FNSNF
Swiss National Science Foundation

70 NRP
Energy Turnaround
National Research Programme

Zurich University of Applied Sciences
zh aw
Life Sciences and Facility Management
Institute of Natural Resource Sciences

Life Cycle Assessment of Renewable Methane for Transport and Mobility




v1.0
Prepared by

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On behalf of HSR Hochschule für Technik Rapperswil
As part of the NRP 70 project «Methane for transport and mobility (RMTM)»
Published with support of the Swiss National Science Foundation

Cover picture: Photovoltaic power plant, power lines, gas industry, traffic
Source: www. colourbox.de

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Version Wettstein, Itten and Stucki_2018_LCA RMTM_v1.0.docx, 25.01.2018 10:22:00

Summary

As part of the National Research Programme NRP 70 «Energy Turnaround», the project «Renewable Methane for Transport and Mobility» analysed the power-to-gas process and its application in the mobility sector in Switzerland. The Life Cycle Assessment research group of the Zurich University of Applied Sciences performed a life cycle assessment of the full value chain, analysing greenhouse gas (GHG) emissions and total environmental impacts according to the Ecological Scarcity Method 2013.

Power-to-gas (PtG) technology converts hydrogen (H_2) and carbon dioxide (CO_2) to synthetic methane (CH_4). Synthetic methane can be stored and transported in the existing natural gas network and is available to be used, for example, in the transport and mobility sector. Various scenarios for the PtG value chain were defined, including prospective scenarios for parameters like hydrogen electrolysis efficiency, electricity supply, CO_2 sources, and methane synthesis technology. Finally, mobility fuelled by PtG methane was compared to mobility fuelled by fossil fuels.

The results of the life cycle assessment showed that driving with PtG methane leads to lower GHG emissions per kilometre driven in comparison to vehicles fuelled with fossil fuels such as petrol, diesel, and natural gas if the electricity supply is associated with low GHG emissions. Up to 52% of the GHG emissions of mobility can be reduced if renewable PtG methane is used. Regarding total environmental impacts per kilometre driven, similar or lower total environmental impacts are only achievable if electricity from hydropower, municipal waste incineration, or surplus production is used for hydrogen production. From a sustainability perspective, it is essential that the development of PtG technology in Switzerland does not lead to an increase of electricity imports from fossil fuel power plants.

Hydrogen production using electrolysis is the crucial life cycle stage in terms of the GHG emissions and total environmental impacts of PtG methane, resulting in a contribution up to 57% and 64%, respectively. Electrolysis efficiency of 80% can significantly reduce GHG emissions and other environmental impacts compared to a lower efficiency. The source of CO_2 for the PtG process also has a significant impact on the LCA results. If CO_2 is collected from industrial waste gases, total GHG emissions decrease by up to 18% compared to absorbing CO_2 from the atmosphere. The LCA results of biogenic methanation in a stirring tank reactor and a trickle bed reactor are very similar to those of methanation in a catalytic adsorption reactor.

The emerging PtG technology was compared with the currently established fossil fuel value chain. It emerged that the PtG value chain has significant potential for further technology development and further reduction of environmental impacts. If the environmental impacts related to energy consumption associated with hydrogen production can be reduced, renewable methane offers considerable potential as an alternative fuel for a more sustainable mobility sector.

Content

Abbreviations

CdTe	Cadmium telluride
CO_2	Chemical formula for carbon dioxide
CH_4	Chemical formula for methane
FU	Functional Unit
GHG	Greenhouse gas
h	hour
H_2	Chemical formula for hydrogen
HCNG	Hydrogen-compressed natural gas
HSR	Hochschule für Technik Rapperswil
LCA	Life cycle assessment
MEA	Monoethanolamine
MW	Energy unit, megawatt
N_2O	Chemical formula for dinitrogen monoxide
NaOH	Chemical formula for sodium hydroxide solution
Nm^3	Standard cubic metre
PSA	Pressure swing adsorption
PtG	Power-to-gas
PV	Photovoltaic
Si	Chemical formula for silicon
UBP	Environmental impact points, eco-points (German «Umweltbelastungspunkte»)
vkm	Vehicle kilometre

1. Introduction

The project «Renewable Energy for Transport and Mobility» analysed the power-to-gas process and its application for the mobility sector in Switzerland. It was part of the National Research Programme NRP 70 «Energy Turnaround» and involved a consortium of research and industry partners under the lead of Prof. Dr. Markus Friedl from the University of Applied Sciences Rapperswil. The research group for Life Cycle Assessment at the Institute of Natural Resource Sciences of the Zurich University of Applied Sciences was responsible for the environmental sustainability assessment of the value chain analysed in the project.

The goal of the subproject environmental sustainability assessment was to assess the environmental sustainability of mobility fuelled by methane produced in a power-to-gas (PtG) process. To this end, a life cycle perspective and a quantitative approach were applied following life cycle assessment (LCA) methodology. The study focused on power-to-gas use in Switzerland and included different scenarios with regard to electricity mixes as well as H_2 and CO_2 sources.

With the power-to-gas technology, synthetic methane is produced from carbon dioxide and hydrogen using electricity for the production of synthetic H_2 and methane (CH_4). The life cycle environmental impacts of different technologies for electricity generation in Switzerland have been assessed by Bauer et al. (2012). They evaluated seven environmental indicators: greenhouse gas emissions, radioactive waste, respiratory effects of particle matter, ecosystem damage potential, cumulative energy demand, abiotic resource depletion, and ionising radiation.

A well-to-wheel analysis of solar powered hydrogen production and utilization for passenger car transportation in the Swiss context has been conducted by Felder & Meier (2008). They showed that using solar hydrogen in fuel cell cars reduces life cycle greenhouse gas emissions by 70% compared to advanced fossil fuel powertrains (Felder & Meier, 2008).

A detailed LCA of the entire power-to-gas process for producing methane was conducted by Zhang et al. (2017) and Parra et al. (2017). A first well-to-wheel LCA of the production and use of synthetic methane has been conducted by Walspurger et al. (2013). The automobile manufacturer Audi calculated a well-to-wheel carbon footprint of about 27 g CO_2-eq./vkm, if cars drive with synthetic methane produced from wind power sold by Audi as «e-gas» in Germany (Trechow & Pester, 2011).

2. Goal and Scope

The next subchapters describe the goal of the study (subchapter 2.1), the functional unit (subchapter 2.2) and the system boundaries (subchapter 2.3) of the study. Subchapter 2.4 describes the life cycle impact assessment method and subchapter 2.5 informs about the most relevant data sources used.

2.1. Goal of the Study

The LCA aimed at identifying environmental hotspots in the methanation value chain and facilitating recommendations for a technology improvement from an environmental perspective. Therefore, the influence of critical factors and assumptions with high uncertainty on the results were evaluated in scenarios. The life cycle impact assessment results were aggregated, interpreted and documented in the present LCA report. Additionally, a calculation tool was developed, which allows to model different scenarios for power-to-gas technology and to compare them with reference values. To gain the life cycle assessment of the methane value chain specific for Switzerland, individual unit process models for various electricity mixes and vehicles were established according to specific Swiss conditions.

2.2. Functional Unit

The functional unit (FU) was defined as driving a passenger car over a distance of 1 km, based on a petrol car of compact size with an average weight of 1200 kg. Scenarios with renewable methane produced by power-to-gas technology were compared to driving with fossil fuels such as petrol or natural gas.

2.3. System Boundaries

In the whole value chain of PtG methane production various scenarios were analysed by varying electricity supply, CO_2 source, electrolysis efficiency and methane reactor type. For electricity supply Swiss consumer mix today, in 2035 and in 2050, hydropower, photovoltaics (polycrystalline silicon (Poly-Si) and Cadmium-Telluride thin film (CdTe) PV panels), municipal waste incineration and surplus electricity were considered. CO_2 was assumed to be collected either from atmosphere or from industrial waste gases of Swiss cement plants. Electrolysis efficiency was varied from low efficiency (62%) to high efficiency (701%) and an additional prospective efficiency of 80% was assumed. H_2 and CO_2 were either converted to methane in a catalytic or a biogenic methane reactor. Additionally, infrastructure, service station and natural gas powered car were considered too. The temporal system boundary reached from the current state of research in 2015 until prospective scenarios in 2050 and the geographical system boundary referred to conditions in Switzerland. The system boundaries of the whole value chain of PtG methane production are illustrated in Figure 2-1.

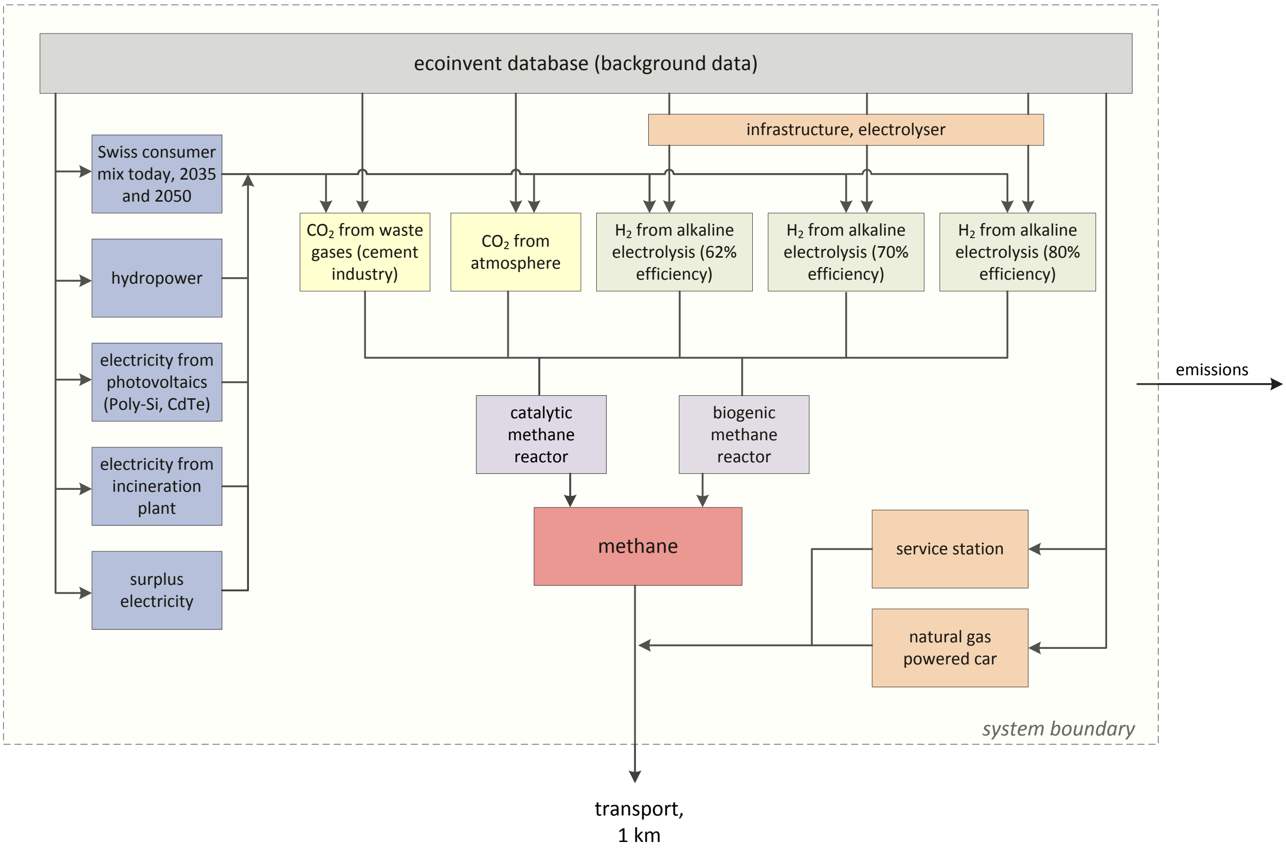


Figure 2-1: System boundaries of the whole value chain of PtG methane production considered

The scenarios of electricity supply, alkaline electrolysis efficiency, CO_2 source and methane reactor type were free combined with all other scenarios, resulting in 72 different scenario combinations in total. All possibilities of combining are given in Table 2-1.

Table 2-1: Specifications of scenarios for PtG methane production regarding electricity supply, alkaline electrolysis efficiency, CO_2 source and methane reactor type

Electricity supply	**Alkaline electrolysis efficiency**	**CO_2 source**	**Methane reactor type**
Swiss consumer mix today, in 2035 and 2050	Low efficiency 62%	Waste gases (cement industry)	Catalytic methane reactor
Hydropower	High efficiency 70%	Atmosphere	Biogenic methane reactor
Photovoltaics (Poly-Si)	Prospective efficiency 80%		
Photovoltaics (CdTe)			
Municipal waste incineration plant			
Surplus electricity			

All considered scenarios refer to Swiss conditions relating to electricity mix, electricity production through hydropower and photovoltaics and road construction. Where available, was referred to European conditions and if not otherwise possible to global conditions. The considered time horizon reached from actual state of research until future scenarios in 2035.

2.4. Life Cycle Impact Assessment Methods

To assess the environmental impact associated with synthetic methane production through power-to-gas technology following largely the ISO 14040 and 14044 standards (International Organisation for Standardization, 2006a; 2006b), the impact assessment methods listed in Table 2-2 were used in order to adequately take into account the greenhouse gas relevant exhaust gas emissions from mobility as well as to gain an comprehensive overview of environmental impacts specific for Switzerland.

Table 2-2: Impact indicators used to calculate the environmental impact of synthetic methane through power-to-gas technology

Indicator	Method	Abbreviation used	Description
Climate change	IPCC (2013)	GHG emissions	The impact indicator climate change accounts for all greenhouse gas (GHG) emissions. The potential climatic effect of each greenhouse gas is compared with the climate impact of CO_2 and expressed in CO_2-equivalents
Set of 19 environmental impact indicators (energy resources, land use, heavy metals, water pollutants, radioactive waste etc.)	Ecological Scarcity 2013 (global model)	Total environmental impact	The method weights 19 environmental impacts (emissions and resources) according to specific eco factors and expresses them in eco-points (UBP). The eco factor of a product is deduced from the Swiss environmental protection law and the Swiss policy objectives. The higher the emissions or resource consumption of a product, the higher is its eco factor and therefore its environmental impact (Frischknecht & Büsser Knöpfel, 2013).

2.5. Most Relevant Data Sources

Life cycle inventory (LCI) data for the different processes were obtained from the project of the Hochschule für Technik Rapperswil (HSR) and simulations, as well as from literature. Data for hydrogen production from electrolysis were based on Zah et al. (2015) as well as information about electricity consumption for gas compression and methanation. As described in Figure 2-1 and Table 2-1, carbon dioxide was either captured from a municipal waste incineration plant or from atmosphere. The former was mainly modelled according to Koornneef et al. (2008) with additional data from Zah et al. (2015), the latter on Climeworks (2016).

Data for passenger cars running on petrol, diesel, natural gas and electricity were based on transport information EURO5 from the international ecoinvent v3.3 database (ecoinvent Centre, 2016) and were adapted to EURO6 standards in accordance with the European Commission[1].

Background data for the life cycle inventories of infrastructure (gas grid, pipelines, service station, passenger car, transport infrastructure and road) as well as emissions relating to burning natural gas and driving wear (road wear, tyre wear, brake wear), were taken from the international ecoinvent v3.3 database (ecoinvent Centre, 2016) as well. The system model «allocation, recycled content» was used. The foreground inventory data were linked to background data from the ecoinvent v3.3 database and modelled using SimaPro 8.4 software (PRé Consultants, 2017).

[1] European Commission – Transport, http://ec.europa.eu/transport/themes/urban/vehicles, accessed at 2.8.2016

3. Life Cycle Inventory

This chapter describes the life cycle inventories of synthetic methane production. In a first step, general assumptions regarding hydrogen production are described (subchapter 3.1). In a second step, main characteristics of the CO_2 source by a CO_2 capture plant and from atmosphere are provided (subchapter 3.2). Subsequently, information on the methanation technologies is given in subchapter 3.3. Prospective electricity mixes 2035 and 2050 are described in subchapter 3.4 and subchapter 3.5 explains the reference vehicles. Methanation applied as gas processing and reduction potential by hydrogen-compressed-natural gas (HCNG) follow in subchapter 3.6 and subchapter 3.7, respectively.

3.1. Hydrogen production

Most of the hydrogen worldwide is produced by steam reforming in refineries. Hydrogen from electrolysis is a niche product in the worldwide hydrogen production and only used if the costs for electricity are low. Alkaline electrolysis, PEM-electrolysis and high-temperature electrolysis are the three principle techniques to gain hydrogen through electrolytic water splitting (Smolinka, 2007). In the present study alkaline electrolysis was taken as the default technique for hydrogen production.

Zah et al. (2015) modelled two scenarios for the electrolysis with two different efficiencies: A conservative efficiency of 62% and a high efficiency of 70%. In this study, a prospective, but realistic electrolysis efficiency of 80% was added, to cover future development and efficiency improvement. By improving electrolysis efficiency from 62% to 80%, less energy is used for electrolysis operation and subsequently hydrogen compression. Energy consumption for electrolysis and subsequently H_2 compression regarding electrolysis efficiencies of 62% and 70% are taken from Zah et al. (2015). Regarding electrolysis efficiency of 80%, electrolysis conduction under atmospheric pressure is assumed (Friedl et al., 2016). To inject the produced hydrogen into the natural gas network, its compression to 6 bar is assumed according to Friedl et al. (2016). The life cycle inventory data for 1 kg H_2 production through alkaline electrolysis with efficiencies of 62%, 70% and 80%, respectively are listed in Table 3-1.

Table 3-1: Life cycle inventory data of H_2 production by alkaline electrolysis for electrolysis efficiencies of 62%, 70% (Zah et al., 2015) and 80%

Material/process	Unit	Amount by efficiency			SimaPro
		62%	70%	80%	
Electrolyser	p	1.0	1.0	1.0	Electrolyzer, for electrolysis, p {CH} | production
Diaphragm compressor	p	1.0	1.0	1.0	Diaphragm compressor, p {CH} | production
Storage module, p {CH}	p	1.0	1.0	1.0	Storage module, p {CH} | production
Walls and foundation	p	1.0	1.0	1.0	Walls and foundation, for electrolysis, p {CH} | production
Maintenance	p	1.0	1.0	1.0	Maintenance, for electrolysis, p {CH} | production
Tap water	kg	10	10	10	Tap water {CH}| market for | Alloc Rec, U
Electricity, low voltage*	kWh	61	49.7	42.2	Electricity, low voltage {CH}| market for | Alloc Rec, U

* Representative electricity supply for electricity supply from hydropower, photovoltaics, municipal waste incineration plant and surplus electricity

To use H_2 in the mobility sector, additional infrastructure as pipelines and gas service station are needed. The life cycle inventory data for 1 kg H_2 provided at service station by considering H_2 production through alkaline electrolysis with efficiencies of 62%, 70% and 80%, respectively is given in Table 3-1. Waste heat and decommission of pipelines were not considered due to data availability.

Table 3-2: Life cycle inventory data of H_2 provisions at service station (ecoinvent Centre, 2016)

Material/process	Unit	Amount by efficiency			SimaPro
		62%	70%	80%	
Hydrogen	kg	0.0899			Hydrogen, at electrolysis, kg {CH} efficiency 62%
Hydrogen	kg		0.0899		Hydrogen, at electrolysis, kg {CH} efficiency 70%
Hydrogen	kg			0.0899	Hydrogen, at electrolysis, kg {CH} efficiency 80%
Gas service station	p	6.45E-8			Natural gas service station {CH}| construction | Alloc Rec, U
Pipeline, high pressure	km	3.49E-8			Pipeline, natural gas, high pressure distribution network {GLO}| market for | Alloc Rec, U
Electricity, low voltage*	kWh	0.593			Electricity, low voltage {CH}| market for | Alloc Rec, U

* Representative electricity supply for electricity supply from hydropower, photovoltaics, municipal waste incineration plant and surplus electricity

3.2. CO_2 capture

The following subchapters include the CO_2 capturing from industrial exhaust gases (subchapter 3.2.1) and from the atmosphere (subchapter 3.2.2).

3.2.1. CO_2 capture from exhaust gases

Energy consumption for CO_2 capturing has a broad range depending on the CO_2 concentration in the source. Biogenic CO_2 with a CO_2 concentration of > 99% can be used without additional effort. Fossil CO_2 from exhaust gases presenting a CO_2 concentration of around 12% needs low energy effort for its processing. The most complicated processing is the CO_2 capturing from the atmosphere due to the low CO_2 concentration of 0.04% in the atmosphere, but this technology has the advantage to be independent from time and location (Koornneef et al., 2008).

As described in Figure 2-1 and Table 2-1, CO_2 capturing from fossil exhaust gases is one of the target processing technology. Simplified, CO_2 separation from exhaust gases is done by separation with monoethanolamine (MEA) and following gas compression. For regeneration of the cleaning agent and the operation of pumps and ventilation system heat and electricity is used, respectively. Required agents, auxiliary materials, energy consumption and resulting emissions referring to the production of one ton CO_2 from industrial waste gases are listed in Table 3-3.

Table 3-3: Life cycle inventory of the CO_2 capturing from industrial waste gases through a CO_2 capture plant. Input parameters refer to 1 t captured CO_2 (Koornneef et al., 2008)

Parameter	Unit	Amount	SimaPro
MEA* consumption	kg/t CO_2	2.34	Monoethanolamine {GLO}| market for | Alloc Rec, U
NaOH use	kg/t CO_2	0.13	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Rec, U
Activated carbon use	kg/t CO_2	0.075	Carbon black {GLO}| market for | Alloc Rec, U
Heat requirement capture	kWh/t CO_2	222.2	Heat, central or small-scale, natural gas {CH}| market for heat, central or small-scale, natural gas | Alloc Rec, U
Electricity requirement (fans, pumps)	kWh/t CO_2	23.60	Electricity, low voltage {CH}| market for | Alloc Rec, U
NH_3 emissions	kg/t CO_2	0.21	Ammonia

* Monoethanolamine

Assuming a lifetime of 30 years 94 Mt CO_2 are captured in total by one plant (Koornneef et al., 2008). A list of used materials and processes to build up a CO_2 capture plant is given in Table 3-4.

Table 3-4: Life cycle inventory data of a CO_2 capture plant (Koornneef et al., 2008)

Material/process	Unit	Amount	SimaPro
Lifetime	year	30	
Total CO_2 captured over lifetime	Mt	94	
Steel (absorber and stripper)	t	235	Reinforcing steel {GLO}| market for | Alloc Rec, U
Steel (piping and small equipment)	t	82	Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, U
Concrete	m^3	1	Concrete, normal {CH}| market for | Alloc Rec, U
Transport	tkm	9500	Transport, freight, lorry >32 metric ton, EURO6 {RER}| transport, freight, lorry >32 metric ton, EURO6 | Alloc Rec, U

3.2.2. CO_2 capture from atmosphere

According to data from Climeworks a CO_2 capture plant, built up from 20 40-foot containers each containing six modules, was modelled. Service life of the plant was assumed to be 30 years. Within this lifetime a total amount of 1'103'760 t CO_2 is captured (Table 3-6). The captured CO_2 from atmosphere has a high purity of > 99.9% and therefore no further processing is required before using the CO_2. In Table 3-5 the characteristics of a CO_2 capture plant are given.

Table 3-5: Life cycle inventory of the CO_2 capturing from atmosphere (Gebald et al., 2016)

Input / Output	Unit	Plant
Service life	years	30
CO_2 capacity per hour	kg	4200
CO_2 capacity per day	kg	100'800
CO_2 capacity per year	kg	36'792'000
Thermal energy demand per hour	kWh	7350
Thermal energy demand per day	kWh	176'400
Thermal energy demand per year	kWh	64'386'000
Electricity demand per hour	kWh	1050
Electricity demand per day	kWh	25'200
Electricity demand per year	kWh	9'198'000
CO_2 purity	%	> 99.9
Module technology	-	filter modules, fitted into standard 40-foot containers
Control unit	-	control module (one 40-foot container)

In a CO_2 capture plant a total energy demand of 2000 kWh is required to gain one ton of CO_2 from the atmosphere (Table 3-6), which is 8 times more than the required energy demand to gain one ton of CO_2 from exhaust gases (245.8 kWh/t CO_2). Thermal energy and electricity demand vary between 1500–2000 kWh/t CO_2 and 200–300 kWh/t CO_2, respectively, resulting in average demands of 1750 kWh/t CO_2 of thermal energy and 250 kWh/t CO_2 of electricity, respectively (Table 3-6).

Table 3-6: Life cycle inventory of the CO_2 capturing from atmosphere (Gebald et al., 2016)

Input	Unit	Plant	SimaPro
CO_2 capacity (total)	t	1'103'760	
Thermal energy demand	kWh/t CO_2	1750	Heat, central or small-scale, natural gas {CH}| market for heat, central or small-scale, natural gas | Alloc Rec, U
Electricity demand	kWh/t CO_2	250	Electricity, low voltage {CH}| market for | Alloc Rec, U*

* Representative electricity supply for electricity supply from hydropower, photovoltaics, municipal waste incineration plant and surplus electricity

3.3. Methanation

In this study, catalytic and biogenic methanation were compared. The catalytic methanation is based on Wettstein et al. (2018b). The biogenic methanation was modelled with data collected in interviews with experts from the Institute of Chemistry and Biotechnology ICBT at the Zurich University of Applied Sciences ZHAW.

H_2 and CO_2 are converted to methane in the catalytic adsorption reactor using a zeolite-nickel granulate as catalyst. In the biogenic methanation, archaea convert CO_2 and H_2 to methane using the generated energy for their growth, whereby to different reactor types, stirring bed reactor and trickle bed reactor, were considered. Data of biogenic reactor types were provided by Judith Krautwald (Institute for Chemistry and Biotechnology, ZHAW personal communication, Email 9.10.2017-1.11.2017) based on (Graf et al., 2014; Strübing et al., 2017). The life cycle inventories of the catalytic adsorption reactor, the biogenic stirring tank reactor and the trickle bed reactor are given in Table 3-7. The dimensions of the reactors refer to a methane formation rate of 1 Nm^3 CH_4 per hour considering a life time of 20 years à 8760 h per year.

Table 3-7: Life cycle inventory of the catalytic adsorption reactor, the biogenic stirring tank reactor and the trickle bed reactor, referring to a formation rate of 1 Nm^3 CH_4 per hour considering a life time of 20 years à 8760 h per year

	Unit	Catalytic Adsorption reactor	Biogenic Stirring tank reactor	Trickle bed reactor	SimaPro
Aluminium	kg	0.45	0	0	Aluminium, cast alloy {GLO}| market for | Alloc Rec, U
Zeolite	kg	1.0	0	0	Zeolite, powder {GLO}| market for | Alloc Rec, U
Nickel	kg	0.063	0	0	Nickel, 99.5% {GLO}| market for | Alloc Rec, U
Steel	kg	0	100	0	
Chrome steel	kg	0	10	465	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Alloc Rec, U
Polyethylene	kg	0	0	8000	Polyethylene, high density, granulate {GLO}| market for | Alloc Rec, U
Electronics	kg	1.0	1.0	1.0	Electronics, for control units {RER}| production | Alloc Rec, U
Water	kg	1.0	0	0	Water, deionised, from tap water, at user {CH}| production | Alloc Rec, U
Building hall	m^2	0.0004	0.0004	0.0004	Building, hall, steel construction {GLO}| market for | Alloc Rec, U
Lorry	tkm	5.8	0	0	Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Alloc Rec, U
Transoceanic ship	tkm	17.7	0	0	Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Rec, U
Transformation from unknown	m^2	0.0063	0.0063	0.0063	Transformation, from unknown
Transformation to industrial area	m^2	0.0063	0.0063	0.0063	Transformation, to industrial area

	Unit	Catalytic Adsorption reactor	Biogenic Stirring tank reactor	Trickle bed reactor	SimaPro
Occupation, industrial area	m^2a	0.315	0.315	0.315	Occupation, industrial area
Electricity, low voltage	kWh	1.667	1.667	1.667	Electricity, low voltage {ENTSO-E}| market group for | Alloc Rec, U
Waste aluminium	kg	0.45	0	0	Aluminium (waste treatment) {GLO}| recycling of aluminium | Alloc Rec, U
Waste zeolite	kg	1.0	0	0	Waste zeolite {CH}| treatment of, inert material landfill | Alloc Rec, U
Waste nickel	kg	0.05	0	0	Nickel smelter slag {CH}| treatment of, residual material landfill | Alloc Rec, U
Steel scrap	kg	0	110	10	Scrap steel {RoW}| treatment of scrap steel, municipal incineration | Alloc Rec, U
Waste polyethylene	kg	0	0	8000	Waste polyethylene {CH}| treatment of, municipal incineration | Alloc Rec, U
Electronic scrap	kg	1.0	1.0	1.0	Electronics scrap from control units {RER}| treatment of | Alloc Rec, U
Wastewater	kg	1.0	0	0	Wastewater, average {CH}| treatment of, capacity 5E9l/year | Alloc Rec, U

In the biogenic methanation, 4–6% of CO_2 for methanation is utilised by the archaea for their growth. In the present study, an additional CO_2 demand of 5% was assumed. Additional H_2 in the same extent is used too in order to offset the additional CO_2 and perform the methanation reaction at equilibrium. Analogous to the CO_2 demand of archaea growth, carbonisation takes places during catalytic methanation. However, carbonisation during catalytic methanation is negligible (personal communication Boris Meier, Institute for Energy Technology, HSR, Email 6.11.2017) and therefore neglected in the present study.

The life cycle inventory of the catalytic methanation with an adsorption reactor and the biogenic methanation with a stirring tank reactor and a trickle bed reactor, respectively are given in Table 3-8. The amount of input gases during operation refer to an output of 1 Nm^3 CH_4 per hour considering a life time of 20 years à 8760 h per year. Due to lacking data, methane leakage was assumed to be zero in the whole PtG methanation value chain.

Table 3-8: Life cycle inventory of the catalytic and the biogenic methanation with stirring tank reactor and trickle bed reactor, respectively, referring to a formation rate of 1 Nm^3 CH_4 per hour considering a life time of 20 years à 8760 h per year

	Unit	Catalytic	Biogenic		SimaPro
		Adsorption reactor	Stirring tank reactor	Trickle bed reactor	
Hydrogen, H_2	kg	0.36	0.38	0.38	Hydrogen, at electrolysis, kg {CH} efficiency 62%
Carbon dioxide, CO_2	kg	1.96	2.06	2.06	Carbon dioxide, from waste gases, at CO2 capture plant, kg {CH}
Electricity, low voltage	kWh	0.64	1.47	0.68	Electricity, low voltage {CH}| market for | Alloc Rec, U
Reactor, catalytic	p	2.7E-05	0	0	Adsorption reactor, at plant, 1 kW, p {CH} | production
Reactor, stirring tank	p	0	5.7E-06	0	Biogenic methanation reactor, stirring tank reactor, at plant, p {CH} | production
Reactor, trickle bed	p	0	0	8.9E-06	Biogenic methanation reactor, trickle bed reactor, at plant, p {CH} | production
Gas factory	p	2.9E-09	2.9E-09	2.9E-09	Synthetic gas factory {CH}| construction | Alloc Rec, U
Heat waste	kWh	2.50	2.04	2.04	Heat, waste
Water, CH	kg	1.61	1.61	1.61	Water, CH

3.4. Electricity mixes for 2035 and 2050

The technology composition of the Swiss electricity mix for the years 2035 and 2050 is based on simulations of the future electricity market (personal communication Patrick Angst, Institute for Energy Technology, HSR, Email 2.10.2017). In 2035 the nuclear power plant Leibstadt is still in operation and produces 21% of the total Swiss electricity demand. This share will decrease to 0% in the year 2050 due to decommissioning of the nuclear power plants in Switzerland. Photovoltaic electricity is assumed to replace electricity produced by nuclear power plants with a total production of 10 and 20 TWh of electricity in the years 2035 and 2050, respectively. Increases in production capacity are also expected for electricity using geothermal energy, hydropower (run-off-river), wind power and natural gas in combined heat and power (CHP) power plant. It is assumed that in 2035 and 2050 Switzerland will cover the domestic electricity demand through domestic power plants and no import will be necessary anymore. Accordingly, the Swiss consumer mix will be equal to Swiss production mix. Table 3-9 shows the technology composition of the electricity mixes for the years 2035 and 2050 in TWh and percent with the corresponding datasets in SimaPro.

Table 3-9: Technology composition for the prospective electricity mixes in Switzerland for the year 2035 and 2050 (personal communication Patrick Angst, Email 2.10.2017). Shares of the biomass based fuels taken from Messmer & Frischknecht (2016)

Technology	2035 TWh	2050 TWh	2035 %	2050 %	SimaPro
Nuclear power plant	14.8	0.0	21.3%	0.0%	Electricity, high voltage {CH}| electricity production, nuclear, boiling water reactor | Alloc Rec, U
Wood	0.8	0.8	1.1%	1.1%	Electricity, high voltage {CH}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U
Biogas	0.8	0.8	1.1%	1.1%	Electricity, high voltage {CH}| heat and power co-generation, biogas, gas engine | Alloc Rec, U
Biomass MSWI	2.4	2.4	3.4%	3.3%	Electricity, medium voltage {CH}| electricity, from municipal waste incineration to generic market for | Alloc Rec, U
Geothermal	0.3	4.0	0.4%	5.5%	Electricity, high voltage {CH}| electricity production, deep geothermal | Alloc Rec, U
Natural gas in co-generation (CHP)	3.8	5.0	5.5%	6.9%	Electricity, high voltage {CH}| heat and power co-generation, natural gas, 1MW electrical, lean burn | Alloc Rec, U
Hydro power, run-off-river	18.8	19.1	27.0%	26.3%	Electricity, high voltage {CH}| electricity production, hydro, run-of-river | Alloc Rec, U
Wind power	2.0	3.5	2.9%	4.8%	Electricity, high voltage {CH}| electricity production, wind, 1-3MW turbine, onshore | Alloc Rec, U
Photovoltaics	10.0	20.0	14.4%	27.6%	electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted/kWh/CH U
Hydropower, storage	14.7	14.4	21.2%	19.9%	Electricity, high voltage {CH}| electricity production, hydro, reservoir, alpine region | Alloc Rec, U
Hydropower, pumped storage	0.6	0.7	0.8%	1.0%	Electricity, high voltage {CH}| Mix RMTM 2035 hydro, pumped storage | Alloc Rec, U | RMTM Methanation
PtG methane in combined cycle	0.7	1.9	1.0%	2.5%	Electricity, high voltage {CH}| heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | Alloc Rec, U | RMTM Methanation Mix 2035
Total	69.7	72.6	100.0%	100.0%	

3.5. Reference vehicles

Methane as a fuel can be used in common natural gas vehicles. The natural gas vehicle fuelled with renewable PtG methane was compared with four vehicle types running with fossil fuels or electricity: diesel, petrol, natural gas and electric vehicle. The ecoinvent datasets of these vehicles types were adapted to real fuel consumption (Table 3-10) according to data provided by Christian Bach, head of the Automotive Powertrain Technologies at the Swiss Federal Laboratories for Materials Science and Technology EMPA. Vehicle size and engine performance were chosen in accordance with a VW Golf, produced in 2015–2016 and with 110–130 horsepower. For the exhaust gases, the limits of EURO6 norm were used. Standard density of natural gas of 0.8 kg/m^3 according to SVGW (2014) was used to convert natural gas weight into volume.

Table 3-10: Real consumption of the reference vehicles with diesel, petrol, natural gas and electric engine, data from Christian Bach, head of Automotive Powertrain Technologies, EMPA

	Diesel [l/100 km]	Petrol [l/100 km]	Natural gas [kg/100 km]	Electric [kWh/100 km]
Real consumption	5.6	6.6	4.2	16.1

3.6. Gas processing

PtG can serve as alternative to conventional gas processing as amine washing, pressure swing adsorption (PSA) and glycol washing. Crude biogas contains 40–75% CH_4 and 25–55% CO_2 along with N_2, H_2S and O_2 (Jungbluth et al., 2007). With the PtG technology the remaining CO_2 in the crude biogas can be converted to CH_4 by enriching the biogas with additional H_2 and conversion to CH_4 through catalytic or biogenic methanation Figure 3-1. This results in a higher CH_4 yield than with conventional gas processing technologies and CO_2 removal is no longer necessary. Methane leakage for amine washing of 0.1% and of 2.6% for PSA and glycol washing is assumed (Stucki et al., 2011).

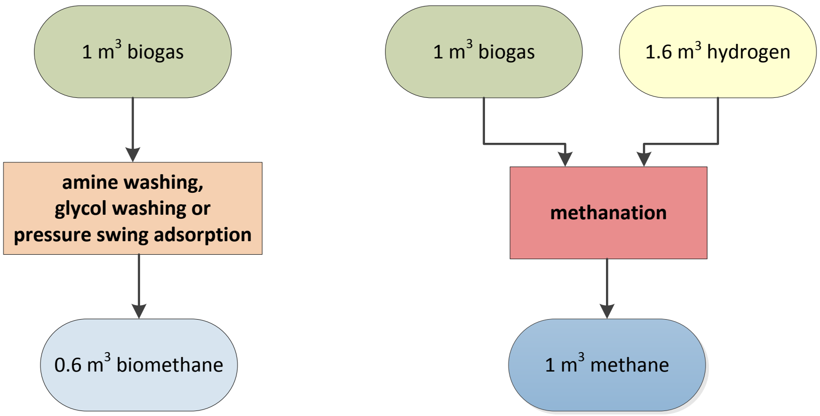


Figure 3-1: Comparison of gas processing of biogas with conventional gas processing as amine washing or PSA compared to gas processing of biogas with methanation (catalytic or biogenic)

3.7. Hydrogen-Compressed Natural gas (HCNG) as fuel

Hydrogen-compressed natural gas (HCNG) is a blend of natural gas and hydrogen, used as a fuel. HCNG typically contains 8–50% hydrogen by volume. HCNG has the potential to reduce nitrous oxide (NO_x), carbon dioxide (CO_2) and carbon monoxide (CO) emissions compared to compressed natural gas (CNG) (NPC, 2012). A reduction of direct CO_2 emission of 4.5–5.5% is achievable with a hydrogen blend of 15 Vol.-% (personal communication Christian Bach, head of Automotive Powertrain Technologies, EMPA, Email 7.12.2016).

According to the reference vehicles (chapter 3.5) by assuming a fuel consisting of 100% natural gas or PtG methane, 4.2 kg fuel (natural gas or PtG methane) per 100 km are used, corresponding to 0.0525 m^3 per km (personal communication Bach, head of Automotive Powertrain Technologies, EMPA, Email 8.7.2016). By substituting 15 Vol.-% of the natural gas or PtG methane fuel by H_2 (HCNG), fuel consumption per kilometre is composed of 0.0446 m^3 CH_4 and 0.0079 m^3 H_2 (Table 3-11). H_2 has a 3.3 times lower heating value compared to fuel consisting of 100% natural gas or PtG methane, leading to a 10.5% higher fuel demand per kilometre.

In the present study, GHG emissions of HCNG with 15 Vol.-% H_2 from electrolysis in the blend were analysed and compared to unblended PtG CH_4 fuel to assess if HCNG consisting of H_2 and PtG CH_4 shows significant GHG emission reductions. Additionally, GHG emissions of HCNG with H_2 from electrolysis substituting 15 Vol.-% fossil natural gas were analysed and compared to unblended fossil natural gas as fuel.

Table 3-11: Fuel composition, fuel consumption and heating value of fuels consisting of 100 Vol.-% natural gas or PtG CH_4 and HCNG with 15 Vol.-% H_2 from electrolysis in the blend

Fuel	**Fuel composition**	**Ratio Vol.-%**	**Fuel consumption m^3/km**	**Heating value MJ/m^3**
Natural gas or PtG methane	CH_4	100	0.0525	35.9
HCNG	CH_4	85	0.0446	32.1
	H_2	15	0.0079	

4. Life Cycle Impact Assessment

In this chapter, the life cycle impact assessment results for driving a passenger car with renewable methane compared to driving with other fuels are presented. Subchapter 4.1 shows how the results for renewable methane depend on the electricity source used in the value chain. Subchapter 4.2 describes the results for renewable methane, if CO_2 is either collected from waste gases or from the atmosphere. Subchapter 4.3 compares the use of hydrogen-compressed natural gas (HCNG) as fuel with PtG methane and fossil natural gas. Subchapter 4.4 shows how the results for renewable methane differ between catalytic and biogenic methanation and subchapter 4.5 compares PtG methane as gas processing with other gas proceeding as amine washing, pressure swing adsorption (PSA) and glycol washing.

4.1. Electricity supply

Greenhouse gas (GHG) emissions per kilometre driven with PtG vehicles are lowest, if the electricity for H_2 production is supplied by surplus electricity that could not be used otherwise (0.10 kg CO_2-eq./km). The highest GHG emissions result from vehicles that are powered by petrol fuelled engines (0.27 kg CO_2-eq./km) as shown in Figure 4-1. The complete results are shown in the appendix Table A - 1 and Table A - 3.

The electricity used for H_2 production has the highest impact on GHG emissions for PtG vehicles. The contribution of the H_2 production to the total impact is highest if H_2 production is supplied by Swiss consumer mix today (57%) and lowest if H_2 production is supplied by surplus electricity (18%).

Figure 4-1 shows the results for a high efficiency of 70% for the electrolysis. The error bars indicate the range between the low electrolysis efficiency of 62% (positive error value) and the prospective electrolysis efficiency of 80% (negative error value). The reduction of GHG emissions through a prospective electrolysis efficiency of 80% and the increase of GHG emissions through a low electrolysis of 62% are both at their maximum, when H_2 production is supplied by Swiss consumer mix today, resulting in a reduction of GHG emissions of 7% and an increase of 11%, respectively.

For vehicles fuelled with fossil energy, direct exhaust emissions have the highest contribution to the total GHG emissions in contrast to vehicles fuelled with renewable methane where direct exhaust carbon dioxide emissions are climate neutral since the same amount of carbon dioxide was an input into the PtG process. Vehicle and road cause the same GHG emissions for all vehicle types independent of the fuel provision, except for electric cars, where vehicles have a higher impact due to the battery production. The GHG emissions of the vehicles are dominated by the production of the glider, which includes the body of the car, steering, braking and suspension system, tyres, cockpit equipment and non propulsion related electronics, contributes most to the environmental impact.

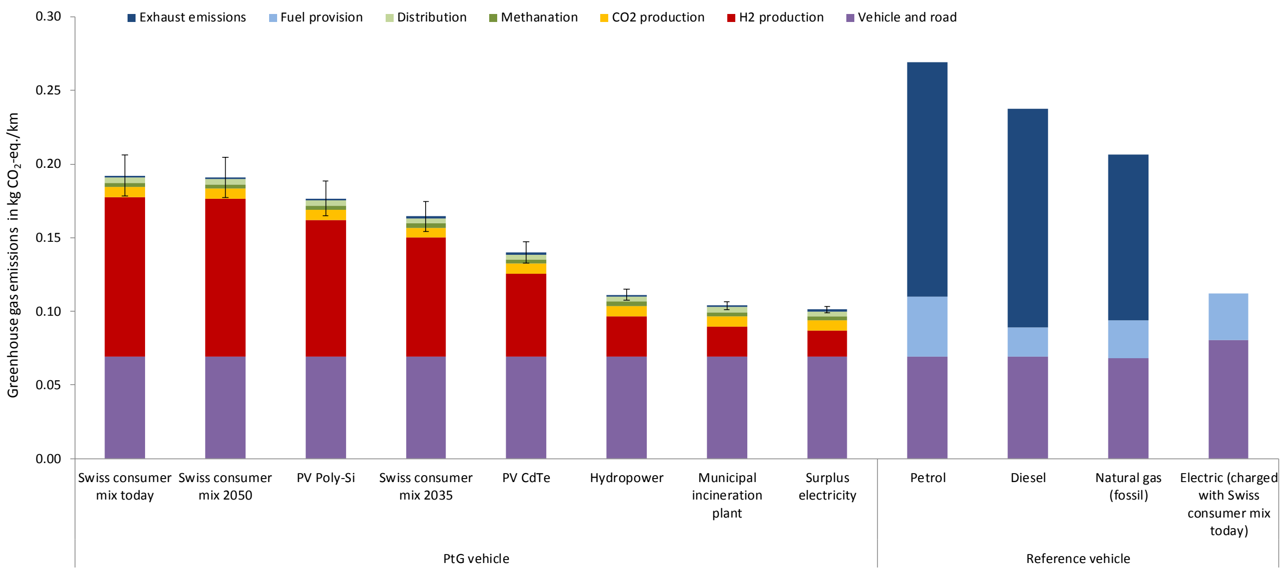


Figure 4-1: Greenhouse gas emissions in kg CO_2-eq. per kilometre driven with PtG vehicle and reference vehicles, fuelled with fossil fuels or charged with Swiss consumer mix today, respectively. Various alternatives for electricity supply for H_2 production of fuel provision for PtG vehicles are assessed. Error bars indicate the range between a low electrolysis efficiency of 62% and prospective electrolysis efficiency of 80%.

The total environmental impact according to ecological scarcity 2013 per kilometre driven is highest if H_2 production is supplied by the Swiss consumer mix today and lowest if H_2 production is supplied by surplus electricity as shown in Figure 4-2. Depending on the electricity supply for H_2 production, the impact of vehicle and road ranges from 30% (Swiss consumer mix today) up to 66% (surplus electricity).

The error bars indicate the range between the low electrolysis efficiency of 62% and the prospective electrolysis efficiency of 80%. In Figure 4-2, an electrolysis efficiency of 70% is illustrated. In comparison with the high efficiency of 70%, the environmental impact increases by 13% if a low electrolysis efficiency (62%) is assumed and decreases 8% if a prospective electrolysis efficiency (80%) is assumed.

For reference vehicles powered with petrol, diesel and fossil natural gas, the operation of the vehicles, with exhaust emissions and fuel provision, plays the most important role regarding total environmental impact, contributing 42–56% to the total environmental impact. The complete results are listed in the appendix in Table A - 2 and Table A - 4.

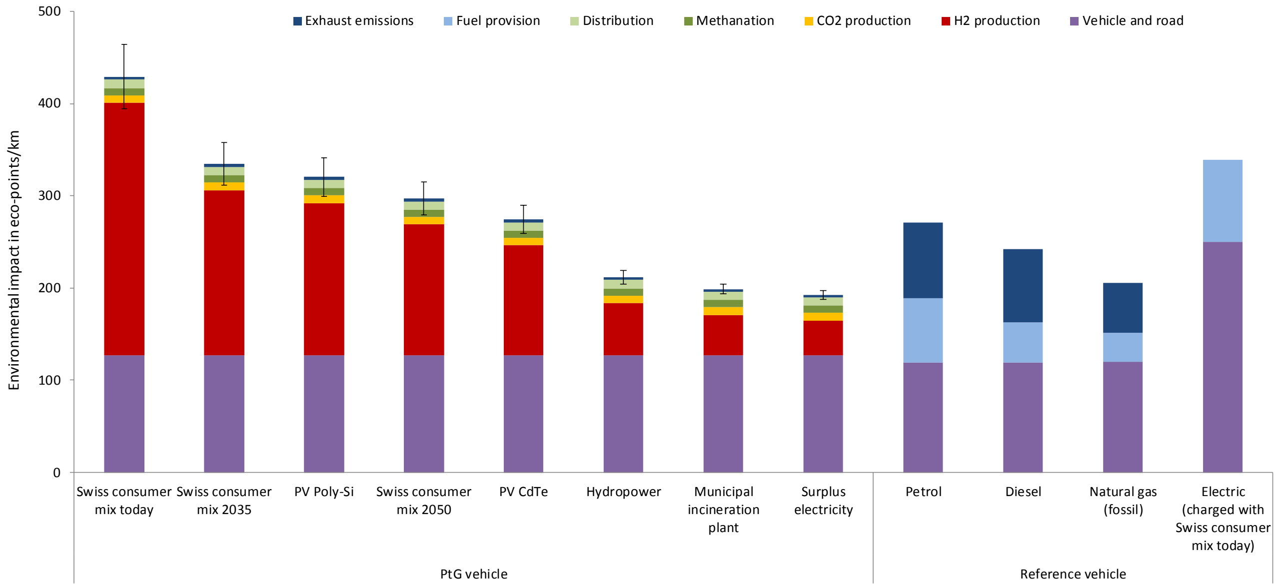


Figure 4-2: Total environmental impact in eco-points per kilometre driven with PtG vehicle and reference vehicles, fuelled with fossil fuels or charged with Swiss consumer mix today, respectively. Various alternatives for electricity supply for H_2 production of fuel provision for PtG vehicles are assessed. Error bars indicate the range between a low electrolysis efficiency of 62% and prospective electrolysis efficiency of 80%.

4.2. CO_2 source

Separation of CO_2 from atmosphere causes 7 times higher GHG emissions than CO_2 collection from industrial waste gases (e.g. cement plants) as shown in Figure 4-3, due to the higher energy demand.

Considering the total GHG emissions per kilometre driven the CO_2 collection plays a minor role compared to H_2 production. If CO_2 is collected from atmosphere, the CO_2 collection contributes 21% of the total greenhouse gas emissions compared to 4% in case of industrial waste gases. The fossil natural gas powered car causes GHG emissions of 207 g CO_2-eq. per kilometre. The PtG vehicle causes higher greenhouse gas emissions compared to the fossil natural gas powered car, if the CO_2 is collected from atmosphere (234 g CO_2-eq./km) but lower greenhouse gas emissions, if the CO_2 is collected from industrial waste gases (192 g CO_2-eq./km), given that the H_2 production is supplied by Swiss consumer mix today and that the electrolysis efficiency is 70% (Figure 4-3). The complete results can be found in the appendix in Table A - 5.

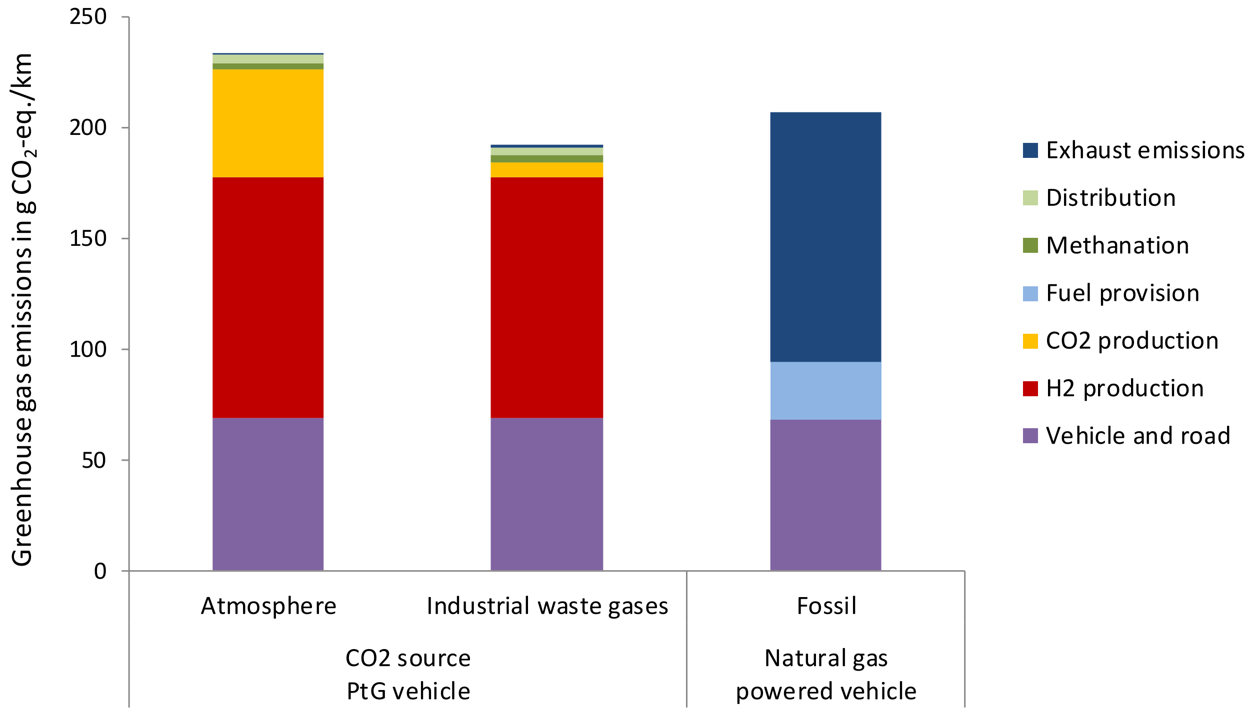


Figure 4-3: Greenhouse gas emissions in kg CO_2-eq. per kilometre driven of the PtG vehicle with CO_2 source either from atmosphere or from industrial waste gases in comparison with the fossil natural gas powered vehicle

Total environmental impact of CO_2 collection from atmosphere is 4 times higher than CO_2 collection from industrial waste gases, due to higher energy demand.

Environmental impact per kilometre driven are lower for fossil natural gas powered vehicle in comparison with PtG vehicles whether CO_2 is collected from atmosphere or from industrial waste gases as shown in Figure 4-4. The environmental impact of CO_2 collection from atmosphere is 4 times higher than CO_2 collection from industrial waste gases and H_2 production has a 8 to 33 times higher environmental impact per kilometre driven than CO_2 collection. Therefore, the importance of CO_2 collection is only minor for the total environmental impacts. The complete table of results is shown in the appendix in Table A - 6.

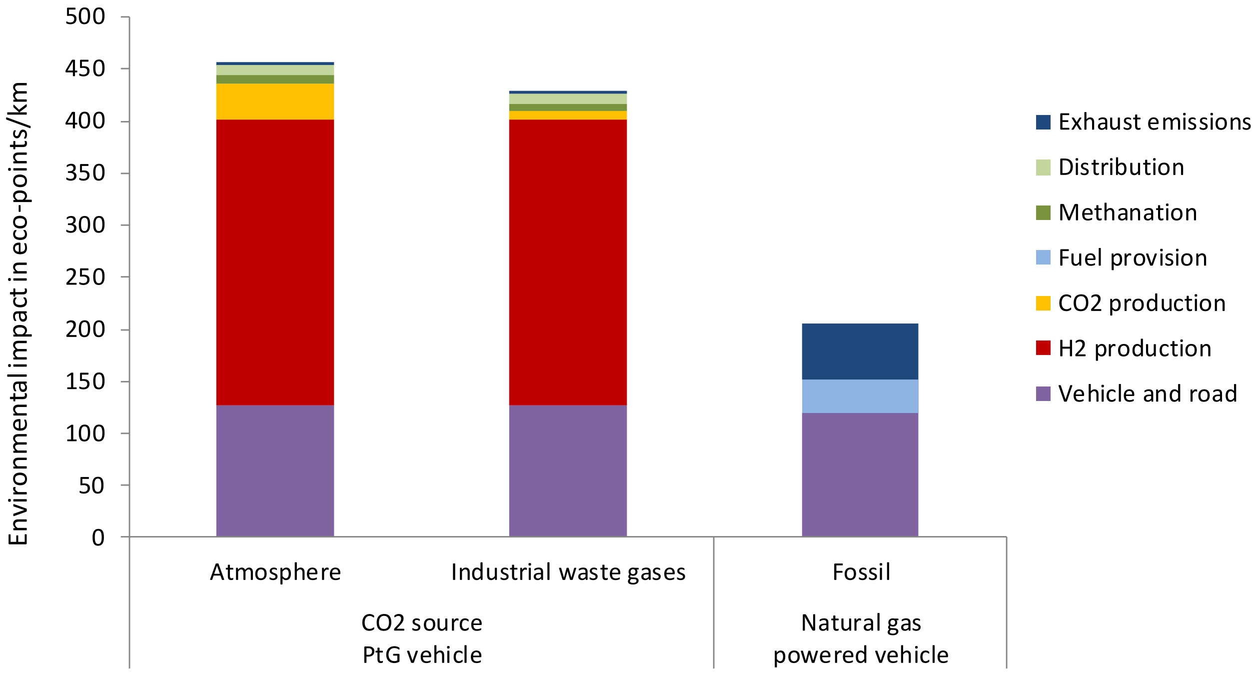


Figure 4-4: Overall environmental impact in eco-points per kilometre driven of the PtG vehicle with CO_2 source either from atmosphere or from industrial waste gases in comparison with the fossil natural gas powered vehicle.

4.3. Hydrogen-Compressed Natural gas (HCNG) as fuel

GHG emissions per kilometre driven with HCNG as fuel with 15 Vol.-% H_2 in the blend has with 176 g CO_2-eq./km 1% lower GHG emissions than PtG methane as fuel (178 g CO_2-eq./km) as shown in Figure 4-5. Apparently, this reduction looks to disaccord with the predicted CO_2 reduction potential of 4.5–5.5% (chapter 3.7). However, the reduction of 4.5–5.5% only refers to direct CO_2 emissions whereof the above mentioned reduction of 1% considers the whole value chain.

Per kilometre driven with HCNG the fuel provision of PtG methane plays a more important role and contributes 58% to the total GHG emission. HCNG with 15 Vol.-% H_2 in the blend has a lower heating value than natural gas or PtG methane and therefore an additional demand of the blend per kilometre driven is necessary, resulting in almost equal GHG emissions as PtG methane used as fuel. The reduction is only minor because the highest share of the GHG emissions and total environmental impacts is caused by the hydrogen production. Therefore, if fossil natural gas is substituted by HCNG comprising 15 Vol.-% renewable H_2 instead of fossil natural gas, a GHG emission reduction of only 2% is achievable (Figure 4-5), due to the additional demand of HCNG per kilometre driven and the GHG emissions caused by the production of the hydrogen. For the complete results is referred to the appendix Table A - 7.

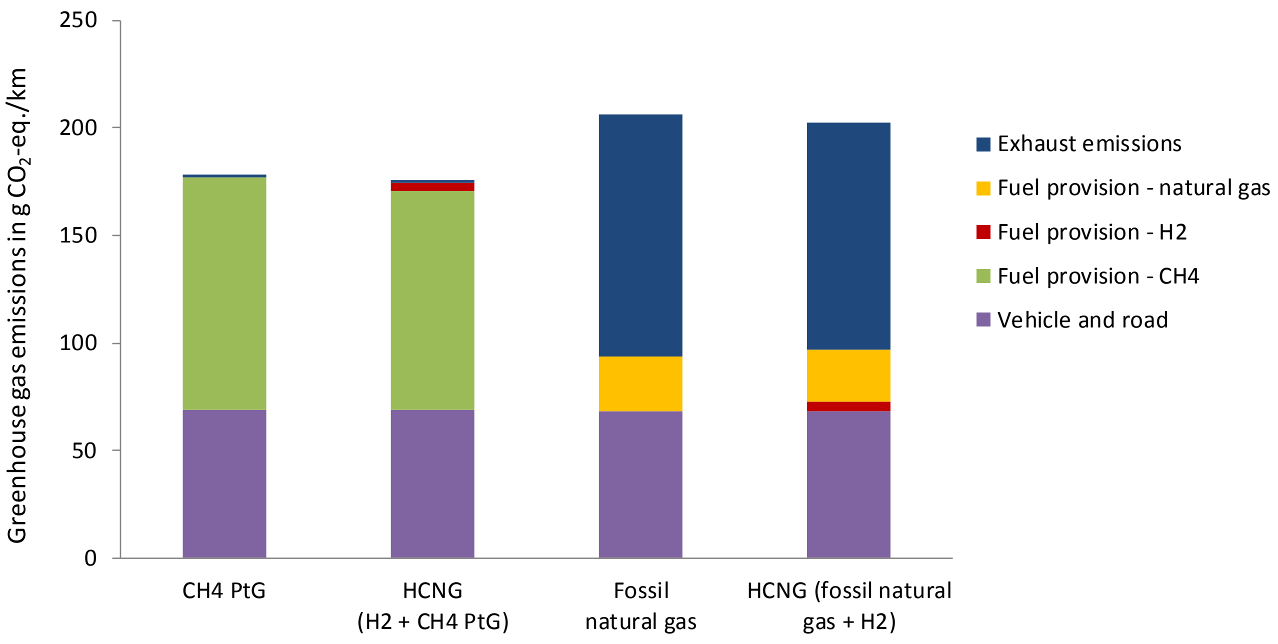


Figure 4-5: Greenhouse gas emissions in g CO_2-eq. per kilometre driven from PtG vehicle powered with catalytic PtG methane, HCNG from PtG methane and H_2 from electrolysis, in comparison with natural gas vehicle powered with fossil natural gas and HCNG from fossil natural gas and H_2 from electrolysis; HCNG blend with 15 Vol.-% H_2 from electrolysis

4.4. Catalytic and biogenic methanation

Greenhouse gas emissions per kg CH_4 produced through catalytic or biogenic methanation range from 2.0 kg CO_2-eq./m^3 CH_4 (catalytic) to 2.1 kg CO_2-eq./m^3 CH_4 (biogenic) (Figure 4-6). In all reactor types, H_2 production has the highest impact on GHG emissions with a contribution of 85% (stirring tank reactor) to 91% (adsorption reactor) if a electrolysis efficiency of 80% is assumed. Electricity consumption during operation is highest in the stirring tank reactor (0.15 kg CO_2-eq./m^3 CH_4), whereas reactor production is highest in the trickle bed reactor (0.09 kg CO_2-eq./m^3 CH_4).

The difference regarding GHG emissions between biogenic methanation through stirring tank reactor or trickle bed reactor are negligible with a difference of 0.03 kg CO_2-eq./m^3 CH_4 or 2%, respectively, caused by the lower energy use during operation of the trickle bed reactor. The complete table of results is given in the appendix in Table A - 8.

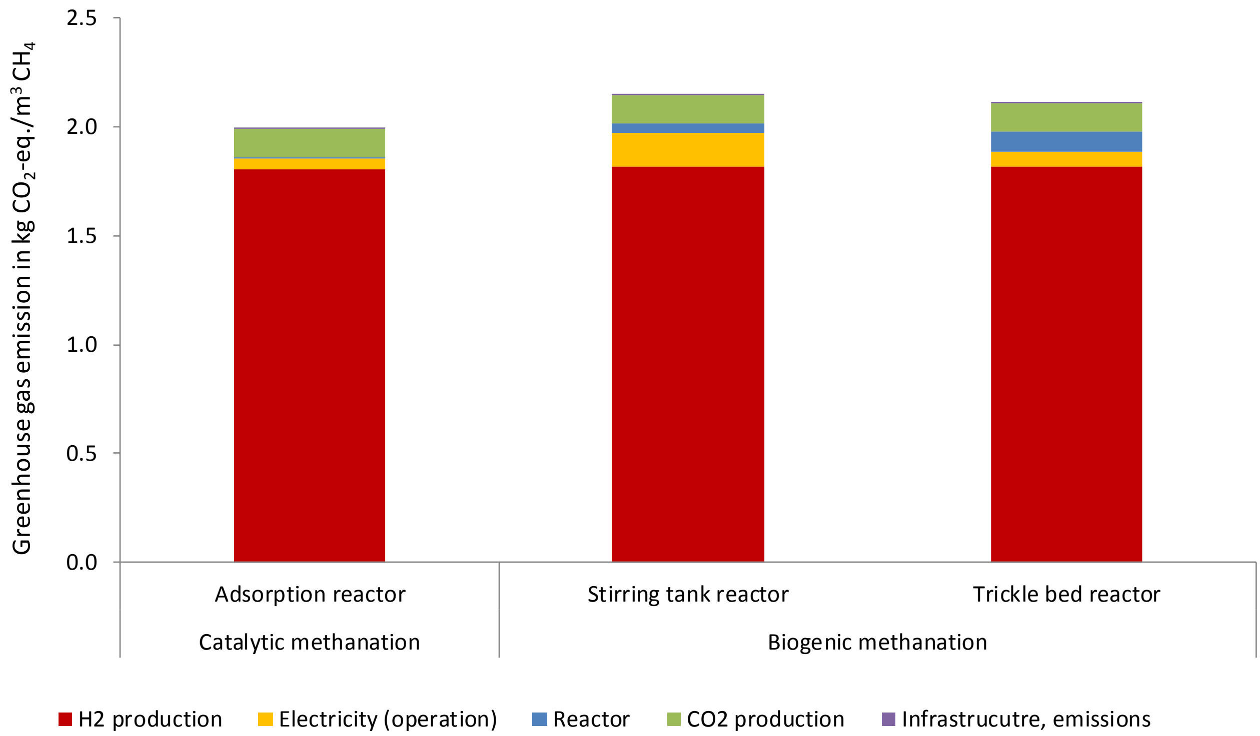


Figure 4-6: Greenhouse gas emissions in kg CO_2-eq. per kg CH_4 produced through catalytic and biogenic methanation in adsorption reactor, stirring tank reactor and trickle bed reactor

4.5. Gas Processing

Greenhouse gas emissions per m^3 methane of alternative gas processing technologies as catalytic and biogenic methanation are lower than conventional gas processing as amine washing, PSA or glycol washing, if H_2 production and methanation are supplied by surplus electricity (Figure 4-7). If biogenic methanation is supplied by Swiss consumer mix today, GHG emissions are similar to amine washing but still lower than GHG emissions of PSA and glycol washing. GHG emissions of crude biogas are lower for catalytic and biogenic methanation due to CO_2 content of 40%, which is converted to methane as well during methanation. Consequently, less crude biogas is need to yield 1 m^3 of methane, if methanation is used for gas processing. The complete results can be found in the appendix in Table A - 9.

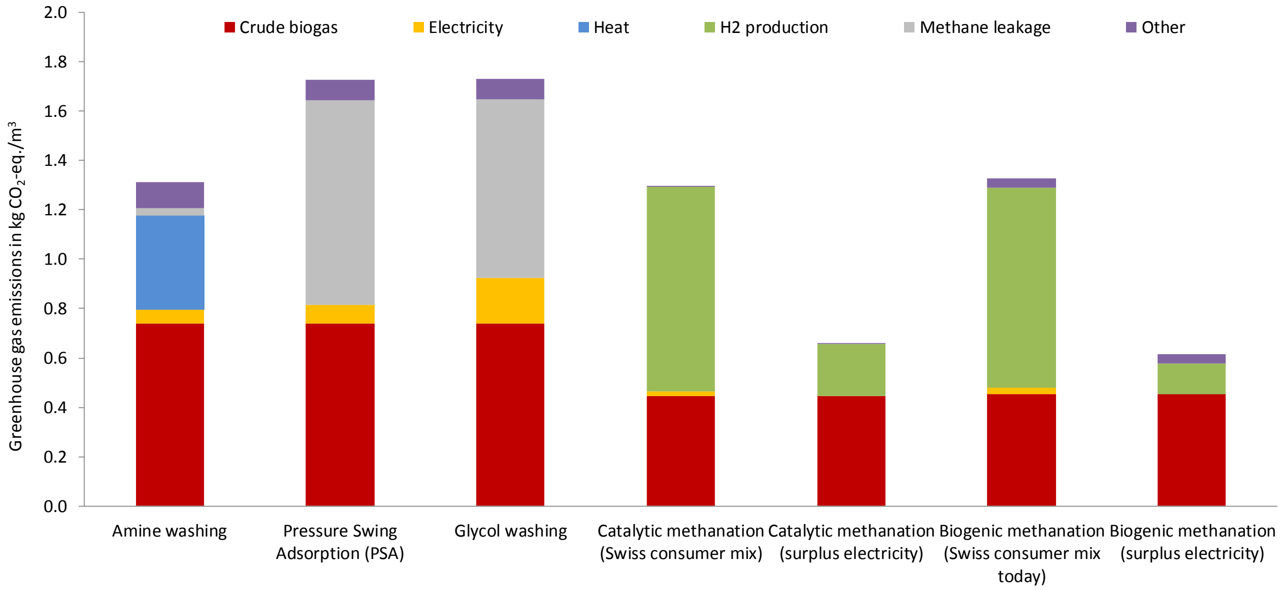


Figure 4-7: Greenhouse gas emissions in kg CO_2-eq. per m^3 methane of conventional gas processing technologies (amine washing, PSA, and glycol washing) and PtG (catalytic and biogenic methanation) as alternative to conventional gas processing

5. Discussion

Driving cars fuelled with fossil fuels like petrol or diesel leads to highest GHG emissions, due to the high amount of exhaust gas emissions, contributing up to 63% of total GHG emissions per kilometre driven. If fossil natural gas is used instead of petrol, a reduction of 23% is achievable, mainly due to lower exhaust gas emissions as CO_2, CH_4 and N_2O. If using PtG methane as fuel instead of fossil natural gas, a reduction of 7–52% of GHG emissions can be achieved, depending on electricity supply for H_2 production and electrolysis efficiency. H_2 production is the crucial factor in the PtG technology regarding GHG emissions and environmental impact. Within H_2 production, electricity supply for H_2 production plays a more important role than electrolysis efficiency, leading to lowest environmental impact if surplus electricity is used and to highest environmental impact if Swiss consumer mix today is used. Swiss consumer mix today is associated with high GHG emissions due to high fossil CO_2 emissions, deriving from electricity import from Germany (card coal plants), whereas surplus electricity is considered to have no environmental impact.

Regarding total environmental impacts in eco-points according to ecological scarcity, driving with PtG methane causes only lower impacts than driving with fossil fuels, if H_2 production is supplied by electricity from municipal waste incineration or surplus electricity, which are associated with low or no environmental impact, respectively. If H_2 production is supplied by electricity from photovoltaics or Swiss consumer mix today, total environmental impact per kilometre driven is increasing, due to the photovoltaic infrastructure (PV panels, converter, mounting system) and the radioactive waste from nuclear power contained in Swiss consumer mix today and 2035.

Energy demand of CO_2 collection from industrial waste gases is 8 times lower than energy demand of CO_2 collection from atmosphere, resulting in lower fossil CO_2 and CH_4 emissions. Regarding GHG emissions or total environmental impact per kilometre driven, CO_2 collection contributes 21% at maximum to environmental impact and is therefore of minor importance in comparison to H_2 production, which contributes up to 64% due to its high electricity demand by assuming Swiss consumer mix today for electricity supply and electrolysis efficiency of 70%.

Hydrogen-compressed natural gas (HCNG) as a fuel has no relevant reduction of GHG emissions per kilometre driven compared to PtG CH_4 or fossil natural gas. GHG emissions and environmental impact per m^3 H_2 at service station are in fact lower than GHG emissions and environmental impact per m^3 PtG CH_4, but this reduction is offset by the increased fuel demand due to the lower heating value of HCNG compared to PtG CH_4 or fossil natural gas. This is also the case, if HCNG applied on fossil natural gas and H_2 from electrolysis substitutes fossil natural gas.

The biogenic methanation contributes to similar GHG emissions than catalytic methanation, regardless of the reactor type (stirring tank reactor or trickle bed reactor). The reactor production is highest in trickle bed reactor, due to the higher chromium steel demand in the reactor production in comparison to the stirring tank reactor, which contains less chromium steel but more steel, which is associated with lower GHG emissions than chromium steel. In contrary, the stirring tank reactor has a higher electricity demand during operation, leading finally to higher total GHG emissions. To the current state of research, methane formation rate is higher in stirring tank reactor (1.0 Nm^3 CH_4/h) than in trickle bed reactor (0.64 Nm^3 CH_4/h), resulting in a lower reactor demand per Nm^3 CH_4 produced under considering of the whole production volume during reactor service life of 20 years.

Due to minor importance of the methanation reactor in the methanation value chain, focussing on whether catalytic or biogenic methanation is used to produce CH_4 is less important than attempting to reduce GHG emissions arising from H_2 production, due to its much greater reduction potential.

The catalytic or biogenic methanation is only an effective alternative for common gas processing as amine washing, PSA and glycol washing, if renewable electricity from CdTe photovoltaics, hydropower, municipal waste incineration or surplus electricity is used as energy supply for H_2 production. The crude biogas production from bio waste, contributes with 47% on average (conventional gas processing) up to 74% (biogenic or catalytic methanation) to a large extent to total GHG emissions. Although the relative impact of biogas is higher in biogenic or catalytic methanation, the absolute impact is 40% lower compared to conventional gas processing.

The existing improvements in the PtG technology (electrolysis efficiency of 80% vs. 70%, CO_2 collection from atmosphere vs. industrial waste gases, trickle bed reactor vs. stirring tank reactor) are of minor importance and are not able to lower environmental impacts substantially. These improvements are of minor importance because at the current state of research, the whole methanation value chain is inefficient due to the rather low electrolysis efficiency of 62–80% and the methanation efficiency of 80%, resulting in an overall efficiency of 64% at maximum. Biogenic reactor production is still material-intensive, contributing over 99% to total environmental impact of a reactor. H_2 production, the most crucial process in the methanation value chain regarding environmental impacts, is mainly limited by its electricity demand and efficiency (80% at maximum). With the goal of reducing environmental impact of the whole methanation value chain, it is of utmost importance to improve electrolysis, by focussing on a decrease of electricity demand during operation, which has the most effective reduction potential.

5.1. Uncertainties and data quality

A number of extrapolations, estimations and assumptions were made in this LCA study concerning future electricity mixes and PtG technology. The life cycle inventory data for photovoltaic electricity production are based on prospective models for 2035 from Itten & Stucki (2017) and therefore subject to uncertainties. The used prospective electricity mixes for the years 2035 and 2050 assume an independent electricity market in Switzerland with 100% of the electricity supplied by the domestic electricity production in Switzerland with no additional imports from neighbouring countries. The independent electricity market for Switzerland strongly differs from the current Swiss electricity consumption of today, which includes a high share of electricity import from neighbouring countries.

The PtG technology is still at laboratory scale and not yet industrially established. Therefore, assumptions for an industrial scale of the PtG supply chain had to be made. Nevertheless, the data used in this analysis were provided by experts, who made possible future projections for an industrial scale value chain based on their research.

In the catalytic methanation, assumptions were made for the lifetime, dimensions and production volume of the adsorption reactor as well as the extrapolation to a power plant. In the biogenic methanation through trickle bed reactor, its lifetime, reaction volume and packaging material were estimated, as well as energy consumption during operation. In the hydrogen production, the prospective electrolysis efficiency of 80% was based on expert opinion.

The uncertainties regarding catalytic methanation affect the comparison of PtG vehicles and vehicles fuelled with fossils on the one hand and the comparison to biogenic methanation on the other hand. The fact, that PtG vehicles cause less GHG emissions in comparison to vehicles fuelled with fossils, will not change, even if GHG emissions of PtG methanation will increase due to underestimation of the data basis. Regarding environmental impact, the difference between PtG vehicles and reference vehicles will increase and manifest in higher environmental impacts of PtG vehicles.

At the current state of research, no final conclusion can be drawn, if catalytic or biogenic methanation will cause lower GHG emissions and total environmental impacts, due the small difference in the results. Depending on the future improvements, the result could change in favour of either catalytic or biogenic methanation.

Although the inherent uncertainty of the assumptions and conservative estimates by experts, the data can be considered as reliable. However, it is important to update the data according to the future research progress in order to refine the results and to adjust the study to the future developments.

In this study, the recently arising PtG technology and its application in the mobility sector are measured against the same standards as fully established technologies (diesel, petrol and natural gas engines), which was optimised and improved over decades. This leads to the fact that the emerging PtG technology is not yet comparable to the traditional energy and mobility system of today, due to the different maturity level of the compared technologies.

5.2. Comparison of literature

This study shows that the PtG methane and its application in the mobility sector doesn't perform better than conventional technologies for the conservative scenarios. This result was also determined by Zhang et al. (2017), who conducted a life cycle assessment of PtG value chain by comparing different scenarios regarding electricity supply for electrolysis, electrolysis technologies and CO_2 capture technologies and CO_2 sources. Zhang et al. (2017) concluded that PtG methane in the mobility sector performs worse than conventional mobility technologies for other impact categories than climate change. The results of Zhang et al. (2017) confirmed, that the PtG technology causes lower greenhouse gas emissions than conventional technologies, if renewable electricity is used for the hydrogen production.

PtG technology in its entirety and electrolysis supplied by Swiss consumer mix today in particular do not show any environmental benefits regarding fossil natural gas, pursuant Parra et al. (2017). However, in the present study a slightly environmental benefit by electricity supply from municipal waste incineration and surplus electricity regarding total environmental impacts and a considerable benefit concerning GHG emission regardless of the electricity supply was remarked.

All existing studies on PtG technology as Zah et al. (2015), Zhang et al. (2017), Parra et al. (2017) as well as this study determined, that the electricity consumption for electrolysis is most sensitive and crucial for all the environmental impacts caused by the PtG supply chain. Although all the studies mentioned above on PtG technologies focused at different scenarios, the results are in the same order of magnitude, as Figure 5-1 shows.

Zhang et al (2017) made the conclusion that CO_2 from air capture contributes to reduce GHG emissions of PtG technology, whereas Zah et al. (2015) determined a considerable reduction concerning GHG emissions by capturing CO_2 from waste gases instead of CO_2 capture from atmosphere. In the present study, we concluded that CO_2 from waste gases reduces total environmental impacts compared to CO_2 from air capture, but the CO_2 source is not relevant if the whole life cycle is considered. However, Zah et al. (2015) pointed out, that the reduction of GHG emissions by CO_2 capture from waste gases is not enough to be entitled to Swiss tax relief. Additionally, Parra et al. (2017) noticed, that even at an economic point of view, PtG systems with CO_2 captured from atmosphere are not profitable at the current state of the technology.

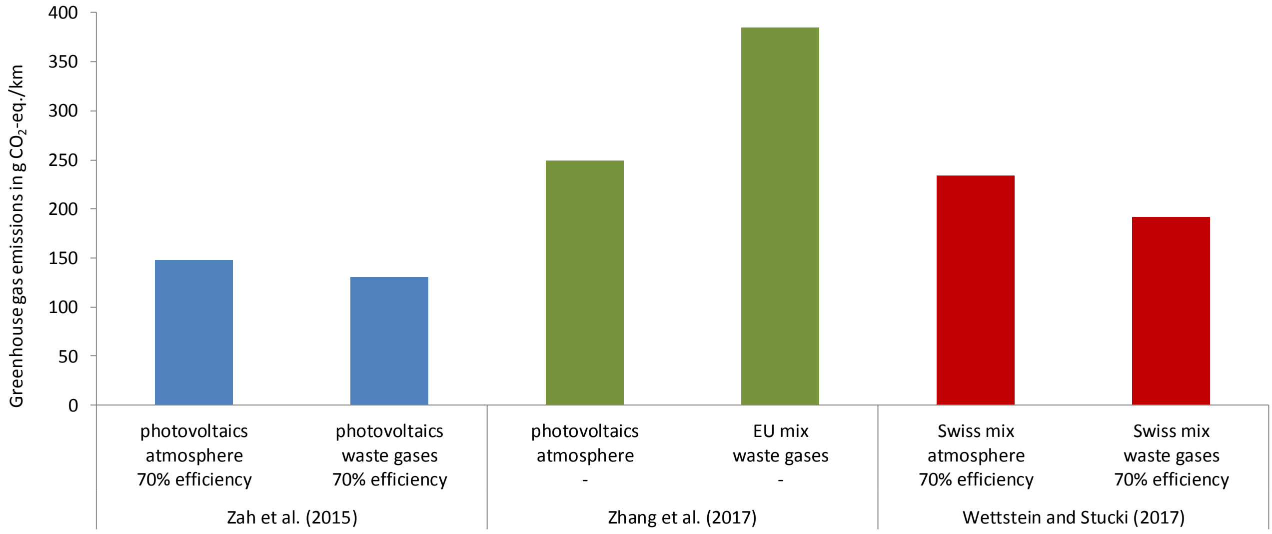


Figure 5-1: Comparison of greenhouse gas emissions in g CO_2-eq. per kilometre driven of PtG methane fuelled vehicles presented in Zah et al. (2015), Zhang et al. (2017) and the present study (Wettstein et al., 2018a). The first labelling row describes the electricity supply for electrolysis, the second row the CO_2 source and the last row the electrolysis efficiency.

5.3. Application tool

We also developed a calculation tool that calculates the environmental impacts depending on electricity source, H_2 production, CO_2 source, methanation process and credit for waste heat. The calculation tool can account for a reduction of fossil energy use due to the use of waste heat as a credit for the methanation process.

The tool is divided into two parts. In the upper part, the individual options for electricity source, H_2 production, CO_2 source, methanation technology and credit for waste heat can be selected. In the lower part, the environmental impacts in GHG emissions (kg CO_2-eq.) and total environmental eco-points (UBP) are calculated and plotted. As comparison, the environmental impacts of the reference vehicles (diesel car, petrol car, natural gas car and electric car) are illustrated next to the individually generated bars for cars fuelled with the specified PtG supply chain. An overview of the calculation tool is given in Figure 5-2.

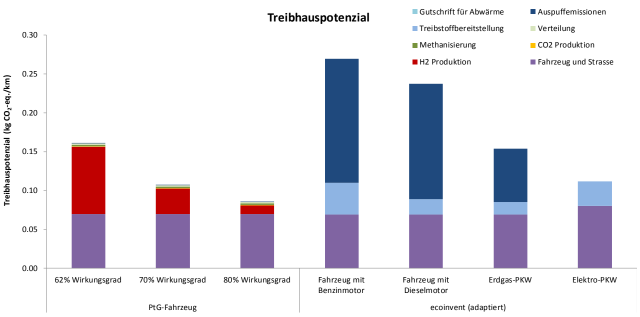
The tool covers eight different electricity sources: Swiss consumer mix today, in 2035 and in 2050, hydropower, photovoltaics with polycrystalline silicon panels, photovoltaics with cadmium-telluride panels, electricity from waste incineration plants and surplus electricity. For electrolysis, low efficiency (62%), high efficiency (70%) and a prospective alternative (80%) can be selected. The CO_2 source can be set on CO_2 from industrial exhaust gases or CO_2 collection from atmosphere. For methanation, catalytic or biogenic methanation can be selected and credits for waste heat can be considered or not.

Parameter	62% Wirkungsgrad	70% Wirkungsgrad	80% Wirkungsgrad	Fahrzeug mit Benzinmotor	Fahrzeug mit Dieselmotor	Erdgas-Auto	Elektro-Auto
Stromquelle H_2-Elektrolyse	CH Strommix	Photovoltaik CdTe	Überschussstrom				
Wirkungsgrad H_2-Elektrolyse	62%	70%	80%				
CO_2-Quelle	Abgase	Abgase	Abgase				
Stromquelle CO_2-Bereitstellung	CH Strommix	CH Strommix	CH Strommix				
Stromquelle Methanisierung	CH Strommix	CH Strommix	CH Strommix				
Gutschrift für Abwärmenutzung	nein	nein	nein				
Stromquelle Batterieladung Elektroauto							CH Strommix

Kommentar:
- für alle gelb markierten Zellen per Dropdown-Me

Ergebnisse für die einzelnen Prozesse (pro Kilometer)			PtG-Fahrzeug			ecoinvent (adaptiert)			
			62% Wirkungsgrad	70% Wirkungsgrad	80% Wirkungsgrad	Fahrzeug mit Benzinmotor	Fahrzeug mit Dieselmotor	Erdgas-PKW	Elektro-PKW
			kg CO_2-eq	kg CO_2-eq	kg CO_2-eq	kg CO_2-eq	kg CO_2-eq	kg CO_2-eq	kg CO_2-eq
H_2 Produktion	0.0126	kg	0.09	0.03	0.01	0	0	0	0
CO_2 Produktion	0.06948	kg	0.001	0.001	0.001	0	0	0	0
Methanisierung	0.0336	m3	0.002	0.002	0.002	0	0	0	0
Verteilung	0.0336	m3	0.002	0.002	0.002	0	0	0	0
Treibstoffbereitstellung	1	km	0	0	0	0.04	0.02	0.02	0.03
Auspuffemissionen	1	km	0.000	0.000	0.000	0.16	0.15	0.068	0.000
Fahrzeug und Strasse	1	km	0.07	0.07	0.07	0.07	0.07	0.07	0.08
Gutschrift für Abwärme	1	km	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	1	km	0.161	0.11	0.09	0.269	0.237	0.154	0.112
			161	107	85	60%			

Ergebnisse für die einzelnen Prozesse (pro Kilometer)	PtG-Fahrzeug			ecoinvent (adaptiert)			
	62% Wirkungsgrad	70% Wirkungsgrad	80% Wirkungsgrad	Fahrzeug mit Benzinmotor	Fahrzeug mit Dieselmotor	Erdgas-PKW	Elektro-PKW
	UBP	UBP	UBP	UBP	UBP	UBP	UBP
H_2 Produktion	233	60	23	0	0	0	0
CO_2 Produktion	3	3	3	0	0	0	0
Methanisierung	5	5	5	0	0	0	0
Verteilung	6	6	6	0	0	0	0
Treibstoffbereitstellung	0	0	0	70	44	20	88
Auspuffemissionen	0	0	0	83	79	33	0
Fahrzeug und Strasse	127	127	127	119	119	119	102
Gutschrift für Abwärme	0	0	0	0	0	0	0
Total	374	201	163	271	242	171	190



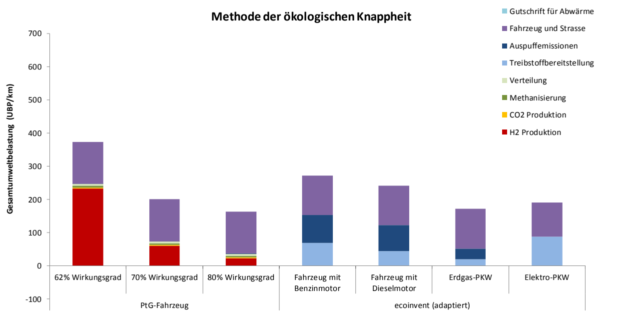


Figure 5-2: Overview of the application tool individually calculate the environmental impacts per kilometre driven (in kg CO_2-eq. and eco-points) of a PtG methane fuelled natural gas car in comparison with fossils fuelled cars.

6. Conclusions and Outlook

Based on the comprehensive analysis of the environmental impacts of the PtG supply chain, the following conclusions concerning PtG technology and its application in the mobility were drawn:

- A significant potential to reduce life cycle greenhouse gas emissions was defined, when comparing renewable and fossil methane value chains.
- Electricity source and consumption in hydrogen production are the crucial parameters for GHG emissions and total environmental impacts of the whole PtG value chain.
- Mobility based on PtG only shows an overall environmental benefit compared to vehicles fuelled with fossils, if electricity demand for hydrogen production is supplied by renewable or surplus electricity with low or no environmental impacts.
- Compared to the high importance of electricity requirement in hydrogen production, other aspects in the value chain are less important for GHG emissions and total environmental impacts per kilometre driven with a PtG vehicle.
- For a positive environmental evaluation, it is essential that the development of value chains for renewable methanation in Switzerland coincides with the change to renewable electricity in the country.

The analysis in this study comprises a wide range of scenarios concerning the PtG application in the mobility sector, but the analysis can still be extended to including other PtG applications beyond the mobility, as in heat and electricity production in households or in industry or as storage technology. PtG is considered as a promising technology due to its storage capacity in the already existing natural gas network. Further research could be made to compare PtG as a storage technology in comparison to conventional storage technologies. Another field of PtG application is the reconversion of PtG methane to electricity by burning it in natural gas power plants with the drawback of a low overall efficiency. In addition, the life cycle inventory data could be expanded with data on potential methane leakage in the PtG value chain. Further approaches for vehicles could be explored, primarily according to vehicle sizes, engine efficiencies and additional vehicle types including lorries.

If environmental impacts related to the energy consumption in the hydrogen production can be reduced, renewable methane offers a considerable potential as an alternative fuel for a more sustainable mobility sector, including additionally improvement potential concerning electrolysis efficiency and CO_2 capture.

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Appendix

The appendix contains detailed tables of the aforementioned results.

A. Tables of Results

Table A - 1: Greenhouse gas emissions in kg CO_2-eq. per kilometre driven of PtG vehicles with various electricity supply and of reference vehicles fuelled with fossil fuels or electricity

Results of each process		PtG vehicle								Reference vehicle			
		Swiss consumer mix today	Swiss consumer mix 2050	PV Poly-Si	Swiss consumer mix 2035	PV CdTe	Hydropower	Municipal incineration plant	Excess electricity	Petrol	Diesel	Natural gas (fossil)	Electric (charged with Swiss consumer
		kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.
H_2 production	0.0246 kg	0.11	0.11	0.09	0.08	0.06	0.03	0.02	0.02	0	0	0	0
CO_2 production	0.1357 kg	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0	0	0	0
Methanation	0.0525 m^3	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0	0	0	0
Distribution	0.0525 m^3	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0	0	0	0
Fuel provision	1 km	0	0	0	0	0	0	0	0	0.04	0.02	0.03	0.03
Exhaust emissions	1 km	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.16	0.15	0.113	0
Vehicle and road	1 km	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.08
Error indication	positive error value	0.0140	0.0138	0.0120	0.0104	0.0073	0.0036	0.0026	0.0023				
	negative error value	0.0136	0.0134	0.0116	0.0101	0.0070	0.0035	0.0026	0.0022				
Total	**1 km**	**0.19**	**0.19**	**0.18**	**0.16**	**0.14**	**0.11**	**0.10**	**0.10**	**0.27**	**0.24**	**0.21**	**0.11**

Table A - 2: Environmental impact in eco-points per kilometre driven of PtG vehicles with various electricity supply and of reference vehicles fuelled with fossil fuels or electricity

Results of each process		PtG vehicle								Reference vehicle			
		Swiss consumer mix today	Swiss consumer mix 2035	PV Poly-Si	Swiss consumer mix 2050	PV CdTe	Hydropower	Municipal incineration plant	Excess electricity	Petrol	Diesel	Natural gas (fossil)	Electric (charged with Swiss consumer
		UBP	UBP	UBP	UBP	UBP	UBP	UBP	UBP	UBP	UBP	UBP	UBP
H_2 production	0.0246 kg	274	179	165	141	119	56	44	37	0	0	0	0
CO_2 production	0.1357 kg	8	8	8	8	8	8	8	8	0	0	0	0
Methanation	0.0525 m3	8	8	8	8	8	8	8	8	0	0	0	0
Distribution	0.0525 m3	9	9	9	9	9	9	9	9	0	0	0	0
Fuel provision	1 km	0	0	0	0	0	0	0	0	70	44	32	89
Exhaust emissions	1 km	3	3	3	3	3	3	3	3	83	79	54	0
Vehicle and road	1 km	127	127	127	127	127	127	127	127	119	119	120	250
Error indication	positive error value	35	23	21	18	15	7	6	5				
	negative error value	34	22	21	18	15	7	5	5				
Total	**1 km**	**429**	**334**	**320**	**297**	**274**	**212**	**199**	**193**	**271**	**242**	**205**	**339**

Table A - 3: Greenhouse gas emissions in kg CO_2-eq. per kilometre driven of PtG vehicles with electrolysis efficiencies of 62%, 70% and 80%, respectively in comparison with a reference vehicle fuelled with fossil natural gas

Results of each process (per kilometre)	Electrolysis efficiency PtG vehicle			Natural gas powered vehicle
	62%	**70%**	**80%**	fossil
	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.	kg CO_2-eq.
H_2 production	0.13	0.11	0.09	0
CO_2 production	0.007	0.007	0.007	0
Methanation	0.003	0.003	0.003	0
Distribution	0.003	0.003	0.003	0
Fuel provision	0.000	0.000	0.000	0.026
Exhaust emissions	0.001	0.001	0.001	0.113
Vehicle and road	0.07	0.07	0.07	0.068
Total	**0.213**	**0.192**	**0.178**	**0.207**

Table A - 4: Environmental impact in eco-points per kilometre driven of PtG vehicles with electrolysis efficiencies of 62%, 70% and 80%, respectively in comparison with a reference vehicle fuelled with fossil natural gas

Results of each process (per kilometre)	**Electrolysis efficiency PtG vehicle**			**Natural gas powered vehicle**
	62%	**70%**	**80%**	fossil
	UBP	UBP	UBP	UBP
H_2 production	328	274	238	0
CO_2 production	8	8	8	0
Methanation	8	8	8	0
Distribution	9	9	9	0
Fuel provision	0	0	0	32
Exhaust emissions	3	3	3	54
Vehicle and road	127	127	127	120
Total	**483**	**429**	**393**	**205**

Table A - 5: Greenhouse gas emissions in g CO_2-eq. per kilometre driven of PtG vehicles with CO_2 collected from atmosphere or from industrial waste gases in comparison with a reference vehicle fuelled with fossil natural gas

Results of each process (per kilometre)	**CO_2 source PtG vehicle**		**Natural gas powered vehicle**
	Atmosphere	**Industrial waste gases**	Fossil
	g CO_2-eq.	g CO_2-eq.	g CO_2-eq.
H_2 production	109	109	0
CO_2 production	49	7	0
Methanation	3	3	0
Distribution	3	3	0
Fuel provision	0	0	26
Exhaust emissions	1	1	113
Vehicle and road	69	69	68
Total	**234**	**192**	**207**

Table A - 6: Environmental impact in eco-points per kilometre driven of PtG vehicles with CO_2 collected from atmosphere or from industrial waste gases in comparison with a reference vehicle fuelled with fossil natural gas

Results of each process (per kilometre)	**CO_2 source PtG vehicle**		**Natural gas powered vehicle**
	Atmosphere	**Industrial waste gases**	Fossil
	UBP	UBP	UBP
H_2 production	274	274	0
CO_2 production	35	8	0
Methanation	8	8	0
Distribution	9	9	0
Fuel provision	0	0	32
Exhaust emissions	3	3	54
Vehicle and road	127	127	120
Total	**456**	**429**	**205**

Table A - 7: Greenhouse gas emissions in g CO_2-eq. per kilometre driven of Hydrogen-Compressed Natural Gas (HCNG) as fuel in comparison with PtG methane as fuel from catalytic methanation

	Catalytic methanation		Fossil natural gas	
	CH_4 PtG	HCNG (H_2 + CH_4 PtG)	Fossil natural gas	HCNG (fossil natural gas + H_2)
	g CO_2-eq./km	g CO_2-eq./km	g CO_2-eq./km	g CO_2-eq./km
Fuel provision - CH_4	108.0	101.4	0	0
Fuel provision - H_2	0	4.3	0	4.3
Fuel provision - fossil natural gas	0	0	25.8	24.3
Vehicle and road	69.1	69.1	68.1	68.1
Exhaust emissions	1.2	1.2	112.7	105.9
Total	**178**	**176**	**207**	**203**

Table A - 8: Greenhouse gas emissions in kg CO_2-eq. per m^3 methane of catalytic methanation through adsorption reactor and biogenic methanation through stirring tank reactor and trickle bed reactor

	Catalytic methanation	Biogenic methanation	
	Adsorption reactor	Stirring tank reactor	Trickle bed reactor
	kg CO_2-eq./m^3	kg CO_2-eq./m^3	kg CO_2-eq./m^3
Emissions	0	0	0
Infrastructure	1.01E-03	1.01E-03	1.01E-03
CO_2 production	1.30E-01	1.30E-01	1.30E-01
Reactor	9.98E-04	4.40E-02	9.20E-02
H_2 production	1.805	1.819	1.819
Electricity (operation)	0.053	0.151	0.070
Total	**1.991**	**2.145**	**2.112**

Table A - 9: Greenhouse gas emissions in kg CO_2-eq. per m^3 methane of conventional gas processing through amine washing, pressure swing adsorption (PSA) and glycol washing in comparison with gas processing of catalytic or biogenic methanation supplied by Swiss consumer mix today or surplus electricity

	Biomethane amine washing Swiss consumer mix today kg CO_2-eq./m^3	**Biomethane Pressure Swing Adsorption (PSA)** Swiss consumer mix today kg CO_2-eq./m^3	**Biomethane glycol washing** Swiss consumer mix today kg CO_2-eq./m^3
Crude biogas	0.740	0.740	0.740
Treatment processes	0.571	0.987	0.990
Electricity	0.057	0.073	0.183
Heat	0.380	0.000	0.000
Methane leakage	0.032	0.832	0.723
H_2 production	0.000	0.000	0.000
Other	0.102	0.082	0.083
Total	**1.311**	**1.727**	**1.730**

	Methane catalytic methanation Swiss consumer mix today kg CO_2-eq./m^3	**Methane catalytic methanation** surplus electricity kg CO_2-eq./m^3	**Methane biogenic methanation** Swiss consumer mix today kg CO_2-eq./m^3	**Methane biogenic methanation** surplus electricity kg CO_2-eq./m^3
Crude biogas	0.444	0.444	0.452	0.452
Treatment processes	0.849	0.214	0.875	0.162
Electricity	0.021	0.000	0.027	0.000
Heat	0.000	0.000	0.000	0.000
Methane leakage	0.000	0.000	0.000	0.000
H_2 production	0.827	0.213	0.811	0.125
Other	0.001	0.001	0.036	0.036
Total	**1.293**	**0.659**	**1.327**	**0.614**