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State of the Art and Perspectives of CO_2 Methanation Process Concepts for Power-to-Gas Applications

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Authors: Manuel Götz, Amy McDaniel Koch, Frank Graf

DVGW Research Center at the Engler-Bunte-Institut of the Karlsruhe Institute of Technology (KIT), Engler-Bunte-Ring 1, 76131 Karlsruhe, Germany

Abstract

In a highly interconnected energy system power to gas might play an increasingly significant role. Renewable electric energy can be transformed into a storable and save chemical energy carrier via electrolysis and methanation. The existing gas grid infrastructure can be used for energy storage and transportation.

Thermochemical methanation means the conversion of H_2 and CO_2 at about 300 - 550 °C usually with nickel-based catalysts. Thermochemical methanation processes can be realized in several reactor concepts. Mainly, these can be subdivided by the nature of the support (e. g. honey combs or pellets), the temperature control (e. g. isothermal or adiabatic) or the phases involved in methanation (two phase vs. three phase reactions).

Another approach is the biochemical conversion. A microorganism serves as biocatalyst. The bioprocess takes place in aqueous solutions at temperatures between 40 - 70 °C. As limiting step, the transfer of hydrogen from gas phase into the liquid phase is named in literature. Hence, there are several reactor concepts under development aiming to reduce these mass transfer limitations. So far the stirred fermenter is the mostly used reactor.

Mainly due to the higher process temperature and the resulting higher reaction velocity, thermochemical methanation requires much lower reactor volumes for a certain feed gas flow than biochemical methanation. However, full CO_2-conversion in a single step thermochemical methanation reactor cannot be achieved due to thermodynamic equilibrium limitations. Therefore, especially for small scale applications biochemical methanation can be advantageous.

Both thermochemical and biochemical methanation processes will be figured in the paper. The main characteristics of the processes with advantages and challenges will be discussed as well as the state of development.

1 Introduction

The Power-to-Gas (PtG) process chain could play a significant role in the future energy system. By utilizing this Power-to-Gas pathway, electrical energy from renewable resources can be converted into storable chemical energy carriers (i.e. methane). E.g. Germany has a well-developed gas grid infrastructure that can be used to both store and transport hydrogen and synthetic natural gas produced in PtG processes [1]. In comparison to traditional methanation processes where hydrogen is supplied by a gasifier, in PtG the hydrogen comes from an electrolysis plant which uses excess electrical energy to split water into hydrogen and oxygen. Then, the hydrogen, together with CO_2, is fed into a methanation reactor. For the methanation process, two possible process concepts exist: biological and thermochemical methanation. This paper will focus on the advantages of these two methods of CO_2 methanation and their possible application in the PtG process chain. The produced methane is then upgraded until it reaches the gas grid appropriate calorific value, and is then injected into the natural gas grid where it can be stored long-term. The first PtG power plants from ETOGAS for Audi AG in Wertle, Germany were focused on thermochemical methanation applying a tube bundle reactor [2, 3]. However, alternative process pathways (three phase thermochemical methanation and biochemical methanation) are currently under development and are being specifically optimized to the requirements of a PtG process chain.

2 Biological Methanation

2.1 Process Overview

Biological methanation is an intriguing option for the PtG process chain. A microorganism serves as a biocatalyst, converting the hydrogen and carbon dioxide into methane. This biological reaction has been known since 1906 [4], however, the technical implementation is still an issue. Biological methanation (BM) proceeds at low temperatures (40 to 70 °C), which makes the process simpler, an advantage for small plants. Additionally, the microorganisms also have a high tolerance for the impurities that are typically found in the types of gases that are used as feed gas for methanation. Such impurities include the sulphur and ammonia that come from the CO_2 source (i.e. biogas) and the oxygen that comes from the electrolysis process. Moreover, load change is, based on current state, a non-issue for biological methanation. This is ideal for the large fluctuations in power supply from renewable resources. However, because the microorganisms are present in a fermentation broth and the methanation reaction takes place within the aqueous solution (hydrogen is poorly soluble in the liquid); the supply of hydrogen to the microorganisms presents the biggest engineering challenge. Thus, several reactor concepts are currently being developed to specifically reduce these mass transfer limitations. Mostly, continuous stirred-tank reactors (CSTR) are used. By increasing the stirrer frequency, the mass transfer of H_2 can be improved. In other concepts such as trickle beds and membrane reactors, the microorganisms are immobilized. An important parameter for evaluating the process efficiency is the specific methane formation rate *MFR*. It depends, among other things, on the microorganisms, the reactor type, the pressure, the pH-value, and the temperature.

Two principle process types are possible for biological methanation: methanation in situ digester (Figure 1) and methanation in a separate reactor (Figure 2). Both the in situ and extern process concepts were investigated by MicrobEnergy GmbH [5] and the extern process concept was investigated by Krajete GmbH [6]. The investigations from both MicrobEnergy GmbH and Krajete GmbH were carried out within the framework of the DVGW project G 3/01/13 designed to determine the potential of biological methanation in comparison to thermochemical methanation.

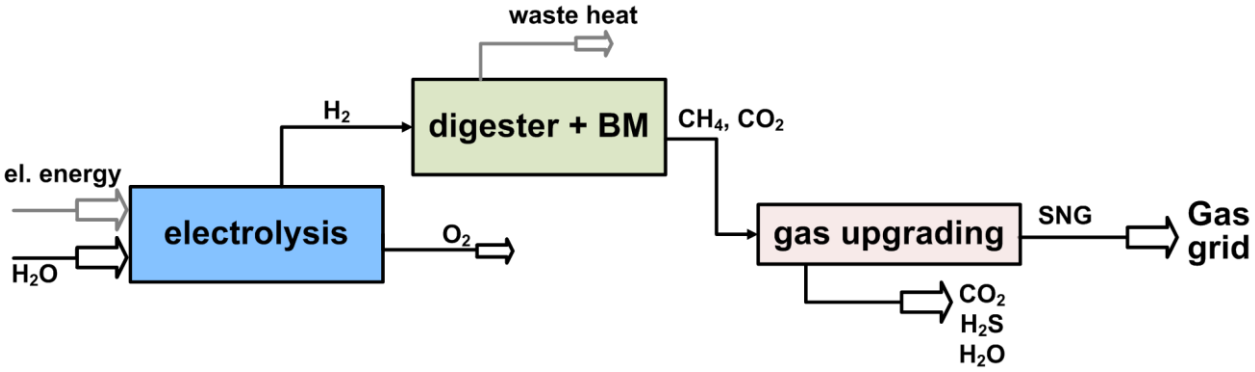

Figure 1: Process flow diagram for in situ variation of biological methanation (BM: Biological methanation)

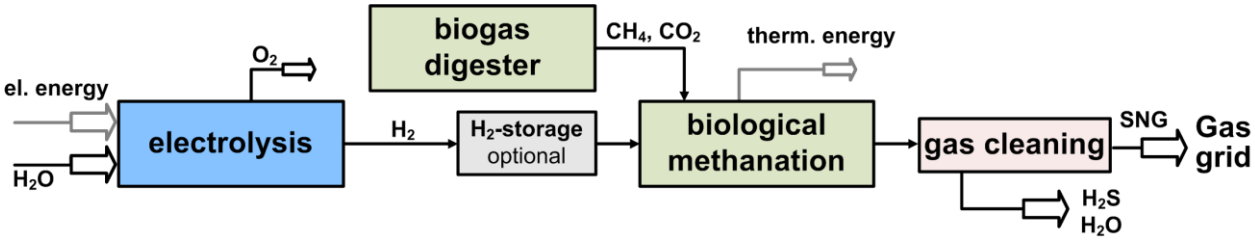

Figure 2: Process flow diagram for biological methanation with a separate reactor (extern)

2.2 In situ biological methanation

Digesters of biogas plants can be used for the PtG process chain. Thereby, hydrogen is fed directly to the biogas digester. A part or all of the produced CO_2 is then in situ converted to CH_4 resulting in a biogas with a higher methane content and calorific value. The methane formation rate of the biological methanation is limited by the CO_2 production rate of the biogas plant, therefore only small *MFRs* of < 0.1 h^{-1} are possible. Nevertheless, no further reactor is necessary resulting in a low investment. A total conversion of the produced CO_2 is very difficult. For biogas plants using energy crops as feedstock, the methane content can be increased from 52 to 75 %. In biogas plants using residues, a methane content of more than 97 % can be achieved (both values are reported by MicrobEnergy GmbH, Germany).

Current research focuses on testing the ability of biogas plants for hydrogen addition. Another issue is to achieve a high gas liquid mass transfer of H_2 in the digester.

2.3 Biological methanation in an external reactor

Another possibility is the biological CH_4 production from pure cultures with pure gases in an external reactor. This concept is not limited to biogas as the carbon source. Another advantage is that the process conditions and the reactor design can be adjusted with respect to the requirements of the biological methanation.

The range of reported *MFRs* is large (Table 1). A comparatively high *MFR of* ≈ *29* h^{-1} was achieved by Nishimura et al. using a CSTR reactor at elevated pressure [7]. However, *MFRs* below 10 h^{-1} have been linked to less efficient microorganisms or too low concentrations of the microorganism in the reaction. Thus, the microorganism needs to be present at a high enough concentration to ensure sufficient methane production. Low concentrations of the microorganisms are normally the result of high resistance in the gas liquid mass transfer of H_2, inadequate nutrient supply, or low temperatures. Both elevated temperature and pressure have been shown to improve methane formation. A temperature increase from 37 to 60 °C doubles the specific rate of methane formation.

Table 1: Reactor performance of some biological methanation reactors

Author	*T* in °C	*p* in bar	reactor type	Culture	*MFR* in h^{-1}
Rittmann et al., 2012 [8]	65	?	CSTR	*Methanothermobacter marburgensis*	7.7
Nishimura et al., 1992 [7]	65	1 - 3	CSTR	*KN-15*	28.7
Burkhardt and Busch, 2013 [9]	37	1	trickle bed	from digested sludge	0.05
Jee et al. 1987 [10]	65	1	membrane reactor	*Methanobacterium thermoautotrophicum*	6

For all investigated reactor designs, the supply of hydrogen to the microorganisms was the rate limiting step. The Henry Coefficient for water at 60 °C is $H_{H2,H2O}$ = 84,320 bar, while the Henry Coefficient for carbon dioxide is $H_{CO2,H2O}$ = 3,400 bar. Thus, carbon dioxide is 25 times more soluble than hydrogen in the aqueous fermentation liquid; therefore the biggest challenge for biological methanation is the delivery of the gaseous hydrogen to the microorganisms. Hence, there is significant potential for process development with respect the method of hydrogen delivery.

2.4 Conclusion

A research project was undertaken at DVGW in conjunction with Krajete GmbH and MicrobEnergy GmbH in order to determine the potential of the biological methanation in comparison to the thermochemical methanation. Krajete GmbH and MicrobEnergy GmbH have experience with biological methanation at the laboratory and partly at the pilot scale. The studies undertaken at MicrobEnergy focused on in situ biological methanation in conventional biogas production (i.e. coupled with waste water treatment facilities) as well as the extern concept, while the studies at Krajete GmbH focused on biological methanation in an external reactor using strong (efficient) pure cultures of the microorganism. Table 2 contains a summary of the design data used by the two companies.

From Table 2, differences between design data for the experimental investigations performed by the two companies can be observed. In particular, the *MFR* and the electrical energy demand should be noted. This strong microorganism used by Krajete accounts for the high *MFRs* from Krajete GmbH. The high *MFRs* may also be due to effective introduction of the gas. However, it remains to be seen whether or not these high *MFRs* can be achieved at a larger scale, in particular regarding the power demand. The higher energy demand reported by MicrobEnergy (especially for the in situ variation), is due to the difficulty of introducing the gas into the fermentation liquid. Here, the gas is not agitated by a stirrer; instead the gas is introduced via two phase pump. Lastly, the investment costs for the extern variation are 1.5 x that of the in situ variation, which is due to the extra process equipment necessary for the extern variation.
It can be concluded that from the work within the framework of this project, that biological methanation is promising as part of a PtG process chain. This possibility of integration into existing biogas or waste water plants, as well as the flexibility and robustness of the system make biological methanation an interesting option, especially for smaller systems. Further development is still necessary at the pilot scale, as well as improved introduction of the gas.

Table 2: Design data used by the two companies in the study: MicrobEnergy investigated both in situ and extern concepts while Krajete only investigated extern concepts

	MicrobEnergy GmbH (in situ)	**MicrobEnergy GmbH (extern)**	**Krajete GmbH**
MFR in h^{-1}	0.01 (in situ)	2.5 (extern)	11.2 – 22.4
GHSV in h^{-1}	0.05	10.5	56 – 112
H_2-Conversion X_{H2} in %	99	99	99
T in °C	40	65	65
p in bar	1	9	4
Process Materials	buffer solution	substrate, buffer solution	nutrient solution, buffer solution
Electrical Energy Demand in kWh/m^3 SNG	1.8 (in situ)	1.2 - 1.3	0.3 - 0.4 (based on lab scale plant)
Specific Investment Cost for a 5 MW SNG Plant in €/kWh SNG	≈ 400	≈ 600	≈ 600

3 Thermochemical Methanation

Thermochemical methanation is defined as the conversion of hydrogen and either CO or CO_2 to CH_4 in the presence of catalyst (usually nickel-based). Typical operating conditions are temperatures in the range of 300 to 550 °C and pressures from 1 to 100 bar. Beside others, the following process concepts for thermochemical methanation exist [11]: fixed bed methanation, fluidized bed methanation, and three phase methanation. The advantages and challenges of each of these processes (with respect to PtG) will be described in the following sections.

3.1 Fixed Bed Methanation (FB)

Currently, adiabatic fixed bed methanation is state of the art and the most widely adopted method of thermochemical methanation. In fixed bed methanation, the reactor is packed with the catalyst with a particle size in the range of millimetres. The primary challenge in fixed bed

methanation is the temperature control in the reactor, which is a result of the extremely exothermic methanation reaction. Reaction temperatures above 550 °C can cause catalyst deactivation by sintering and need to be avoided. Furthermore, the methane conversion is limited by the thermodynamic equilibrium at temperatures above ≈ 300 °C (depends on pressure, Figure 3). Therefore, several reactors in series with interstage cooling are used. Some concepts use recycle streams, additionally.

Well know concepts include the Lurgi process, which is used at the first commercial methanation plant in North Dakota [12], and the TREMP process from Haldor Topsøe which is used in coal-to-gas plants in China [13] and for the biomass-to-gas plant GoBiGas in Sweden [14, 15]. The methanation reactor used in the Werlte plant (see section 1) is based on an isothermal methanation [2, 3].

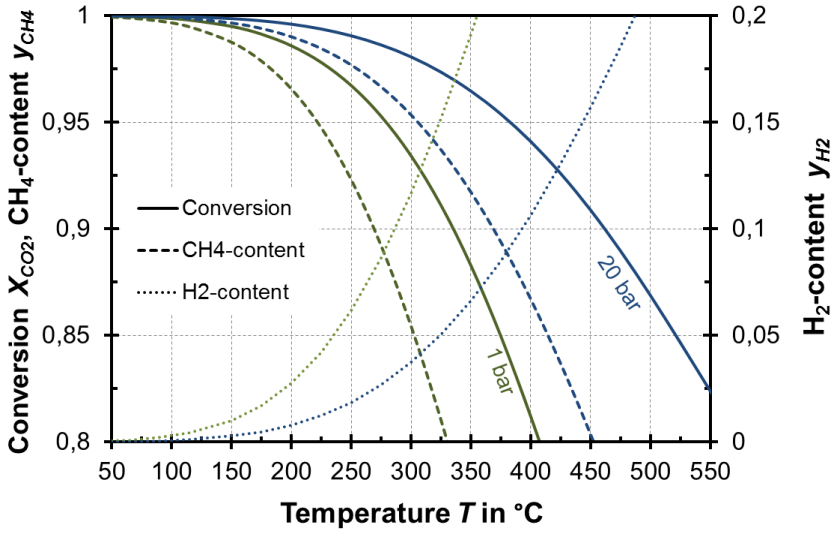

Figure 3: Equilibrium calculations for methanation (feed gas: $H_2/CO_2/CH_4$ = 4/1/1)

3.2 Fluidized Bed Methanation

As an alternative to fixed bed methanation, fluidized bed reactors are also established technologies for methanation, well suited for large scale operation. As an example, the Comflux process was developed by Engler-Bunte-Institut in conjunction with Thyssengas GmbH from which a demonstration plant was built to produce 2,000 m^3/h SNG [16]. In 2009, the Comflux process was used to produce SNG from solid biomass in a 1 MW plant in Güssing, Austria [14].

In fluidized bed methanation, fine catalyst particles are fluidized by the gaseous reactants. Due to the uniform mixing of the fluidized solids in the gas, the heat removal is more effective creating nearly isothermal conditions in the reactor. This is advantageous because it enables the use of a single reactor with a relatively simple design. Negative aspects of this process include attrition and breakage of the catalyst. Incomplete conversion due to bubbling is also an issue.

3.3 Three Phase Methanation (3PM)

In three phase methanation (Figure 4), a solid catalyst (powder < 100 µm) is suspended in a temperature stable inert liquid such as dibenzyltoluene. The first three phase methanation concept was developed by Chem Systems, Inc. from 1975 – 1981. The concept was based on a

three phase fluidized bed [17]. Currently, the three phase methanation in a slurry bubble column reactor is under investigation at laboratory scale at the Engler-Bunte-Institut, Germany [18, 19] and at the Institute of Coal Chemistry, China [20]. Good heat dissipation of the reaction is a significant advantage for this method, as it allows for good heat control of the reaction. This is especially beneficial in the PtG process, since the high heat capacity of the liquid phase makes it easier for the methanation process to handle the fluctuations/downtime. Moreover, the catalyst can be replaced during operation. However, a major disadvantage of the three phase methanation is the liquid side mass transfer limitation, which reduces the effective reaction rate. Further information on the three phase methanation can be found elsewhere.

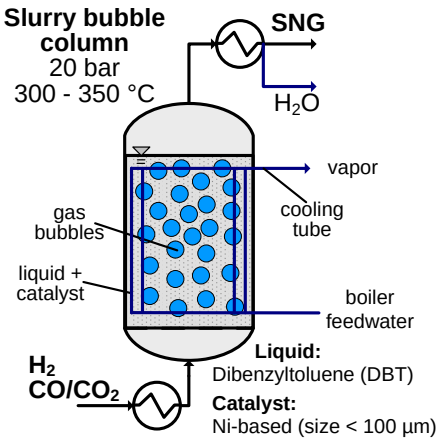

Figure 4: Schematic diagram of the three phase reactor concept

In any kind of bubble column, a minimum gas velocity is necessary to fluidize the solid particles. A gas velocity that is too low prohibits a homogeneous distribution of the catalyst particles, may reducing the overall conversion. Based on own calculations, a minimum load of less than 20 % is necessary. Unlike fixed bed methanation, 3PM is tolerant of rapid load change. A load change from 25 to 100 % takes only about 10 minutes to achieve steady state (Figure 5). Furthermore, the time needed for load changes is only a function of the gas residence time. The reactor hydrodynamics and reaction kinetics are not the limiting factors. This is a promising finding regarding the flexibility of the slurry bubble column for methanation purpose.

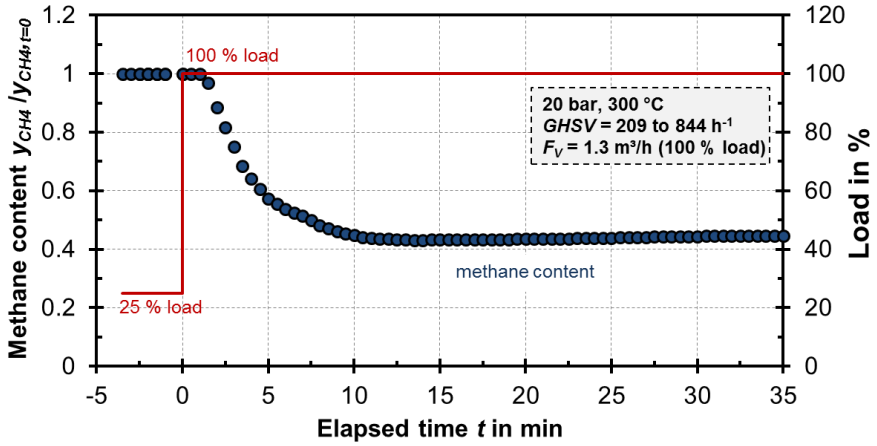

Figure 5: Required time for a load change from 25 to 100% in a three phase methanation reactor

4 Comparison of Biological and Thermochemical Methanation

A further aspect of the DVGW study was a comparison of the biochemical and thermochemical methanation. Data for the biological methanation was taken from experimental investigations from Krajete GmbH and MicrobEnergy GmbH and the data for thermochemical methanation was taken from our own investigations at the DVGW Research Center at Engler-Bunte-Institut (KIT) as well as from Outotec GmbH.

4.1 Comparison of technical parameters

Based on own data (for 3PM) and data from the companies MicrobEnergy GmbH, Krajete GmbH (both for BM) and Outotec GmbH (FB), a comparison of the process characteristics of biological and thermochemical methanation processes was done. A summary of the results is given in Table 3.

Table 3: Comparison of biological and thermochemical methanation processes

Reactor Type	**BM (extern)** Isothermal CSTR	**3PM** Isothermal slurry bubble column	**Fixed Bed** adiabatic
Catalyst	enzyme of microorganism	Ni-based	Ni-based
Stages	1	1 - 2	2 - 6
T in °C	40 - 70	300 - 350	300 - 550
p in bar	> 4 (see Table 2)	> 20	> 5 - 10
Stage of development	lab scale/pilot	lab scale	commercial
GHSV in h^{-1}	< 100	500 - 1,000	2,000 - 5,000
Limitation	GL mass transfer	GL mass transfer	equilibrium
Tolerance of impurities	high	medium	low
Minimum load in %	?	10 - 20	40
Load change behaviour	limited by process control, not by chemistry/biology		
Electricity demand in kWh/m^3 SNG (injection pressure of 16 bar)	0.4 - 0.8	< 0.4	< 0.4
Process materials	nutrients, buffer solution	heat transfer liquid, (catalyst)	(catalyst)
Reaction Heat Utilization	poor	good - very good	very good

GHSV

It is of interest to compare the required reactor size of biological methanation with conventional thermochemical methanation since reactor size is a crucial aspect regarding the investment. A direct comparison of the overall reaction rate of thermochemical and biological methanation is possible by comparing the Gas Hourly Space Velocity *GHSV*. It is defined as $GHSV = F_{V,gas,in} / V_R$. Therefore, $GHSV = 5\ MFR$ (if the feed gas consists only of stoichiometric H_2 and CO_2).

In comparison to biological methanation (*GHSV* < 100 h^{-1}), thermochemical CO_2 methanation in a fixed bed reactor proceeds at a much faster rate (2,000 - 5,000 h^{-1}), followed by three phase methanation (500 - 1,000 h^{-1}). The stark differences between the *GHSVs* are largely due to the

much higher process temperatures, 300 to 550 °C for thermochemical methanation versus 40 to 70 °C for biochemical methanation. Because gas liquid mass transfer limitations are non-existent in the fixed bed reactor, this reactor type achieves the highest *GHSV*.
Another disadvantage of the biological methanation is the higher backmixing in gas and liquid phase resulting in a lower overall reaction rate. The backmixing in the three phase methanation is moderate while in fixed bed reactors, almost no backmixing is present.

Tolerance of Impurities
Biological methanation is more robust against impurities than thermochemical methanation. For biological methanation, process upset or infection from foreign organisms was not found to be an issue. This is especially the case for process setups when the biological methanation takes place in a separate reactor. Minor disruptive components such as sulphur and oxygen were found to have no effect on the biological methanation. Furthermore, both of these components can partly be removed by biological methanation. The remaining sulphur components have to be removed before the gas injection.
Contrastingly, sulphur and sulphur containing components are a known catalyst poison for the Nickel catalysts used for thermochemical methanation. Thus, the feed gas for thermochemical methanation process must be cleaned upstream of the methanation reactor(s). In case of fixed bed reactors, higher hydrocarbons are also an issue since they decompose at temperatures above ≈ 500 °C forming coke. The deposited coke leads to catalyst deactivation [21].

Process Flexibility and Minimum Load
For methanation to be operated dynamically as part of a PtG chain, both the minimum load rate and the load change rate need to be considered. A more flexible methanation reactor reduces the costs for upstream storage of hydrogen significantly. Since hydrogen storage is a high cost factor, minimization of this process factor is crucial.
Biological methanation is a flexible process with respect to load change. Krajete GmbH experimentally demonstrated in a lab scale biological methanation process that an immediate load change from 100 to 0 % can be realised with no negative effect on the process. It was also demonstrated that a restart following a 560 h (23 d) of stagnant operation was also possible without harmful consequences.
The catalyst in the thermochemical methanation reacts very fast to load changes, too. It is reported that fast load changes can damage the methanation catalyst; however, our own measurements as well as measurements from Outotec GmbH and ZSW Stuttgart [22] have shown that dynamic operation has no negative effect on the CO_2 methanation catalyst.
For biological as well as for thermochemical methanation, the limiting factor for load changes is related to the process control system and not to the process itself.
The minimum load of biological methanation is unknown. For fixed bed reactors, a minimum load rate of 40 % is recommended. Lower minimum loads could be possible with special reactor designs. Three phase methanation can operate within a larger load range. A minimum load of less than 10 - 20 % is necessary for homogeneous distribution of the catalyst in the heat transfer oil. Minimum loads of less than 10 % should be possible, too. However, this needs to be evaluated in a demo scale process.

Current state of development

Currently, biological methanation and three phase methanation have only been investigated at the laboratory scale; the former is currently being tested at the pilot/demo scale. Thus, data and experiences from commercial operations are not available at this time. A challenge of the BM is the adequate mixing of a large scale biological reactor with respect to hydrogen supply. The crucial part of the upscaling of 3PM is the backmixing behaviour in large scale reactors.
In contrast, FB methanation is well established in commercial industry (see section 3.1).

4.2 Energy efficiency

Power Requirements

All of the thermochemical methanation processes have a lower power requirement than the biological methanation. The high power demands are due to the mass transfer limitations that are present in the biological methanation. A stirrer or some kind of agitation mechanism is needed to effectively introduce the gas into the liquid phase. Although, three phase methanation is also subject to mass transfer limitations, the mass transfer in this case is better than that for the biological methanation. For three phase methanation, the elevated temperature increases the solubility of the H_2 in the heat transfer oil, the mass transfer coefficient, and increases the phase boundary by reducing the viscosity and the surface tension. For example, the solubility of H_2 in the heat transfer oil of the 3PM at 300 °C is approximately 6 times higher than the solubility of H_2 in water at 65 °C. As a consequence, a stirrer is not required; instead the dispersion of the gas throughout the reactor occurs using the gas sparger that is present at the bottom of the reactor.

Efficiency of Power-to-SNG and Utilization of waste heat

The energy efficiency of the PtG chain is $\eta_{PtG,PE} \approx 53$ % (electrolysis + BM) if the electricity demand of the BM is considered. The energy efficiency is calculated using Eq. 1.

$$\eta_{PtG} = \frac{P_{SNG}}{P_{el,Ely} + P_{el,Meth}} \qquad \text{Eq. 1}$$

P_{SNG} is the chemical energy of the SNG produced, $P_{el,Ely}$ is the electrical power required for the electrolysis process, and $P_{el,Meth}$ is the electrical power required for the methanation. By using the waste heat of the biological methanation for heating of the biogas digester (420 kW for a 5 MW plant), the overall efficiency is increased to 58 %. Further opportunities for utilization of the waste heat from biological methanation are sparse due to the low temperature level (< 65 °C), which yield few potential uses.
The higher temperature level (at least 300 °C) of the thermochemical methanation yields more opportunities for integration/utilization of the waste heat streams. Relatively high valuable steam and power could be produced, respectively. If the waste heat streams are utilized in a PtG process chain with thermochemical methanation, then the overall efficiency is between 74 and 82 %. An example with an overall efficiency of > 80 % for a 5 MW SNG PtG plant is given in Figure 6. However, the utilization of waste heat increases the investment of the methanation plant; especially the gas turbine is expansive. For a 5 MW SNG plant, the investment is increased by ≈ 30 % if the waste heat streams are used as given in Figure 6.

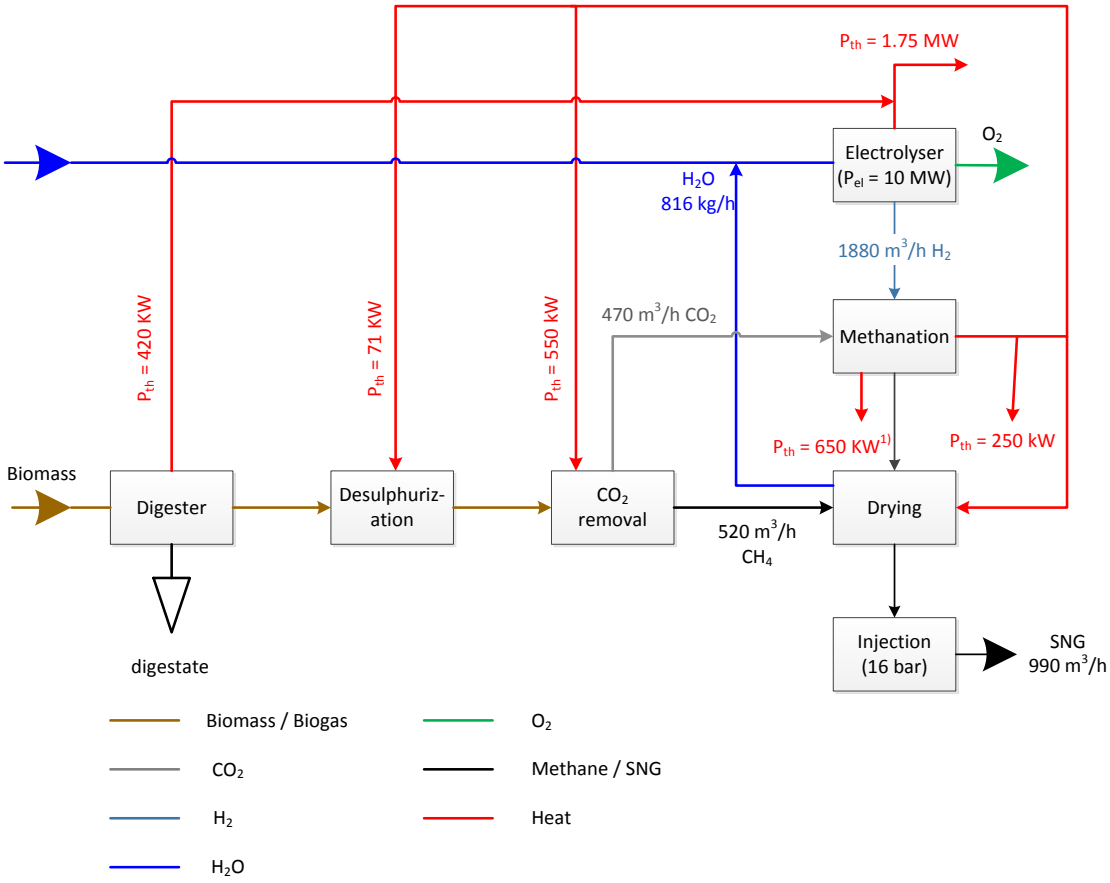

Figure 6: Heat integration for thermochemical methanation ([1)] to steam turbine)

4.3 Economics

As mentioned in section 2, the in situ variation of biological methanation has lower investment costs than the extern variation. Due to the process similarities, it is of interest to compare the investment costs for “extern” variation of biological methanation with thermochemical methanation. Figure 7 compares the costs for a 5 MW and 110 MW SNG plants for thermochemical methanation (fixed bed) and biological methanation (3,000 h of operation, electricity costs of 5 ct/kWh). In the cases shown, the added influence of the hydrogen production (electrolysis) costs are considered and compared with the costs for the methanation process only. For biological and thermochemical methanation, the costs for hydrogen production are well above the costs for SNG; which increases the specific production costs significantly. Moreover, for the smaller plant size (5 MW) the production costs for biological methanation are only slightly higher than for thermochemical methanation. When the costs for electrolysis are considered the difference is negligible. However, for larger plant sizes (110 MW), the methanation production costs for biological methanation are nearly 2.5 times that of thermochemical methanation. Thus, it can be concluded that when only the methanation based SNG production costs are considered, biological methanation is more attractive for smaller plants sizes. However, for all cases considered the costs for hydrogen production are still the most significant contributor to the overall SNG production costs.

In future, the hydrogen storage needs to be taken into account, too. However, the required storage capacity depends on the flexibility of the methanation process which is under investigation.

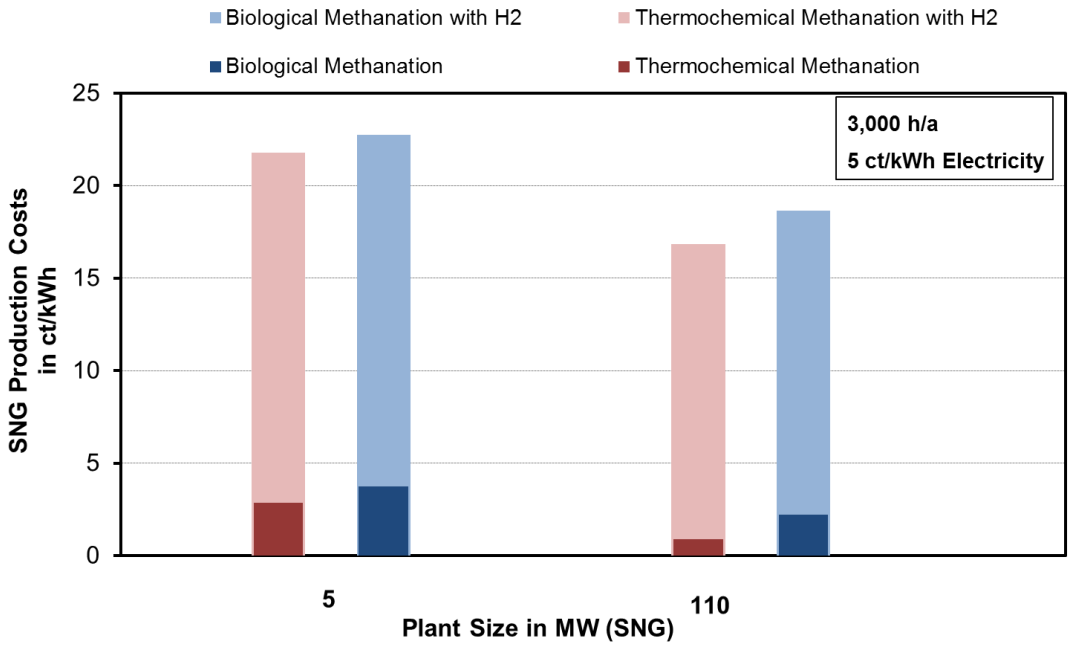

Figure 7: Comparison of specific investment cost for methanation based on capacity and type of methanation (H_2 storage not considered)

5 Conclusion

Both biological and thermochemical methanation processes have potential for integration into the Power-to-Gas process chain. Biological methanation is ideal for its simple process design and tolerance of gas impurities. However, the slower reaction times, higher power requirements, and lack of options for utilization of the waste heat stream are disadvantages leading to a lower process efficiency than for thermochemical methanation. However, biological methanation is an attractive option for small plants and impure gas feeds. On the other hand, thermochemical methanation is attractive for its high reaction rates. Moreover, the high temperature level of thermochemical methanation results in more options for process integration, which yields more efficient processes. Biological methanation is currently being tested at the pilot and demonstration scale, results from these processes are necessary in order to gain more practical experience for further development.

6 Symbols and Abbreviations

Symbols		
Symbol	Unit	Name
F_V	m^3/h	Volume flow at STP
GHSV	h^{-1}	Gas Hourly Space Velocity
$H_{i,j}$	bar	Henry coefficient of gas *i* in liquid *j*
MFR	h^{-1}	Methane formation rate ($F_{V,CH4,out} / V_R$)
η	-	Efficiency
P_{el}	kW	Electrical power
P_{SNG}	kW	Chemical power in the SNG produced
P_{th}	kW	Thermal power
p	bar	Pressure (absolute)
T	°C	Temperature
t	min	Time
V_R	m^3	Reactor volume
X_i	-	Conversion of component *i*
y_i	-	Mole fraction of *i* in gas phase
Abbreviations		
3PM		Three phase methanation
BM		Biological methanation
CSTR		Continuous stirred-tank reactor
Ely		Electrolysis
GL		Gas liquid
Meth		Methanation
PtG		Power-to-Gas
SNG		Substitute natural gas
ZSW		Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

7 Literature

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