ANNEX 1 ForskEL 2014-1-12164

Life Cycle Analysis

Work package 2 of the project includes a life cycle assessment (LCA) according to DIN EN ISO 14040 ff of the BioCat II plant and the fuel produced under certain operating scenarios. The objective of this analysis is the determination of the total environmental impact of the BioCat II technology.

FIGURE 1 shows the system boundaries of the BioCat II plant assume for the present analysis. The processes within the boundaries are included in the total emissions.

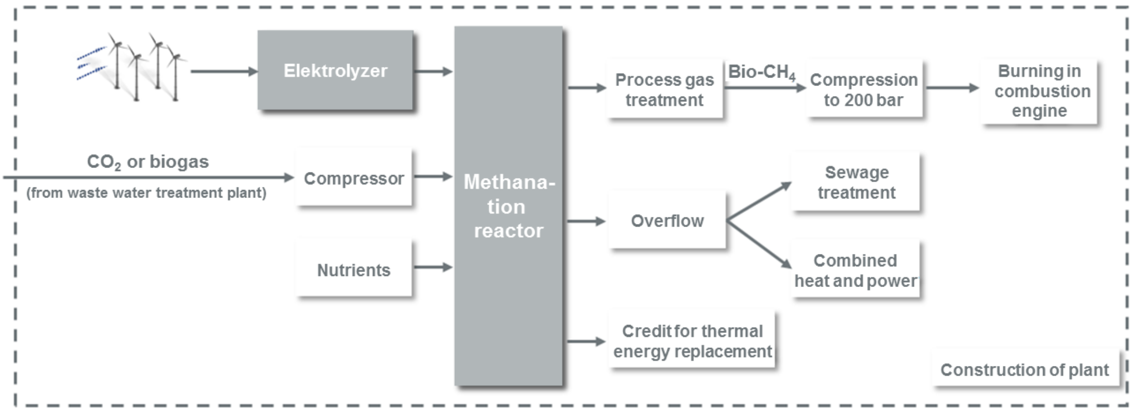


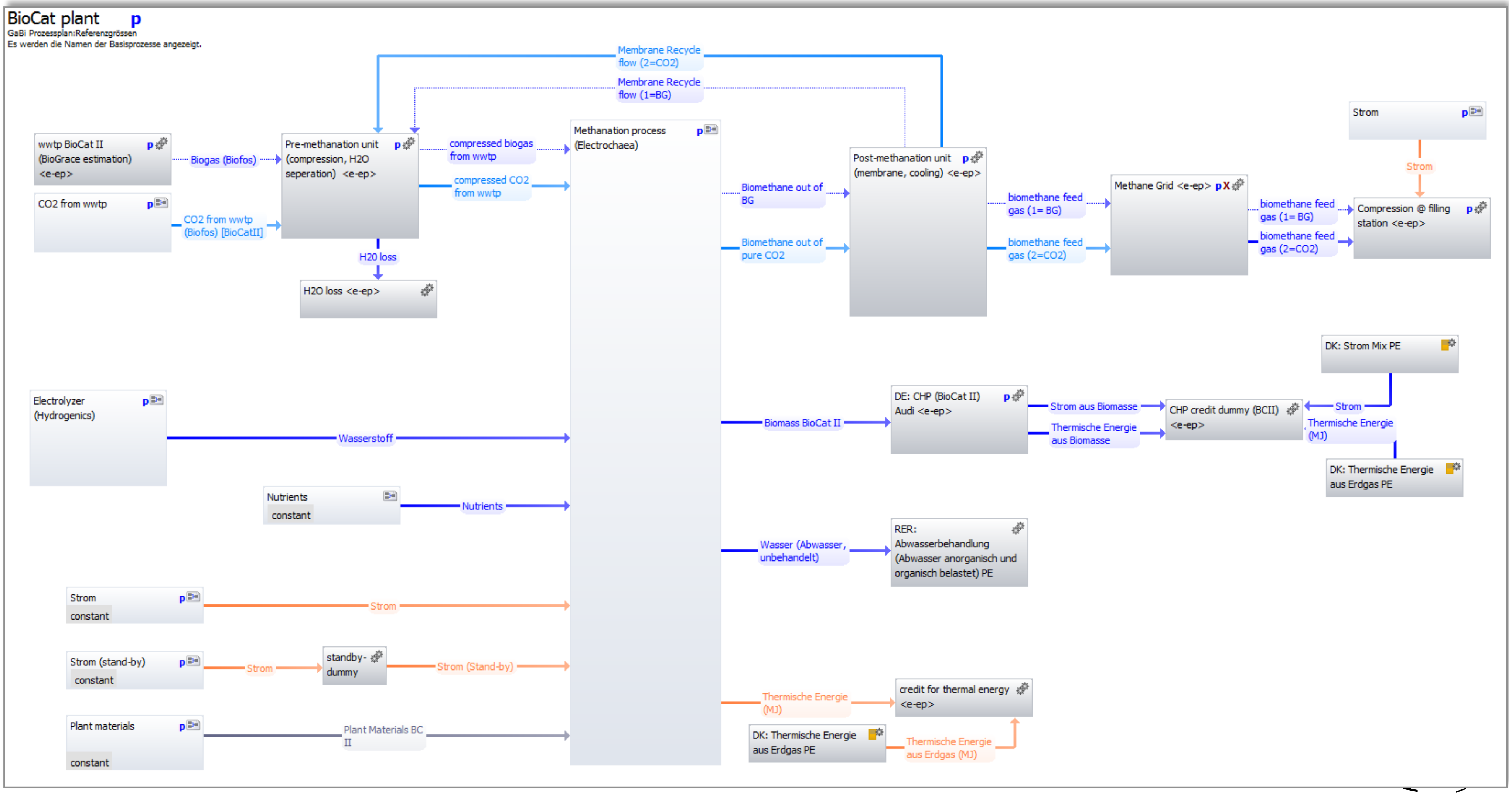
FIGURE 1: LCA system boundaries of the BioCat II plant

The reference unit (= functional unit) is chosen to be **1 kg biomethane used in a natural gas vehicle,** i.e. production, grid feeding, compression to 200 bar at filling station and the burning in the combustion engine are considered. For all these steps the energy and material flows are referenced and scaled to the unit of 1 kg biomethane to indicate their impact on the environmental effect.

The necessary data for the material and energy flows were provided by the participating project partners: Electrochaea GmbH, BIOFOS, Hydrogenics, NEAS Energy and HMN Gashandel.

Based on the project partners' data and with the help of the LCA software GaBi (database 6.1, service pack 28) from thinkstep AG a LCA model is built (FIGURE 2 shows the main GaBi model of the BioCat II plant).

During the LCA modelling phase emissions are related to each BioCat process step and are therefore basis for the later calculation of the environmental impact of the plant.


BioCat plant p
GaBi Prozessplan:Referenzgrössen
Es werden die Namen der Basisprozesse angezeigt.
wwtp BioCat II (BioGrace estimation) <e-ep>
CO2 from wwtp
Biogas (Biofos)
CO2 from wwtp (Biofos) [BioCatII]
Pre-methanation unit (compression, H2O seperation) <e-ep>
H2O loss
H2O loss <e-ep>
Membrane Recycle flow (2=CO2)
Membrane Recycle flow (1=BG)
compressed biogas from wwtp
compressed CO2 from wwtp
Methanation process (Electrochaea)
Biomethane out of BG
Biomethane out of pure CO2
Post-methanation unit (membrane, cooling) <e-ep>
biomethane feed gas (1= BG)
biomethane feed gas (2=CO2)
Methane Grid <e-ep>
biomethane feed gas (1= BG)
biomethane feed gas (2=CO2)
Strom
Strom
Compression @ filling station <e-ep>
Electrolyzer (Hydrogenics)
Wasserstoff
Nutrients constant
Nutrients
Biomass BioCat II
DE: CHP (BioCat II) Audi <e-ep>
Strom aus Biomasse
Thermische Energie aus Biomasse
CHP credit dummy (BCII) <e-ep>
DK: Strom Mix PE
Strom
Thermische Energie (MJ)
DK: Thermische Energie aus Erdgas PE
Wasser (Abwasser, unbehandelt)
RER: Abwasserbehandlung (Abwasser anorganisch und organisch belastet) PE
Strom constant
Strom
Strom (stand-by) constant
Strom
standby-dummy
Strom (Stand-by)
Plant materials constant
Plant Materials BC II
Thermische Energie (MJ)
credit for thermal energy <e-ep>
DK: Thermische Energie aus Erdgas PE
Thermische Energie aus Erdgas (MJ)

The emissions of the BioCat II plant are related to different environmental impact categories with the help of the CML methodic. The results of the categories show the respective potential environmental impact of the plant.

The relevant environmental impact categories for the VW group and hence the AUDI AG are:

- global warming potential
- acidification potential
- eutrophication potential
- ozone depletion potential
- photochemical ozone creation potential
- primary energy consumption.

On the following pages different scenarios for biomethane from the BioCat II plant are assessed and the results are discussed in more detail to identify optimization potentials.

The assessment starts with real data from the BioCat II testing operation and leads over other scenarios to the basic scenario which represents the intended long-term operation of the plant.

Based on the basic scenario a more detailed examination of the influences of the plant components and certain operating scenarios are given.

Out of the above mentioned six environmental impact categories there is a strong focus on the global warming potential (GWP). It is the only category with an overall global impact (the others only have a local impact) which makes this category very important. Because of this, all results will focus on the global warming potential. Subsequently the results for the other environmental impact categories are shown for the basic scenario.

From a LCA point of view CO_2, respectively the C-atoms bound in the biomethane (biogenic origin) do neither have a negative nor a positive impact on the results. Hence neither CO_2 emissions were released when biomethane is burned.

To better value the LCA results they are compared to the production and incineration of a fossil equivalent (natural gas) scaled to the same net calorific value of the BioCat II biomethane (49,9 MJ/kg).

The following assumptions for the BioCat II plant (BCII) are agreed with the project partners and are constant in all scenarios unless other assumptions are mentioned:

- **3000 full-load hours (flh)/ year**
- **20 years of plant lifetime**
- **240 Nm³ H_2/ h= total capacity of the electrolyzer**
- **Regular Danish grid mix is used for the electricity needed during standby hours**
- **Danish wind energy is used for the electricity needed during production hours**
- **7 Nm³ H_2/ standby hour = minimum production quantity of the electrolyzer**
- **10 kW electricity consumption during standby hours for the methanation part**
- **Further use of reactor heat in the waste water treatment plant (Therefore more biomethane from the waste water treatment plant is fed in-to the natural gas grid and a credit for replacing thermal energy from natural gas is given.)**

A more detailed overview of the data and assumptions used to build the GaBi model and assess the environmental impact are shown in the appendix.

Results of scenario 1: BioCat II plant with current data

In this scenario the measured data from the BioCat II testing operations (real in- and output data) are assessed and biogas from the waste water treatment plant (wwtp) is used for the methanation, i.e. there is no previous separation of CO_2 from biomethane in the biogas stream. FIGURE 3 shows the Global Warming Potential (GWP) of scenario 1.

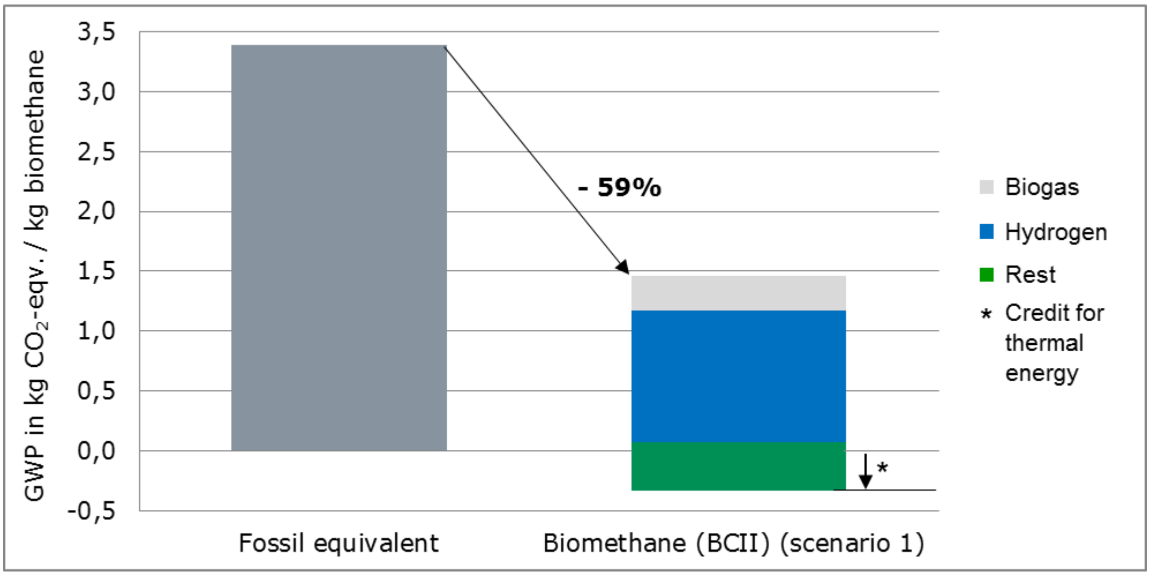


Figure 3: Global Warming Potential (GWP) scenario 1: BioCat II plant with current data

The biomethane produced on this pathway has a 59% lower GWP as the fossil equivalent. The highest impact on the GWP of the biomethane is the hydrogen production. The value of the hydrogen production is dominated by the grid electricity used during standby hours for the minimum production of 7 Nm^3/h. With a negative CO_2 burden the second largest influence has the credit for replacing thermal energy from natural gas followed by the biogas. The CO_2 burden of the biogas results from methane leakages in the waste water treatment plant. The CO_2 that is carried within the biogas does not have any impact on this burden because it has a biogenic origin.

Results of scenario 2: BioCat II plant with planning data

Since the BioCat II plant is a demonstration plant, process optimizations are still in progress. That is why scenario 2 values the BioCat II plant with planning data assumed for system improvements (FIGURE 4).

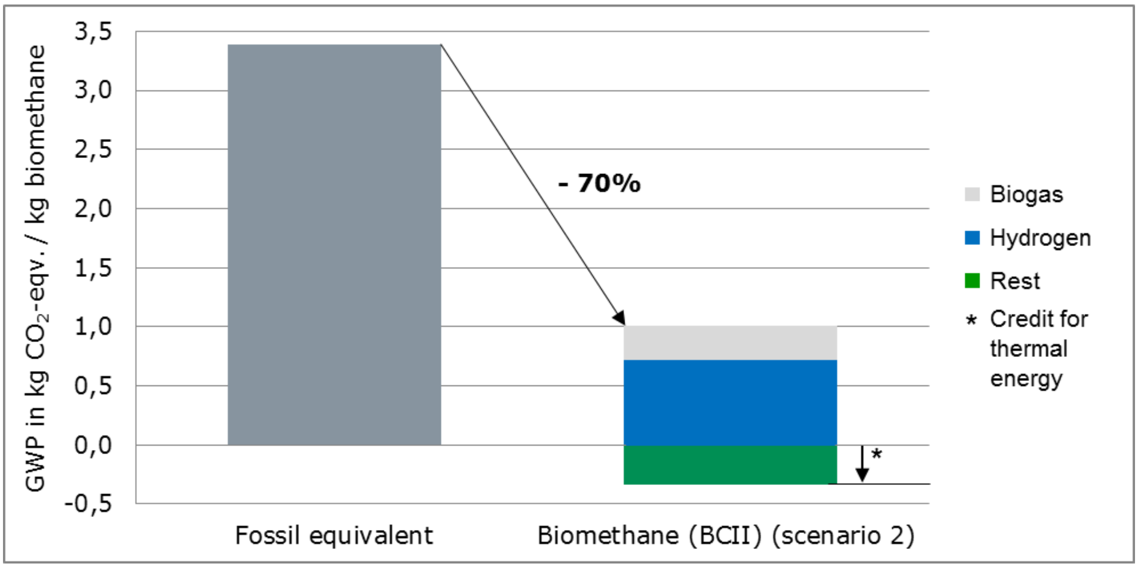


Figure 4: Global Warming Potential (GWP) scenario 2: BioCat II plant with planning data

In comparison to the fossil equivalent the biomethane in scenario 2 has a 70% lower GWP. The higher reduction potential compared to scenario 1 has several reasons.

First of all the influence of the hydrogen production is considerably reduced because the energy consumption of the electrolyzer during standby hours is split to more biomethane output. Additionally, the impact of all plant construction materials is allocated to more biomethane output. Furthermore, the decrease results from the more efficient utilization of the constant energy consumption of the BioCat II plant during full load hours (except the electrolyzer).

Results of scenario 3: BioCat II plant with planning data and pure CO_2 input with allocated burdens of separation

The carbon dioxide that reacts with hydrogen to methane does not necessarily have to be a component of biogas. It also could be pure CO_2 that is separated from the biomethane prior to use in the methanation reactor. The BioCat II plant is also designed to test the direct input of CO_2. For this case actual data are not yet available due to the absence of purified CO_2 on site. Therefore scenario 3 is based on planning data as well as scenario 2.

In the case that pure CO_2 comes from the waste water treatment plant, it carries another CO_2 burden than if biogas is used.

Biogenic CO_2 which is 'waste' and would be released into air does not carry any CO_2 burden. Under the condition that the separation process is not already done by the previous process, the biogenic CO_2 would additionally carry the allocated CO_2 burden caused by the separation process. This is shown in scenario 3 and the CO_2 burden is allocated over the CO_2-biomethane-volume ratio of the biogas. FIGURE 5 illustrates the results of this scenario.

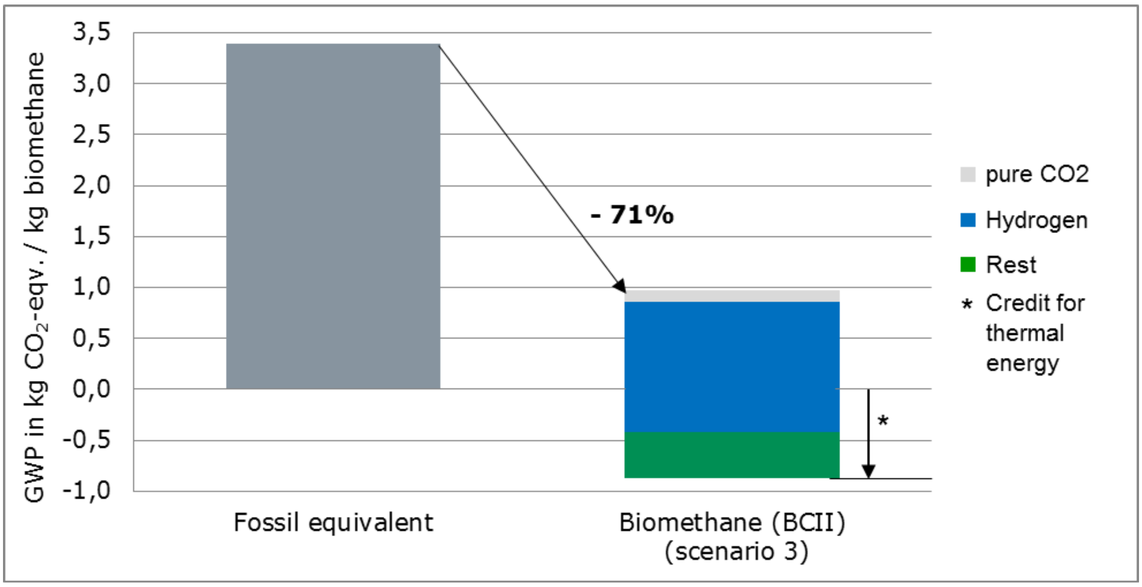


Figure 5: Global Warming Potential (GWP) scenario 3: BioCat II plant with planning data and pure CO_2 input with allocated burdens of separation

The biomethane produced on this pathway has a 71% lower GWP than the fossil equivalent.

In comparison to scenario 2 more biomethane is produced via the exothermic methanation process in the reactor. That is why this scenario has a higher credit for thermal energy.

However, it is recognizable that the CO_2 burden (without thermal energy credit) is higher than in scenario 2. This is due to the fact that in total less biomethane leaves the plant during the same time* and therefore the impact of plant materials and constant electricity consumption per hour are allocated to less output.

Additionally, more hydrogen is necessary in this scenario which has a high impact.

* In scenario 1 and 2 less biomethane is produced in the reactor but biomethane comes already with the biogas into the reactor.

Results of scenario 4: BioCat II plant with planning data and pure CO_2 input without burdens of separation

From 2017 going forward, the waste water treatment plant is going to feed biomethane in the natural gas grid. Therefore the waste water treatment plant is responsible to split the biogas in biomethane and CO_2. This CO_2 would be released into air if the BioCat II plant did not use it. Thus the waste water treatment plant has to carry the environmental burdens of the separation process and therefore the pure CO_2 do not have any CO_2 burden for the BioCat plant (see FIGURE 6).

From a long-term perspective scenario 4 is the most realistic scenario for the BioCat II plant because the waste water treatment plant already prepares the implementation of the separation process and the planning data with the input of pure CO_2 reflect the results that could be reached over time. Therefor, scenario 4 is chosen to be **the basic scenario** for the BioCat II plant. Figure 6 shows the GWP of the biomethane of the BioCat II plant with planning data for mass flows and the input of pure CO_2 without separation burdens (basic scenario).

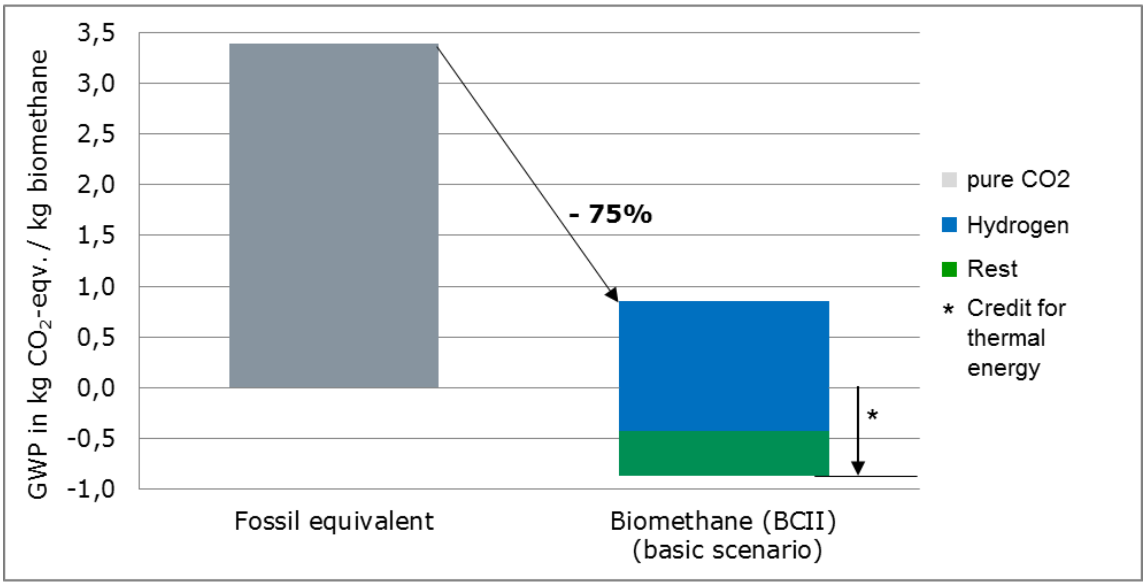


Figure 6: Global Warming Potential (GWP) of the basic scenario (scenario 4)

In comparison to the fossil equivalent the biomethane produced on this pathway has a 75% lower GWP. Without any additional burden for the separation of CO_2 this scenario has the highest reduction potential of all scenarios.

Figure 7 illustrates the major influences on the GWP of the basic scenario.

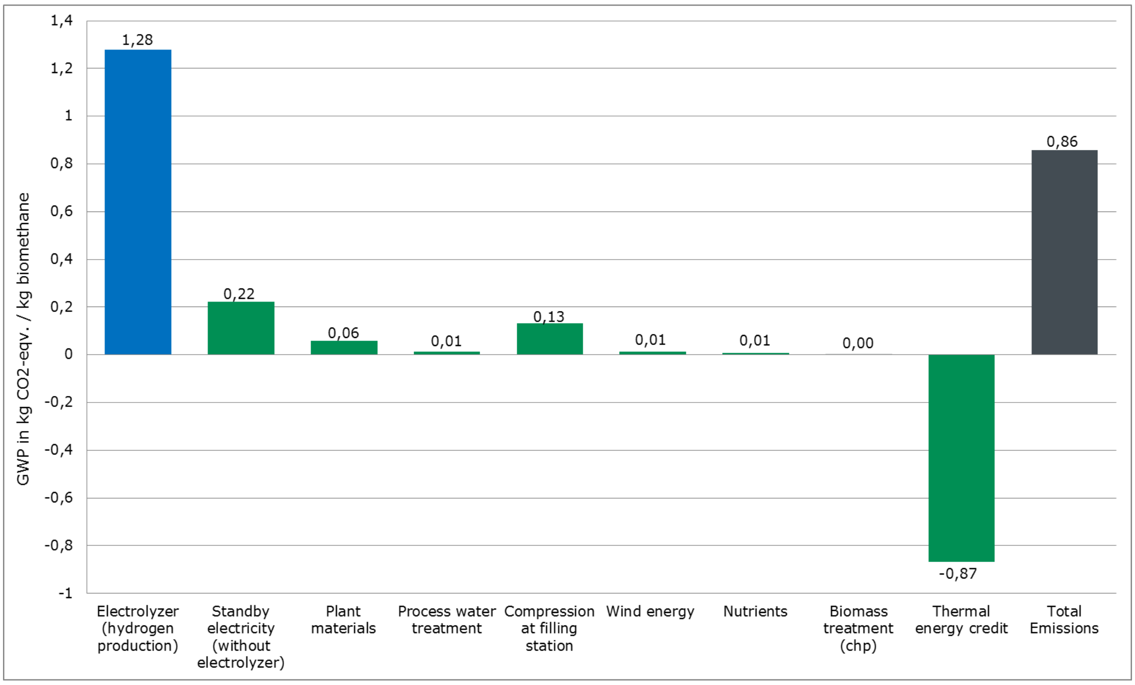


Figure 7: Major influences on the GWP of the basic scenario

The electrolyzer has the highest impact on the GWP of the biomethane. Two-thirds of this impact are produced by the standby electricity that is assumed to come from the regular Danish grid mix which in turn is still dominated by fossil energy carriers. The rest of the electrolyzer's burden results from the construction material and, with a slightly lower impact, by the amount of renewable electricity that is needed to split water into hydrogen and oxygen.

The second largest influence on the GWP of the biomethane of the basic scenario comes from the thermal energy credit. This credit is given for the replacement of thermal energy from natural gas because the surplus thermal energy of the reactor is used for heating in the waste water treatment plant and allows the plant to feed more biomethane in the natural gas grid.

The third and fourth highest impact on the GWP result from the standby electricity for the BioCat II plant (without electrolyzer) and the energy needed for the compression at the filling station. For both regular Danish grid mix is assumed.

The construction materials of the plant have a comparatively low impact on the total GWP. Their value is dominated by the steel which is supposed to be used in a high amount to build the plant.

Furthermore, only low impacts on the GWP of the basic scenario do have the treatment of the process water, the wind energy used for the overall methanation unit (i.e. without the energy needed for the electrolyzer), the nutrients for the microorganism and the treatment of the biomass leaving the methanation reactor.

To identify optimization potential a sensitivity analysis is done to see the influences of prior determined parameter.

FIGURE 8 displays the sensitivity of changing the energy source of electricity, the number of full load hours per year and the source of thermal energy that is replaced with reactor heat.

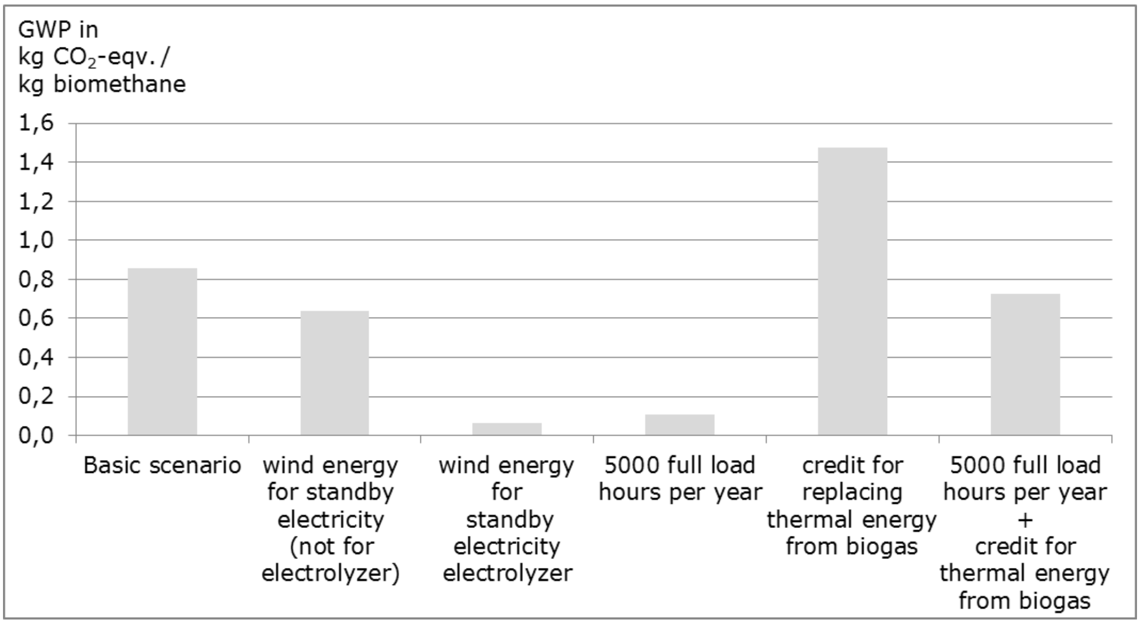


Figure 8: Results of the sensitivity analysis

The biomethane of the basic scenario could have 25% less impact on the GWP if the BioCat II plant uses wind energy instead of the regular Danish grid mix for standby energy consumption.

A significant reduction of the GWP would have the use of wind energy instead of the Danish grid electricity for the standby electricity of the electrolyzer.

With an increase of full load hours to 5000 per year the GWP of the BioCat II biomethane could be reduced by 88%.

The scenarios of this report display the case that synergies between the waste water treatment plant and the nearby located BioCat II plant are used and a credit for replacing thermal energy from natural gas with heat of the reactor is given.

In the case there are no synergies or there is another CO_2 source it has to be proven which kind of thermal energy could be replaced. That is why a sensitivity analysis is also done for the case that the thermal energy of the reactor replaces biogas. This case would lead to a reduction of 56% in comparison to the fossil equivalent, i.e. the CO_2 burden is higher than in the basic scenario.

Combining the cases of 5000 full load hours per year and the thermal energy credit for replacing biogas results in 15% less CO_2 burden compared to the basic scenario.

To finalize the LCA, the results for the other considered environmental impact categories are summarized in FIGURE 9.

Environmental Impact Category	**result per kg biomethane (BC II)**
Acidification Potential [kg SO2-eq.]	5,00E-03
Eutrophication Potential [kg Phosphate-eq.]	3,86E-04
Ozone Depletion Potential [kg R11-eq.]	4,30E-09
Photochemical Ozone Creation Potential [kg Ethene-eq.]	3,45E-04
Primary energy consumption [MJ]	289,6

Figure 9: Results of the LCA for 1 kg biomethane out of the BioCat II plant for the basic scenario

Conclusion

The results of the life cycle assessment of the BioCat II plant indicate that regardless of the CO_2 input source, the plant and the BioCat II technology have a good reduction potential in comparison to the fossil equivalent.

The basic scenario (scenario 4) which is the long-term perspective of the BioCat II plant in Avedøre has the lowest environmental impact with a Global Warming Reduction Potential of 75% compared to the fossil equivalent.

The GWP emissions of the scenarios are dominated by process steps where regular Danish grid mix is used, i.e. the standby electricity of the electrolyzer, the standby electricity of the rest of the plant and the compression of the biomethane at the filling station to 200 bar. Additionally, the thermal energy credit for replacing thermal energy from natural gas has a high impact.

A further lowering of the environmental burdens is possible by using wind power also for the standby energy consumption and/or by increasing the amount of full load hours per year.

To conclude, from an environmental perspective the BioCat II plant is a very good concept to provide renewable methane with significant lower environmental impact as fossil methane.

Appendix

General assumptions

8760 h/ a
3000 full load hours / a
5760 standby hours / a

Mass flows (data from Electrochaea)

Flow number Flow name	100 biogas or pure CO2 from wwtp	130 compressed gas to reactor	900 H2 input to reactor	150 Biomethane at reactor exit	sewage	biomass	530 Membrane recycling loop	510 Biomethane feeding
Input & Output flows:								
Scenario 1: biogas from wwtp								
REAL (Nm³/ flh)	60,1	77,8	84,0	77,5	34	0,265	18,7	57,0
REAL (kg/ flh)	70,9	79,34	7,6	51,3			9,14	40,72
Scenario 2: biogas from wwtp								
PLAN data (Nm³/flh)	85	110	125,7	112,8	49,5	0,386	27,2	83
Scenario 3: pure CO2 from wwtp								
PLAN data	51,6	80,5	200,7	83	80	0,624	30,2	50,9

Further data respectively assumptions

Electrochaea		source
energy consumption	**10** kW during standby mode	Liam Bansen, Electochaea
	60 kW during full load hour	Liam Bansen, Electochaea
Nutrients	**0,0833** kg Ammonia/ full load hour	Manuel Hörl, Electrochaea
	Specific nutrients in the GaBi database of Audi not available therefore ammonia is good approach.	Manuel Hörl (Electrochaea) and Juliane Seipt (AUDI AG)
Sewage	Sewage is organic and anorganic contaminated.	
Biomass	**7,8** g biomass/l sewage	Manuel Hörl, Electrochaea
	17,7 MJ/ kg biomass	Manuel Hörl, Electrochaea
	$CH_{1.68}O_{0.39}N_{0.24}$ molar composition	Manuel Hörl, Electrochaea
	send to heat and power plant	Doris Hafenbradl (Electrochaea) and Juliane Seipt (AUDI AG)
	replacing danish grid mix and thermal energy from natural gas	
thermal energy output	**90,3** kW during full load hour for scenario 2	Jose Blazquez, Electrochaea
	62,0 kW during full load hour for scenario 1	Juliane Seipt (AUDI AG), scaling
	145,2 kW during full load hour for scenario 3	Jose Blazquez, Electrochaea
Biofos		
separation of CO2 in wwtp	**0,433** kWh heat/ Nm³ biogas	Peter Jørgensen, Biofos
	0,1 kWh electricity/ Nm³ biogas	Peter Jørgensen, Biofos
	Necessary energy allocated over volume to biomethane (from waste water treatment plant) and CO2	Laurent Lardon (Electrochaea) and Juliane Seipt (AUDI AG)
CO2 burdens of biogas	**9,11** g CO2-eq. /MJ biogas	Juliane Seipt, AUDI AG: Approach with BioGraceTool 1 recognised by EU Commission.

Hydrogenics	**50**	% efficiency of the Reverse Osmosis system, i.e. half of the input water is used as demineralised water for the H2 generation.	Dimitri van Dingenen, Hydrogenics
	7	Nm³ H2/h minimum production	Dimitri van Dingenen, Hydrogenics
	5,23	kWh /Nm³ H2 generation	Dimitri van Dingenen, Hydrogenics
energy consumption	**36,6**	kW during standby hour	Dimitri van Dingenen, Hydrogenics
	divers	kW during full load hours appropriate to the needed H2 amount	Dimitri van Dingenen, Hydrogenics
filling station			
compression to 200 bar	**0,314**	kWh/ kg methane	Juliane Seipt (AUDI AG)
vehicle			
combustion emissions	**0**	kg CO2-eq./ kg biomethane	Juliane Seipt (AUDI AG)
	2,799	kg CO2-eq./ kg fossil methane	Juliane Seipt (AUDI AG)
production emissions	**0,592**	kg CO2-eq./ kg fossil methane	Juliane Seipt (AUDI AG)
	49,9	MJ/kg = LHV for BioCatII biomethane also for fossil methane (scaled)	
Plant Materials	**20**	years of lifetime	Due to the assumed 20 lifetime of the electrolyser.
Electrochaea	**diverse**		Jose Blazquez (Electrochaea), email 09.08.2016
Hydrogenics	**diverse**		Dimitri van Dingenen (Hydrogenics), email 20.07.2016