AEC have an aqueous alkaline electrolyte and are the most developed electrolyzer types. They are commercially available at high capacities of up to 760 Nm³/h and represent the cheapest of electrolyzer technologies. Their performance is good if operated continuously but problems occur when AEC are operated with strongly fluctuating power input.[14] PEMEC have a simpler design and employ a polymer electrolyte membrane. They are in a pre-commercial stage and are only available for small capacities of up to 30 Nm³/h. PEM electrolyzers are better suited for operation with fluctuating power input as they have faster reaction to load changes and a better hydrogen quality in part load. One of the main challenges is the limited lifetime and the high initial costs due to noble metal catalysts.[15] SOEC are at an early stage of development and are operated with additional thermal energy input, which reduces the required amount of electricity and therefore increases efficiency. Due to the high temperatures, there is no need for expensive catalysts on the one hand, but on the other hand several material problems arise.[16] When operated with fluctuating power input, all types of electrolyzers have problems with efficiency, reliability and decreased durability.

Synthetic methane can be produced from hydrogen and CO or CO_2 in a methanation reactor. CO methanation is applied in large-scale coal gasification processes. CO_2 methanation is a combination of the water-gas shift reaction and the CO methanation. The synthesis reactor operates at temperatures from 180 to 350 °C and at pressures of around 8 bar.[17] Typically applied catalyst materials are Ni or Ru. One big advantage of CO_2 methanation is the additional environmental benefit of the reuse of the greenhouse gas CO_2. The CO_2 methanation reactor is under development and although comparable efficiencies (83 %[18]) to the CO methanation are achieved, challenges

10. Rubin E-S, Mantripragada H, Marks A, Versteeg P, Kitchin J, The outlook for improved carbon capture technology. Progress in Energy and Combustion Science 2012, 38(5), 630–671. DOI 10.1016/j.pecs.2012.03.003.

11. Breyer CH, Rieke S, Sterner M, Schmid J, Hybrid PV-Wind-Renewable Methane Power Plants. European Photovoltaic Solar Energy Conference, Hamburg, Germany, 2011. http://www.q-cells.com/uploads/tx_abdownloads/files/6CV.1.31_Breyer2011_HybPV-Wind-RPM-Plants_paper_PVSEC_preprint.pdf, accessed 17.12.2012.

12. Ursua A, Gandia LM, Sanchis P, Hydrogen Production from water electrolysis: current status and future trends. Proceedings of the IEEE 2012; Vol. 100, No. 2: 410-426. DOI 10.1109/JPROC.2011.2156750.

13. Smolinka T, Günther M, Garche J, Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien. Kurzfassung NOW-Studie. Fraunhofer ISE, FCBAT, 2011. http://www.now-gmbh.de/fileadmin/user_upload/RE-Mediathek/RE_Publikationen_NOW/NOW-Studie-Wasserelektrolyse-2011.pdf, accessed 17.12.2012.

14. Smolinka et al., 2011

15. Smolinka et al., 2011

16. Ursua et al., 2012

17. Breyer et al., 2011

18. Dickinson RR, Battye DL, Linton VM, Ashman PJ, Nathan GJ, Alternative carriers for remote renewable energy sources using existing CNG infrastructure. Int J Hydrogen Energy 2012, 35 (3): 1321-1329. DOI 10.1016/j.ijhydene.2009.11.052

arise with long-term stability and poisoning of catalysts and heat management.[19]

Carbon dioxide for the methanation process can be obtained from various renewable and non-renewable sources. CO_2 can be sequestered from flue gas in power plants with combustion processes or is produced in industrial processes like in lime or cement production. Renewable CO_2 sources are biomass gasification, fermentation process in biogas plants or other biotechnological production processes. With a high energy input, CO_2 could even be extracted from the ambient air.[20] CO_2 capture technologies are described in more detail in IPPC, 2005[21] or Li et al. 2013[22].

REALIZED POWER-TO-GAS DEMONSTRATIONS FOR TRANSPORT APPLICATIONS

Numerous power-to-gas pilot plants for transport applications have already been realized or are planned in Europe and some of them are shown in Table 1[23, 24]. The projects are categorized by type of fuel and additional application. Seven of the realized pilot plants were built for stationary applications such as electricity production in a fuel cell and have an additional refuelling station for a small number of hydrogen vehicles. Five of the pilot plants are going to feed in hydrogen into the gas distribution grid and three pilot plants are going to produce synthetic methane that is fed into the gas distribution grid. All of these projects that are going to feed in hydrogen or synthetic methane are located in Germany and have been recently realized or are planned for the next years. Power-to-gas pilot plants that produce H_2 for refuelling stations have been realized since the year of 1991 and are located in several European countries.

Power-to-gas pilot plants have been evaluated by Gahleitner, 2013,[25] and some of the main conclusions of the projects are shortly summarized. Alkaline electrolyzers are mainly applied since they are commercially available and occurring problems are for instance low hydrogen purity and high stack degradation. PEM electrolyzers are increasingly utilized in the last few years as they are better suited for fluctuating input but problems with short lifetimes and rapid degradation were reported. Other challenges are the lack of mass-produced hydrogen components, low reliability and problems with fluctuating and intermittent power input. Further research is required to improve efficiency, lifetime and costs of hydrogen components. System integration should be addressed and pilot plants should be operated continuously over years to gather long-term experiences.

ECOLOGIC EVALUATION

In this section, the environmental impacts of applying power-to-gas for mobility purposes are evaluated. The primary energy demand for hydrogen and synthetic methane is compared to other transportation fuels and the overall greenhouse gas emissions are assessed from the life cycle perspective with the system boundary well-to-wheel. The environmental impact of H_2 and synthetic CH_4 produced in power-to-gas plants mainly depends on the origin of electricity and carbon dioxide.

CO_2 can either be obtained from renewable or fossil sources. Allocation of CO_2 is not discussed in this article, but if carbon dioxide is sequestered from fossil point sources such as flue gas from coal combustion, it has to be considered. The power-to-gas approach is only relevant as CO_2 storage strategy if the CO_2 balance of the resulting product is negative (net CO_2 consumption) over its entire life cycle. From an ecological perspective the product life cycle time and thus the duration of the binding of CO_2 and the possibly substituted fossil based reference product play an important role. The use of synthetic methane from power-to-gas instead of natural gas or diesel in transport applications additionally imposes co-benefits in reduced PM (particulate matter), SO_x, HCl and HF emissions. However, additional emissions and resource consumption of sorbent, strong increase in water consumption and increase in primary energy use (approximately 15–45 %) are reported for carbon capture technologies, especially for post-combustion capture.[26] All of these aspects have to be traded off by resource substitution through synthetic methane from captured CO_2 and the associated co-benefits for fossil fuel substitution.

Table 2[27] presents greenhouse gas emissions for various electricity sources in Austrian electricity labelling, showing that no emissions are allocated to renewable power sources.

Comparing environmental impacts of different automotive fuels, the whole life cycle from raw material extraction, fuel production, distribution and utilization in vehicles has to be considered. The evaluated impacts of different transportation fuels from well-to-wheel are taken from Edwards et al., 2011.[28]

Figure 2[29] shows the primary energy demand of different fuels for transportation, based on data for the year 2010 and distinguishing between fossil and renewable primary energy input. It shows that conventional fossil fuels such as gasoline, diesel and CNG have nearly the same primary energy input per 100 km. The primary energy input is considerably higher (+87 % on average) for biofuels such as biodiesel, ethanol or biogas but mainly originates from renewable sources. One of the highest primary energy input with 434 MJ per 100 km is obtained for compressed hydrogen produced via electrolysis with the conventional EU-mix electricity as input power source.

A comparison of overall greenhouse gas emissions is provided in Figure 3[30]. The highest GHG emissions per km are obtained with compressed H_2 produced in electrolysis with EU-mix electricity. Even conventional gasoline vehicles have lower impact, although representing the highest GHG emis-

19. Project homepage iC4 – Integrated Carbon Capture, Conversion and Cycling. http://www.ic4.tum.de/index.php?id=1235, accessed 17.12.2012.

20. Breyer et al., 2011

21. IPPC, Carbon dioxide capture and storage. Cambridge University Press, 2005.

22. Li B, Duan Y, Luebke D, Morreale B, Advances in CO2 capture technology: A patent review. Appl Energ 2013; 102: 1439 – 1447. DOI 10.1016/j.apenergy.2012.09.009.

23. Based on information from http://www.h2stations.org, accessed January 04, 2013.

24. Gahleitner, 2013

25. Gahleitner, 2013

26. Koornneef J, Ramirez A, Turkenburg W, Faaij A, The environmental impact and risk assessment of CO2 capture, transport and storage - An evaluation of the knowledge base. Progress in Energy and Combustion Science 2012, 38(1), 62–86. DOI 10.1016/j.pecs.2011.05.002.

27. Based on information from E-Control, Electricity Labelling Regulations. 2011. http://www.e-control.at/en/businesses/renewables/electricity-labelling-regulations, accessed 20.02.2013

28. Edwards et al., 2011

29. Based on information from Edwards et al., 2011.

30. Based on information from Edwards et al., 2011

Table 1. European power-to-gas pilot plants for transport applications.

Project Name	Country	Start-up	End
Power-to-gas pilot plants for stationary applications with hydrogen refuelling station			
SWB Project in Neunburg vorm Wald	Germany	1991	1999
Laboratory Plant Stralsund	Germany	1998	-
PURE Project at the island of Unst	United Kingdom	2005	-
Baglan Energy Park Wales	United Kingdom	2008	-
Hydrogen Mini Grid System Yorkshire	United Kingdom	2012	-
H2Herten	Germany	2012	-
RABH2	United Kingdom	n/a	-
Power-to-gas pilot plants with hydrogen fed into gas distribution grid			
Hybrid Power Plant Enertrag in Prenzlau	Germany	2011	-
RH2 WKA	Germany	2012	-
Demonstration Plant EON in Falkenhagen	Germany	2013	-
Demonstration plant Thüga in Laufen	Germany	2013	-
Windpark Suderburg Greenpeace Energy	Germany	n/a	-
Power-to-gas pilot plants with synthetic methane production			
Solar Fuel Beta-Plant Audi in Werlte	Germany	2013	-
R&D plant (methanation) in Karlsruhe	Germany	n/a	-
P2G plant Erdgas Schwaben	Germany	n/a	-
Power-to-gas pilot plants with hydrogen refuelling station			
Residential Home Friedli	Switzerland	1991	-
H2argemuc at Munich Airport	Germany	1999	2006
Grjóthāls Hydrogen Station in Reikjavik	Iceland	2003	-
Hamburg CUTE	Germany	2003	-
WIV Hydrogen Station in Barth	Germany	2003	-
BP Cute Hydrogen Refuelling Station Barcelona	Spain	2003	2007
CUTE Station Amsterdam	Netherlands	2003	2008
Multifuel refuelling station Malmö	Sweden	2003	-
CUTE station Stockholm	Sweden	2003	2005
CEP Aral Station Berlin Messedamm	Germany	2004	2008
Zero Emission Hydrogen Bus ENEA	Italy	2004	-
Volkswagen Technology Center Isenbüttel	Germany	2005	-
RES2H2 Attica in Greece	Greece	2006	-
AGIP Mulitenergy Station in Collesalvetti	Italy	2006	-
Mobile Filling Station of Fraunhofer Institute in Dresden	Germany	2006	-
Samsoe non road - Energy Academy	Denmark	2006	-
ITHER - Green hydrogen from Wind and Solar for Mobile Applications	Spain	2007	-
Expo Zaragoza 2008	Spain	2008	-
Solar Hydrogen Station Fronius	Austria	2009	-
Althytude Dunqerqe	France	2009	-
ITM Power Green Hydrogen Refuelling at Nottingham University	United Kingdom	2009	-
Hydrohybrid at ITC Gran Canaria	Spain	2009	-
CEP Total Station Berlin Holzmarktstraße	Germany	2010	-
H2Seed	United Kingdom	2010	-
Walqa Hydrogen Filling Station (ITHER)	Spain	2010	-
Las Columnas, Hynergreen	Spain	2010	-
Hynor Lillestrom hydrogen station	Norway	2010	-
Stand-alone power system in Thessaloniki	Greece	2011	-
H2 moves Oslo	Norway	2011	-
WaterstofNet Station Halle in Brussels	Belgium	2012	-
Aargau Chic Station 1 in Brugg	Switzerland	2012	-
Hamburg Hafen City CEP	Germany	2012	-
H2 Move at ISE Fraunhofer	Germany	2012	-
Stuttgart EnBW Station	Germany	2012	
Hydrogen Refuelling at Arctic Driving Center	Finland	2012	-
Loughborough hyrogen refuelling	United Kingdom	2012	-
Hynor CHIC Oslo Bus Station	Norway	2012	-
Refuelling Station at Golden Horn Estuary in Istanbul	Turkey	2012	-
Hynor Lyngdal	Norway	2013	-
IDYLHYC	France	n/a	-

Table 2. Greenhouse gas emissions for various electricity sources from the Austrian electricity labelling.

Energy Vector	GHG emissions [g/kWh$_{el}$]
Solid or liquid biomass	0
Biogas	0
Geothermal energy	0
Wind power	0
Solar energy	0
Hydro power	0
Natural gas	440
Oil	645
Coal	882
Nuclear energy	0
Others	650

sions among fossil fuels. As a consequence, hydrogen or synthetic methane production by utilizing EU-mix electricity should not be favoured. If 100 % wind electricity is utilized for H_2 production, only 9 g_{CO2eq} are emitted per kilometre and substantial reduction in greenhouse gases could be achieved.

Figure 3 only provides information on GHG emissions of H_2 but not of synthetic methane as such WTW calculations were not performed by Edwards et al., 2011[31]. Supposing that both electricity and CO_2 originate from renewable sources, a rough estimation of overall GHG emissions of synthetic methane could be obtained by including a methanation efficiency of 80 %. This results in 11.3 g_{CO2eq} per kilometre, which is still lower than for all the other fuels. Based on this result, a reduction of about 93 % in greenhouse gas emissions can be achieved with synthetic methane compared to diesel. A more detailed well-to-wheel analysis should be performed in future research.

Besides the low greenhouse gas emissions per kilometre, other advantages of fuel production from power-to-gas are the long-term storage of excess electricity, the higher operation times of renewable power sources and the reduced effort for the public electricity grid as energy transport is shifted to the gas distribution grid.

OVERALL POTENTIAL

The overall potential of the technology power-to-gas for transport or other applications is depending on various parameters and trends. Since power-to-gas could be employed for energy storage, the overall potential of the technology depends on the future storage demand for electricity. The energy storage demand is influenced on the one hand by the percentage of fluctuating renewables in the overall electricity generation and on the other hand on the efficiency, costs and availability of alternative storage technologies such as pumped hydro, compressed air, flywheels, or batteries.

Another influencing parameter is the desired percentage of renewables in the transport sector. Due to the lack of renewable alternative fuels with adequate potential, H_2 or SNG from power-to-gas could be interesting alternatives to replace fossil fuels. The future potential in transport applications also depends on the development of CNG infrastructure (refuelling stations, cars) and H_2 infrastructure.

The quality of the power network also influences the potential of power-to-gas technology as in weak grids there is a stronger need for energy storage and balancing power. Especially in remote areas, for instance near large offshore wind parks, the local electricity demand is low and the grid often cannot absorb the total amount of generated electricity. Since the power grid expansion is time consuming and very often accompanied by strong public resistance, energy transport via the gas distribution grid and application for transport could be an interesting alternative.

If SNG is produced via power-to-gas technology, the availability of an adequate carbon dioxide source is decisive too. Theoretically, CO_2 could be extracted from ambient air but the energy input for these processes is very high.

Case Study Austria

In the case study for an Austrian public bus fleet, production costs of SNG via power-to-gas are calculated for the mid-term and the long-term perspective. Operational costs for a whole CNG bus fleet are calculated and compared to the operation with conventional diesel buses. Taxes and charges for the gas distribution system and the public electricity grid are outlined and the influence of certain parameters such as full load hours, investment costs and operation mode of the power-to-gas plant are discussed. H_2 is not considered as transportation fuel for this case study as SNG has the great advantage that it can be fed into the gas distribution without restrictions and that CNG refuelling stations and buses are state-of-the-art technologies.

SYSTEM DESIGN AND DEMAND

For the design of the power-to-gas system, a bus fleet with 70 buses is assumed. Table 3[32, 33, 34] shows the main parameters of the bus fleet and the required power-to-gas system with information on efficiency, nominal power and consumables. When assuming 6,000 full load hours per year, a power-to-gas plant with a nominal capacity of 8.9 MW_{el} is required for supplying a bus fleet with 70 buses. The calculations were performed for a lower heating value for synthetic methane of 10.4 kWh/Nm³ and a density of 0.8 kg/Nm³. Carbon dioxide has a density of 1.977 kg/m³ and oxygen has a density of 1.43 kg/m³. With an energy efficiency of 50 % the power-to-gas plant consumes about 53,000 MWh_{el} electricity per year. This is comparable to the yearly produced electricity of four 7 MW_{el} wind turbines in Austria with approximately 2,000 full load hours per year. Compared to the overall electricity that is produced from wind energy in Austria (1.9 million MWh_{el}[35]) 2.7 % would be re-

31. Edwards et al., 2011

32. Table 3 Fuel demand remark: Fokkens E, Final report: Analysis of different production processes, which produce biogas with a higher amount of hydrogen. 2012. http://www.balticbiogasbus.eu/web/Upload/Supply_of_biogas/Act_4_4/WP%204%204_Final%20report_310812.pdf, accessed 20.02.2013

33. Table 3 Efficiency power-to-gas plant remark: Rieke S, Regenerative Vollversorgung – von der Vision zur Praxis. Hannover, 2011. http://www.bee-ev.de/_downloads/bee/2011/HannoverMesse/20110404_HMI_SoarFuel_Rieke_Vollversorgung.pdf, accessed 17.12.2012.

34. Table 3 Heat utilization remark: Rieke, 2011

35. Statistics Austria, Energy Balances Austria 1970 to 2011. http://www.statistik.at/web_en/statistics/energy_environment/energy/energy_balances/index.html, accessed 08.01.2013

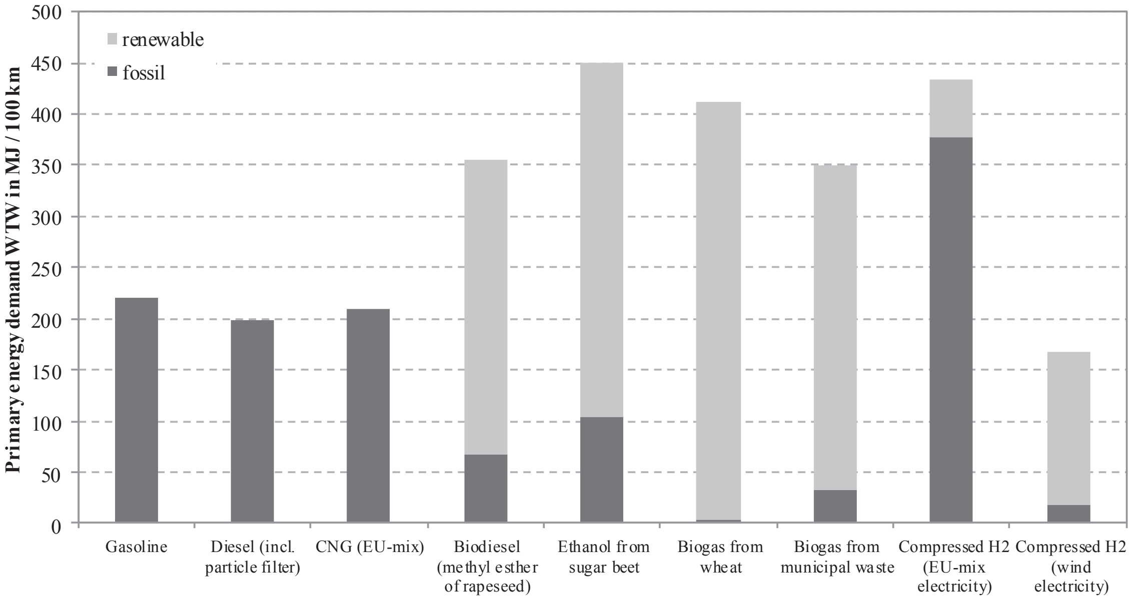

Figure 2. Primary energy demand WTW of various automotive fuels.

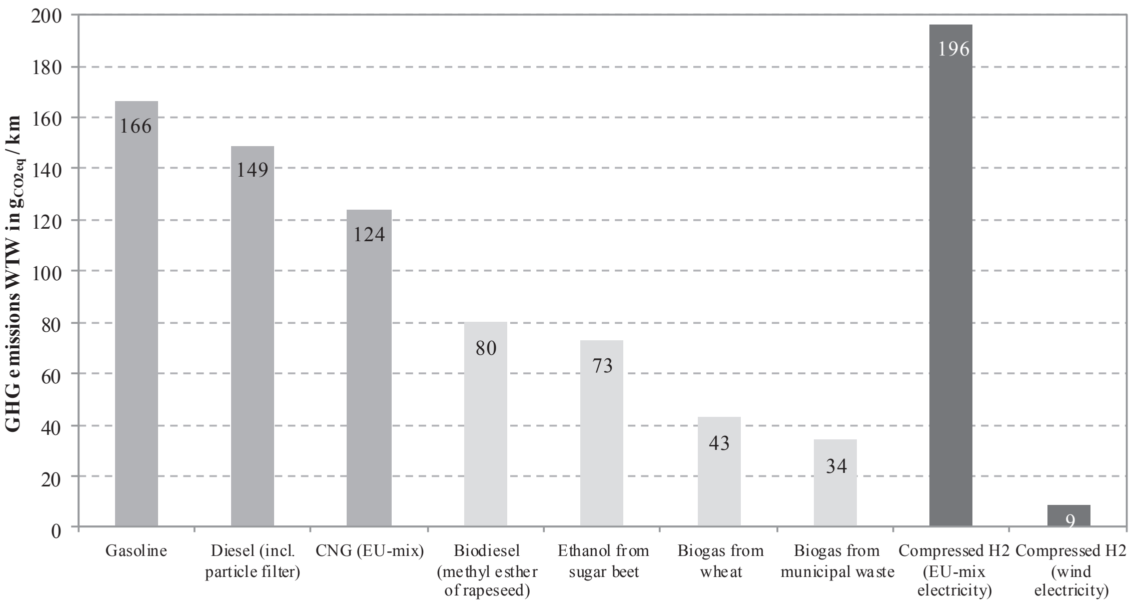

Figure 3. Greenhouse gas emissions WTW for various automotive fuels.

quired for the power-to-gas system. Heat and oxygen are useful by-products of power-to-gas plants that could decrease the fuel production costs.

PRODUCTION COSTS

This section provides calculations on the production costs for SNG from power-to-gas plants. The calculations are based on economic data from peer-reviewed articles and data from manufacturers. Three cases are considered in the evaluation of fuel production costs.

The first case 1a represents the production costs for the mid-term perspective with some exemptions from payment of electricity system charges. The second case 1b includes the current charges for the gas distribution system and the public electricity grid. The third case 2 represents the fuel production costs for the long-term perspective without charges for the electricity and gas system and decreased investment costs. The main assumptions for the different cases are displayed in Table 4[36, 37, 38]. The calculations of the production costs for synthetic methane from power-to-gas consider a component lifetime of 12 years and a rate of interest of 5 %. The yearly costs in case 1a are 4.4 million Euro

36. Table 4 Investment power-to-gas plant remark: Rieke, 2011

37. Table 4 Carbon dioxide remark: Grollmisch C, Regelenergie und Power to Gas. Systemstabilisierung im deutschen Stromübertragungsnetz durch Nachfragesteuerung und Bewertung der wirtschaftlichen Effekte am Beispiel einer Methanerzeugungsanlage. 2011. www.praktikumspark.hszigr.de/download/Vortrag-ConradGrollmisch-20111018.pdf, accessed 13.6.2012.

38. Table 4 Oxygen remark: Grollmisch, 2011

Table 3. Main parameters for the bus fleet design of power-to-gas system.

Parameter	Value	Unit	Remark
Bus fleet			
Amount of buses	70	-	Typical bus fleet for Austrian city
Driven distance per year	65 000	km / (a bus)	Information according to local public transport systems
Fuel demand per 100 km	45	kg/100 km	Typical fuel demand of CNG buses
Total fuel demand per year	2 559 375	Nm³/a	
Power-to-gas system			
Full load hours power-to-gas plant	6 000	h/a	Author's assumption
Efficiency power-to-gas plant	50%		according to manufacturer information
Heat utilization	15%		according to manufacturer information
Capacity power-to-gas plant	427	Nm³/h	
Nominal power	8.9	MW_{el}	
Consumables and by-products			
Electricity	53 235	MWh_{el}/a	
Carbon dioxide	5 060	t/a	Approximately 1 Nm³ CO_2 per Nm³ CH_4
Heat	8 108	MWh_{th}/a	
Oxygen	7 315	t/a	Approximately 2 Nm³ O_2 per Nm³ CH_4

Table 4. Main parameters for the calculation of fuel production costs.

Parameter	Case 1a	Case 1b	Case 2		Remark
Investment power-to-gas plant	2 000	2 400	1 000	€/kW_{el}	According to manufacturer information
Operation and maintenance costs	2%	4%	2%		Author's assumption
Carbon dioxide	20	50	20	€/t_{CO2}	Assumption according to
Electricity	50	90	50	€/MWh_{el}	Author's assumption
Public electricity grid (Austria)*					
Electricity system charge (power)	0	34.92	0	€/kW_{el}	* Charges and fees are taken from the Austrian regulation on system charges 2012, the Austrian regulation on green electricity 2012 and the Austrian electricity tax act.
Grid provision charge (network level 5)	0	101.48	0	€/kW_{el}	
Grid utilization charge (power)	0	0.0014	0	€/kW_{el}	
Metering fee, load-profile	900	900	900	€/a	
Green electricity fee	5 200	5 200	5 200	€/a	
Electricity system charge (energy)	0	0.00800	0	€/kWh_{el}	
Transmission loss charge (network level 5)	0	0.00120	0	€/kWh_{el}	
Electricity tax	0	0.01500	0	€/kWh_{el}	
Grid utilization charge (energy)	0	0.00023	0	€/kWh_{el}	
Gas distribution system (Austria)					
Grid provision and access charge	0	0	0	€/kW	Assumed to be available
Grid utilization charge	0	117 212	0	€/a	Austrian regulation on gas system charges 2008 (2012)
Metering fee	0	270	0	€/a	
Natural gas tax	0.066	0.066	0.066	€/m³	Assumption according to biogas
Additional costs - carbon capture	0	0.229	0	€/Nm³	
Heat	20	0	20	€/MWh_{th}	Author's assumption
Oxygen	50	0	50	€/t_{O2}	Assumption according to

which result in production costs for SNG of 17 Eurocent per kWh. For case 1b that includes all charges that have to be paid currently, the overall costs sum up to 10.8 million Euro per year and fuel production costs of 41 Eurocent per kWh. In the long-term perspective, represented by case 2, total annual costs of 3.4 million Euro and fuel production costs of 13 Eurocent per kWh could be achieved. Figure 4 shows the fuel production costs for SNG according to the type of investment.

For the power-to-gas plant in the Austrian case study, electricity costs account for the largest share. Whereas in case 1a, the investment costs for the power-to-gas plant sum up to a high percentage too, the investment costs are not so dominant in the other two cases. In case 1b it is obvious that the gas distribution system and the public electricity system charges lead to high fuel production costs as they account for 31 % of the overall costs. These system charges should be reduced to a minimum to make power-to-gas more competitive as fuel for transportation purposes. Another important aspect is that the costs for CO_2 only account to a very small amount between 2 % and 3 % of overall production costs. A small reduction in costs could additionally be achieved by selling heat and oxygen that are produced as by-products.

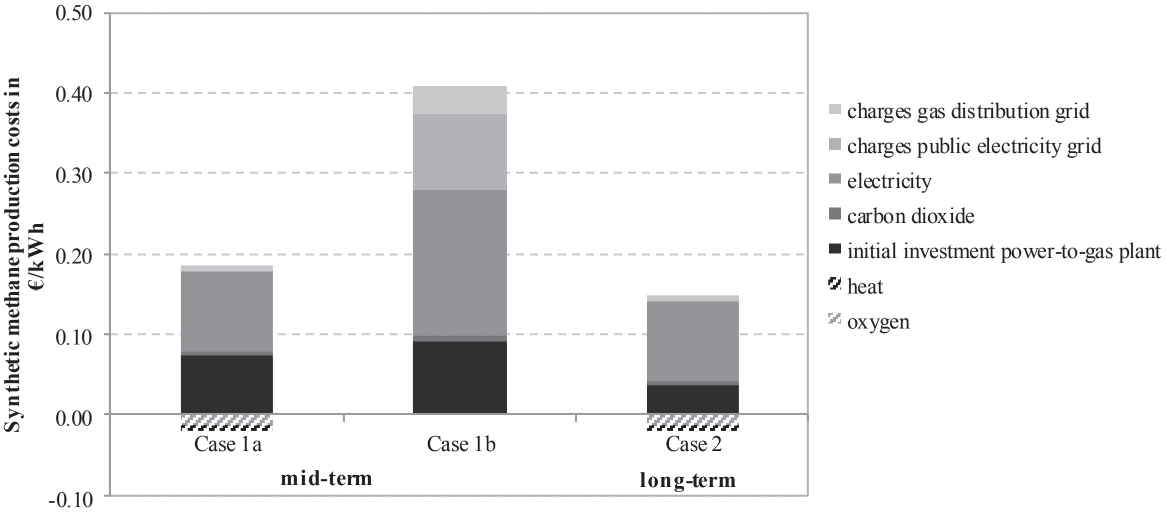

Figure 4. Fuel production costs for synthetic methane from power-to-gas.

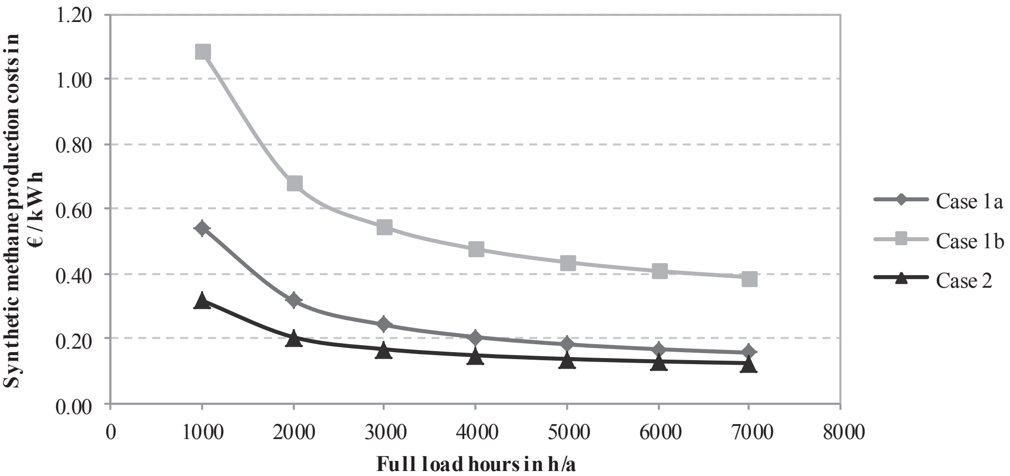

Figure 5. Sensitivity analysis of synthetic methane production costs against full load hours.

Figure 5 shows a sensitivity analysis of the SNG production costs as a function of annual full load hours.

It is evident in Figure 5 that the production costs of SNG via power-to-gas strongly depend on the achievable full load hours. Since case 1b has the highest initial investment costs, this is the case for which the fuel production costs depend most on the full load hours. For being cost competitive on a long-term perspective, full load hours for power-to-gas systems should reach a minimum of 3,000 hours per year.

OVERALL COSTS

The overall costs for a public bus fleet do not only depend on the fuel production costs but also on the investment and maintenance costs of the buses, which are higher for CNG buses than for conventional diesel buses at the moment. The calculations again are based on a lifetime of 12 years and a rate of interest of 5 %. The CNG demand is determined with 45 kg per 100 km and the diesel demand is 45 l per 100 km. The lower heating value of diesel is 10.0 kWh/l and the density is 0.85 kg/l. Schloffer et al., 2010[39] state that the initial capital investment for a CNG bus is 304,750 Euro and the initial costs for a diesel bus are 265,000 Euro. The annual costs for maintenance and operation (without fuel costs) are determined to be 4 % of the initial investment costs. Table 5[40, 41] provides information on the fuel costs applied in the calculation of overall costs in each case.

The overall annual costs for CNG buses with fuel production via power-to-gas lie between 6.7 and 14.1 million Euro for case 2 and 1b respectively. The overall costs for operation with fossil CNG are lower and range between 5.0 and 5.8 mil-

39. Schloffer M et al., Alternative Treibstoffe und umweltfreundliche Antriebssysteme im öffentlichen Regionalverkehr. Programmlinie "A3plus" – eine Initiative des Bundesministeriums für Verkehr, Innovation und Technologie (BMVIT) – Endbericht, Kapfenberg, 2010. www2.ffg.at/verkehr/file.php?id=248, accessed 08.01.2013.

40. Table 5 CNG remark: http://www.oeamtc.at/?id=2500%2C%2C1340655%2C, accessed 08.01.2013.

41. Table 5 Diesel remark: http://www.oeamtc.at/?id=2500%2C%2C1340655%2C, accessed 08.01.2013.

Table 5. Fuel costs for the calculation of overall costs.

Fuel	Case 1a	Case 1b	Case 2	Unit	Remark
SNG from power-to-gas	0.17	0.41	0.13	€/kWh	See calculation of fuel production costs
CNG	0.06	0.07	0.10	€/kWh	Assumptions according to
Diesel	0.10	0.12	0.20	€/kWh	Assumptions according to

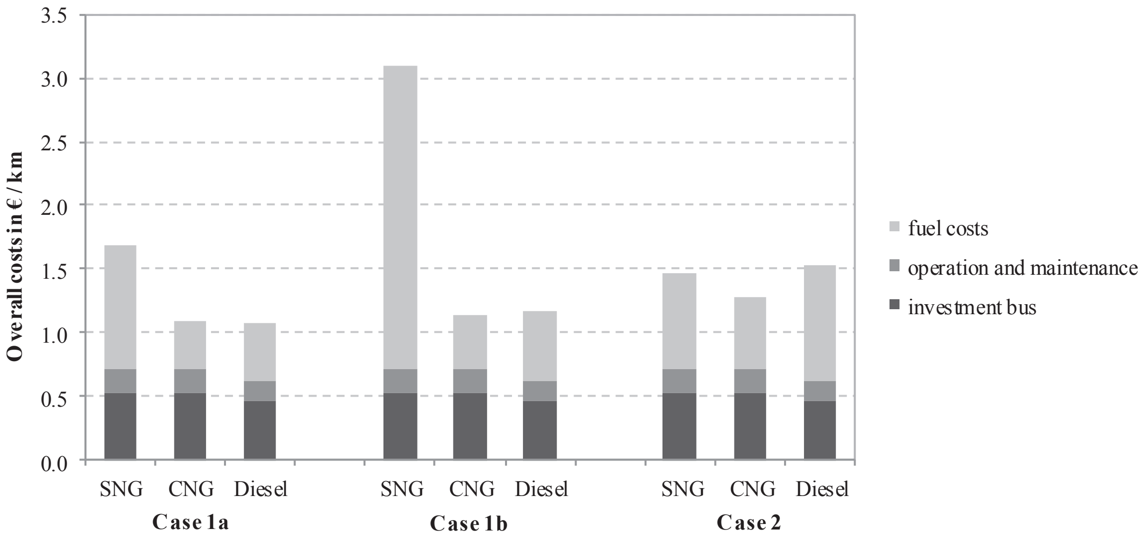

Figure 6. Overall costs for operating the bus fleet with SNG, CNG or diesel.

lion Euro per year. Operation with conventional diesel buses entails total costs between 4.9 and 6.9 million Euro per year. Figure 6 illustrates the overall costs for the public bus fleet per kilometre.

Figure 6 shows that in the mid-term (cases 1a and 1b) the costs for SNG produced from power-to-gas plants are considerably higher than for conventional fuels such as CNG and diesel. These results from the higher fuel production costs as the investment and operational costs are nearly the same for all of the three fuel types. With an adaptation of the legal framework and a reduction in investment costs for the power-to-gas plant due to technological improvements, the production costs of SNG could be significantly reduced. Therefore, synthetic methane could be competitive in the long-term as represented by case 2.

Conclusions

For reducing overall greenhouse gas emissions in the transportation sector, not only efficiency improvements, but also alternative renewable fuels are required. Power-to-gas could be one possible technology for providing renewable fuel and at the same time utilize overproduction from renewable power sources. There are various pathways that could be realized with power-to-gas as hydrogen or synthetic methane can be produced out of excess electricity. Both energy vectors can be either directly utilized in a refuelling station or be fed into the gas distribution grid for utilization elsewhere. For the synthesis of methane out of hydrogen, carbon dioxide is required that could be obtained from fossil or renewable sources such as flue gas from coal combustion or biogas plants respectively. Challenges for electrolyzers, being the main component of power-to-gas systems, arise especially with fluctuating power input as it leads to decreased durability and efficiency. The overall potential of power-to-gas depends on various parameters such as energy storage demand, percentage of renewables in electricity and transportation sector or quality of the power grid.

The overview of realized and planned European power-to-gas pilot plants for transport applications show that H_2 refuelling stations with on-site production via electrolysis have been built since 1991. Feeding hydrogen or synthetic methane into the gas distribution has not yet been realized but several pilot plants are planned for the next years in Germany. Reported problems are the unreliable operation with fluctuating power input, low efficiencies, high stack degradation and high investment costs.

The ecological evaluation of transportation fuels from power-to-gas shows that the origin of electricity and CO_2 has strong influence on the ecological performance. The comparison of various automotive fuels shows that H_2 produced from EU-mix electricity causes the highest greenhouse gas emissions per 100 km. Therefore it is indispensable that only renewable electricity is utilized for production of transportation fuels via power-to-gas. From an ecological perspective the additional resource consumption for CO_2-capture and the power-to-gas-conversion process have to be traded off by the substituted emissions of fossil fuel transport systems.

The case study for an Austrian public bus fleet provides information on synthetic methane production costs and overall costs for a CNG bus fleet. It is shown that the greatest part of production costs result from electricity costs and initial investment for the power-to-gas system. Charges for the energy infrastructure (gas distribution system and public electricity grid) sum up to considerable costs too and so an adaptation of the legal framework is necessary. A sensitivity analysis shows that full load hours of the power-to-gas plant have great influence on the production costs and a minimum of 3,000 hours per year should be achieved. Overall costs for operation of a bus fleet are compared for SNG via power-to-gas, conventional CNG and diesel as transportation fuels. In the mid-term SNG cannot compete against conventional fuels due to the high initial investment costs. However, it could be cost-competitive in the long-term when reduction of initial investment and adaptation of the legal framework in Austria could be achieved.

Future research should focus on the comparison of fuels from power-to-gas with other renewable transportation technologies such as the utilization of biofuels or electric vehicles powered by renewable electricity. Especially for excess renewable electricity as input the power-to-gas concept offers ecological benefits which should be addressed by comprehensive well-to-wheel studies. Further work is also required on the allocation of carbon dioxide that is obtained from fossil sources. Additionally, the optimum system integration into the energy infrastructure has to be addressed as power-to-gas is suited for both, electricity storage and fuel production.

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