Climate impacts & cost of Biogas-based H_2 production coupled with carbon capture and storage (CCS)

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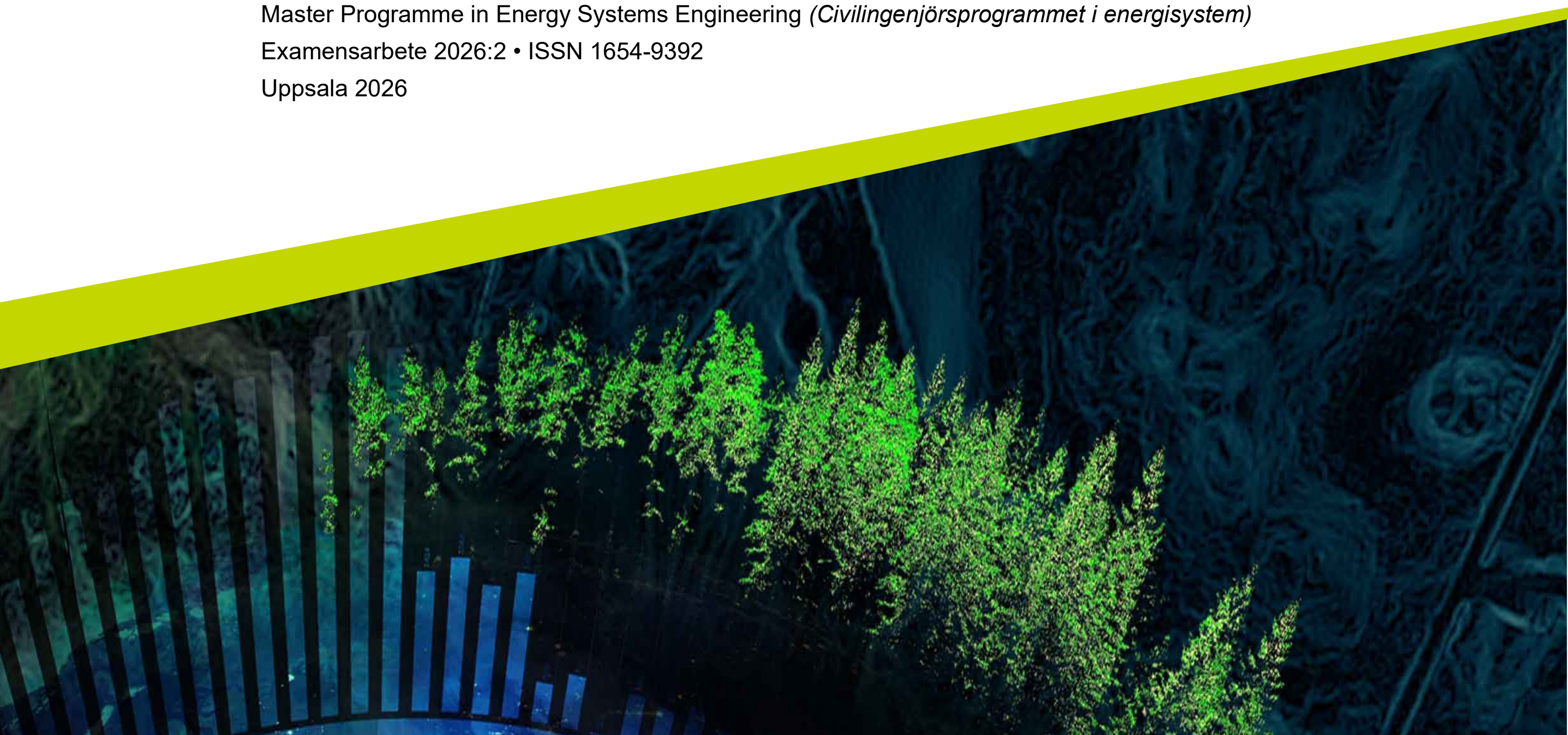

Climate impacts & cost of Biogas-based H_2 production coupled with carbon capture and storage (CCS)

Klimatpåverkan & kostnad för biogasbaserad H_2 produktion med koldioxidavskiljning och lagring

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Abstract

To reach the climate goal set under the Paris Agreement in 2015, which aims to limit the global temperature increase to no more than 2 degrees, a reduction in emissions is required. In Uppsala, biogas is currently produced at Uppsala Vatten's biogas plant at Kungsgården. The purpose of this study is to examine the climate impact and economic cost of instead producing hydrogen at the plant. To achieve this, a production step is added to the biogas plant to convert methane gas into hydrogen. This way, the carbon is taken out and can be stored in bedrock, creating a carbon sink. The study investigated three methods to achieve this: steam methane reforming, pyrolysis, and dark fermentation. These methods were evaluated through a life cycle analysis of their climate impact and economic cost per kilogram of produced hydrogen. The results showed emissions for steam methane reforming at -2.4 $kgCO_2/kgH_2$, pyrolysis at -8.9$kgCO_2/kgH_2$, and dark fermentation at 6.5$kgCO_2/kgH_2$. The leveled cost was between 4-8 €/kg for steam methane reforming, 4-12 €/kg for pyrolysis, and -3-(-0.25) €/kg for dark fermentation. Since steam methane reforming resulted in a balance with negative emissions, significant hydrogen production, and the lowest leveled cost, this method was considered the most suitable for implementation in Uppsala's biogas plant.

Populärvetenskaplig sammanfattning

För att nå klimatmålet som ställdes under parisavtalet 2015 att globala temperaturen inte ska öka med mer än 2 grader krävs en minskning av utsläpp. I Uppsala produceras idag biogas i Uppsala Vattens biogasanläggning vid Kungsängens gård. Syftet med den här studien är att undersöka klimatpåverkan samt ekonomisk kostnad för att lägga istället producera vätgas vid biogasverket. För att uppnå detta läggs ett produktionssteg till vid biogasverket så den producerade metangasen konverteras till vätgas. På så sätt kan kolen istället förvaras i berggrund och ge en kolsänka. I studien undersöktes tre metoder för att uppnå detta, ångmetanreform, pyrolys samt mörk fermentering. Dessa metoder bedömdes genom en livscykelanalys på sin klimatpåverkan samt ekonomiska kostnad per kilo producerad vätgas. Resultaten visade utsläpp för ångmetanreform på -2.4 $kgCO_2/kgH_2$, pyrolys -8.9 $kgCO_2/kgH_2$ och mörk fermentation 6.5 $kgCO_2/kgH_2$. Den utjämnade kostnaden var mellan 4-8 €/kg för SMR, 4-12 €/kg med pyrolys och -3-(-0.25) €/kg för mörk fermentation. Eftersom ångmetanreform gav en balans med negativa utsläpp, stor production av vätgas samt med den lägsta utjämnade kostnaden bedömdes motoden som mest lämplig för tillämpning i Uppsalas biogasverk.

Executive summary

The purpose of this study was to estimate greenhouse gas emissions and economic cost of three hydrogen production methods coupled with carbon capture and storage in Uppsala. The production methods chosen were steam methane reform and methane pyrolysis using biogas as and dark fermentation. A life cycle assessment was performed with the functional unit of 1 kgH_2. Results showed that emissions for steam methane reform were -2.4 $kgCO_2/kgH_2$, pyrolysis was -8.9 $kgCO_2/kgH_2$ and dark fermentation 6.5 $kgCO_2/kgH_2$. Levelized cost of hydrogen produced with ranged between 4-8 €/kg for SMR, 4-12 €/kg with pyrolysis and -3-(-0.25) €/kg for dark fermentation. Results show that SMR and pyrolysis yield negative emissions and since SMR yields higher production of hydrogen with lower cost than pyrolysis, this method is judged to be the most suitable for hydrogen production in Uppsala.

Abreviations

GHG	Greenhouse gas
CCUS	Carbon capture utilization and storage
CCS	Carbon capture and storage
SMR	Steam methane reform
NET	Negative emissions technology
LCA	Life cycle analysis
GWP	Global warming potential
WGS	Water gas shift
PSA	Pressure swing adsorbtion
LHV	Lower heating value
LCOH	Levelized cost of hydrogen
WACC	Weighted average cost of capital
kWh	Kilo Watt hour
O&M	Operation and maintenance
$\mathbf{CO_{2aci}}$	Carbon dioxide abatement cost
Ph	Annually produced hydrogen
$\mathbf{C_p}$	Investment cost production plant
$\mathbf{C_e}$	Cost of annual energy
$\mathbf{GHG_{ref}}$	Emissions from reference hydrogen production
$\mathbf{COH_{ref}}$	Cost of reference hydrogen

Glossary

H_2	Hydrogen	
CO_2	Carbon dioxide	
O_2	Oxygen	
CH_4	Methane	
N_2O	Nitrous Oxide	
ΔH_r^0	Enthalpy	KJ/mol
ρ	Density	$[kg/m^3]$
mw	Molar weight	$[g/mol]$
m	Mass	$[kg]$
n	Amount of substance	

Contents

1 Introduction

Due to climate change caused by greenhouse gas (GHG) emissions, a transition from fossil to renewable energy sources is necessary. The 2015 Paris agreement set a climate target at no more than a 2-degree Celsius temperature increase from pre-industrial levels (*The Paris Agreement* 2022). Hydrogen has potential to be a renewable fuel source in the future energy system because of its' high energy density and abundance. Today the main hydrogen production method is based on SMR using fossil natural gas (Simpson & Lutz 2007). Low-carbon hydrogen has yet to be commercialized due to high production cost and lack of hydrogen infrastructure (Luberti & Ahn 2022*a*). With upcoming policies and incentives to decarbonize hard- to-abate sectors, the economic situation for bio-hydrogen could change. For bio-hydrogen to be commercialized, it must be cost effective while also being environmentally friendly. A study of different methods for producing low-carbon hydrogen and analysis of their respective environmental impact and cost is therefore necessary.

The biogas plant in Uppsala is based on anaerobic digestion of organic waste products producing biogas and biofertilizer. The produced biogas is used as an energy source for the buses in Uppsala. (*Uppsala Vattens Biogasanläggning* 2021). This biogas could instead be used to produce biohydrogen.

A life cycle assessment is used to asses the environmental impacts of a product or process. The method considers the entire cycle from raw material extraction, production to the end-of-life (Jens et al. 2016). For this study a life cycle assesment is used to consider CO_2 emissions of biohydrogen production.

This study will examine the life cycle GHG emissions and economic cost of three bio-based methods. These are methane pyrolysis, steam methane reforming (SMR) and dark fermentation. Carbon capture use and storage (CCS) combined with production of bio-based hydrogen can remove carbon from the atmosphere and/or reduce the use of fossil fuels. The GHG emissions and economic costs of each bio-hydrogen production method with CCS will be used to calculate levelized hydrogen cost as well as CO_2 abatement costs. The abatement cost is based on the difference in emissions and cost between produced bio-hydrogen and traditionally produced fossil hydrogen. Levelized cost of bio-hydrogen will be compared to the reference fossil hydrogen.

Goals & purpose

The goal of this study is to calculate the GHG emissions and economic costs of three hydrogen production system with CCS to examine if they are competitive as negative emission technology (NETs).

The following objectives are defined to reach this goal:

1. Perform a literature review on three hydrogen production methods: SMR, Methane Pyrolysis, and Dark Fermentation.
2. Identify and quantify GHG emissions along the life cycle of each H_2 production method.
3. To estimate levelized H_2 cost with CCS as well as CO_2 abatement cost compared to reference production.
4. Analyze the competitiveness of bio-hydrogen coupled with CCS as a negative emission technology (NET).

Research questions

- What are the GHG emissions and economic costs of producing bio-based H_2 via SMR, pyrolysis and dark fermentation in Uppsala?
- What is the competitiveness of the bio-based H_2 production methods as NET?

2 Background

In this section, necessary information to understand the rest of the thesis are presented. The different production methods of biohydrogen compared in this study are described as well as the current dominant technology for fossil hydrogen production. The current production path of upgraded biogas at Uppsala Vatten Biogas Plant in Uppsala is described and a brief description of emissions from electricity is included. In addition to this the mechanisms of CCS technology used by Carbfix are explained. Finally, the LCA methodology is described including climate impact metrics for different greenhouse gas emissions.

2.1 Steam methane reforming (SMR)

To produce hydrogen from methane the method Steam methane reform can be used. The name SMR will be used to describe a method containing three steps, including SMR, water gas shift (WGS) and pressure swing adsorption (PSA). The first step in this process is the reaction between steam and methane, shown in equation 1. This reaction requires high temperatures and a catalyst, typically nickel-based (Simpson & Lutz 2007).

$$CH_4(g) + H_2O(g) \longrightarrow CO(s) + 3H_2(g) \qquad \Delta H_r^0 = +251KJ/mol \tag{1}$$

Equation 1 shows the ideal SMR reaction. In practice there might be some CH_4, H_2O and CO_2 in the resulting gas products (Simpson & Lutz 2007). The positive enthalpy indicates an endothermic reaction, meaning energy is consumed by the chemical reaction.

The next step is the WGS. In this step CO and H_2O is converted to H_2 and CO_2 according to equation 2. The reaction is exothermic and can therefore help reduce the total amount of energy required for the system (Simpson & Lutz 2007).

$$CO(g) + H_2O(g) \longrightarrow CO_2(g) + H_2(g) \qquad \Delta H_r^0 = -41.2KJ/mol \tag{2}$$

Finally, PSA separates CO_2 and H_2 gas, allowing for production of pure CO_2 and H_2. PSA operates by pressurizing gas within a tank also containing an adsorbent material that one of the gases is adsorbed in. This increases the concentration of the gas not adsorbed by the solid substance and allows for separation of gases (Luberti & Ahn 2022*b*).

2.2 Methane pyrolysis

Methane pyrolysis is the thermal decomposition of methane into hydrogen and solid carbon as shown in equation 3. The byproduct is solid carbon, no carbon dioxide is produced (Sánchez-Bastardo et al. 2021). The reaction is endothermic and requires temperatures of around 1273 - 1773 degrees Kelvin for high conversion rates. The solid carbon produced has industrial applications and could be sold for profit (Bhaskar et al. 2021).

$$CH_4(g) \longrightarrow C(s) + 2H_2(g) \qquad \Delta H_r^0 = +76KJ/mol \tag{3}$$

Equation 3 shows the reaction enthalpy of the pyrolysis reaction. Energy to power this reaction needs to be added in the form of heat.

The energy required for pyrolysis shown as ΔH_r^0 in equation 3 is significantly lower than the energy ΔH_r^0 required for SMR shown in equation 1. This means that in theory hydrogen could be produced using less energy.

2.2.1 Plasma reactor

In this thesis, pyrolysis biohydrogen will be produced using a plasma reactor. The plasma reactor operates by the chemical reaction shown in equation 3. The byproduct is solid carbon or in other words carbon black, which is easier to store and transport than CO_2 while also having a market value (Kerscher et al. 2021).

The plasma process for hydrogen production can be divided into two categories, thermal plasma, and non-thermal plasma. In the thermal process plasma is generated through extreme heat created by an electric arc powered electricity. This process is very power intensive with temperatures exceeding 4 727 degrees Celsius. Since the temperatures are high, thermal losses are large for this process. Due to this, the process is mainly focused on the production of carbon black (Kerscher et al. 2021).

The non-thermal process is associated with lower temperatures and smaller losses. In this process the operation temperature is 900 degrees Celsius. Plasma sources are either microwaves, a dielectric barrier discharge, a gliding arc, or an electron beam. An illustration of the electron beam process is shown in figure 1. Among these plasma sources, the electron beam has shown the highest yield of hydrogen and carbon and also the lowest energy consumption (Kerscher et al. 2021).

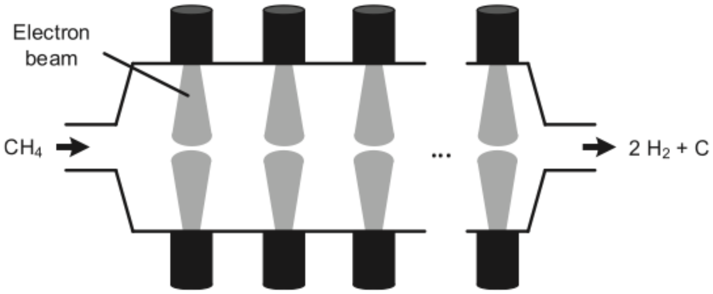

Figure 1: Electron beam methane pyrolysis reactor (Kerscher et al. 2021)

2.3 Dark fermentation

In dark fermentation, an organic substrate is metabolized by anaerobic microbes in the dark generating H_2 as a byproduct (Lukajtis et al. 2018). Different microbe species play different, important roles for hydrogen production and the dynamics in their communities can lead to fluctuating hydrogen production (Dahiya et al. 2021).

The substrate plays a crucial role for the system efficiency of dark fermentation. A simple organic compound such as monosaccharides and disaccharides are the most beneficial while longer sugar-chains such as starch and cellulose requires pre-treatment. Starch can be hydrolyzed into simpler carbohydrates while cellulose is resistant to chemical and biological processing significantly raising system costs (Lukajtis et al. 2018).

In the ideal case giving the theoretical maximum value of hydrogen production from glucose we get the following reaction shown in equation 4 according to Lukajtis et al. (2018):

$$C_6H_{12}O_6 + 6H_2O \longrightarrow 6CO_2 + 12H_2 \qquad \Delta H_r^0 = -1919.98KJ/mol \tag{4}$$

According to equation 4, 1 mole of substrate glucose provides 12 moles of H_2 and 6 moles of CO_2. Real systems in general yield lower efficiencies due to unwanted byproducts and suboptimal substrate. Commonly 1 - 1.5 moles of hydrogen per mole glucose (Lukajtis et al. 2018).

2.4 Carbon credit market

In the 2015 Paris Agreement, almost 200 countries set a goal of limiting global warming to no more than 2 degrees Celsius warmer than preindustrial levels. Additionally, an ideal goal of no more than 1.5-degrees Celsius warmer. To reach the 1.5-degree Celsius target, global GHG emissions have to be reduced by 50 % by 2030 from 2021 levels and net zero by 2050 (Blaufelder et al. 2021).

For some companies reducing emissions is expensive and difficult. To achieve the 1.5-degree Celsius goal negative emissions are required to compensate instead. A Carbon credit represents 1 tonne of carbon dioxide kept out of the atmosphere or removed from it. Companies can buy these carbon credits on the market to mitigate for their own emissions (Blaufelder et al. 2021).

2.5 Carbon capture and storage

Carbon capture and storage (CCS) is a technology aimed at mitigating the release of CO_2 into the atmosphere. It is a multi-step process. Capturing CO_2 from various sources, for example from an industrial process. Separating the CO_2 from other substances, transporting it to an appropriate storage site and finally monitoring the site to ensure no leakages occur (Snaebjörnsdóttir et al. 2020).

Separating CO_2 from other gases can be achieved using PSA. The method is based on an sorbent absorbing gaseous CO_2 removing it from other gases. The other gases can then be vented before the pressure is dropped and CO_2 is released (Kwon et al. 2011). This is an energy intensive process powered by electric compressors (Simpson & Lutz 2007).

For permanent storage of CO_2 two options are currently being explored for subsurface application. These are injecting captured CO_2 into sedimentary basins where it is trapped physically below impermeable cap rock. This is necessary since CO_2 is buoyant and would otherwise migrate back to the surface as shown in figure 2 method b. Another method is injecting CO_2 dissolved in water into basaltic rocks as shown in figure 2 method a. The CO_2 then mineralises into carbonate minerals and is permanently fixed (Snaebjörnsdóttir et al. 2020). This second method is being developed by Carbfix and creates artificial carbon sinks (Ratouis et al. 2022).

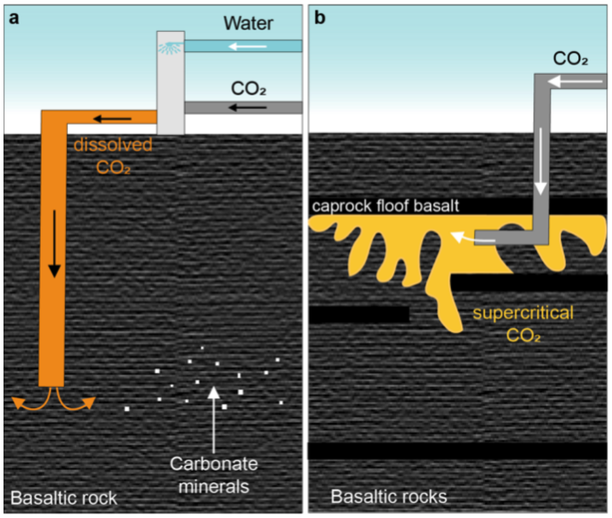

Figure 2: CCS CO_2 storage methods (Snaebjörnsdóttir et al. 2020)

2.6 Life cycle assessment

A method for assessing environmental impacts of a product or process is life cycle assessment (LCA). LCA can consider the entire life cycle of a process or product from raw material extraction, production, use phase to end-of-life (Jens et al. 2016). A functional unit is defined for an LCA so that different systems can be easily compared.

Common greenhouse gases emitted are CO_2, CH_4 and N_2O. These can come from fossil or biogenic sources. In the fossil case the compounds come from outside the current carbon cycle and have a higher global warming potential (GWP) than biogenic GHG that is already in the carbon cycle (IEA-Bioenergy 2020).

Global warming potential over a period of 100 years for different sources of emissions, are used to measure climate impact. These values are given in table 1 (EPA 2023).

Table 1: GWP_{100} for greenhouse gases (EPA 2023).

Greenhouse gas	**GWP_{100}**
Fossil CO_2	1
Fossil CH_4	30
N_2O	265
Biogenic CO_2	0
Biogenic CH_4	28

3 System description

In this section the current biogas production system is described. Following this the three separate systems for producing biohydrogen are described as well as reference hydrogen production and CCS.

3.1 Uppsala Biogas plant

The Biogas plant in Uppsala collects organic waste from the municipally and converts it into biomethane and bio fertilizer (*Uppsala Vattens Biogasanläggning* 2021). The facility received 43 000 tonnes of organic waste in 2019 (*Uppsala Vattens Biogasanläggning* 2021) but has clearance to treat up to 50 000 tonnes on an annual basis (*Miljörapport 2018 Biogasanläggningen vid Kungsängens gård* 2018). Figure 3 shows the pathway of organic waste through the plant and is followed by a brief technical description of the mechanisms involved.

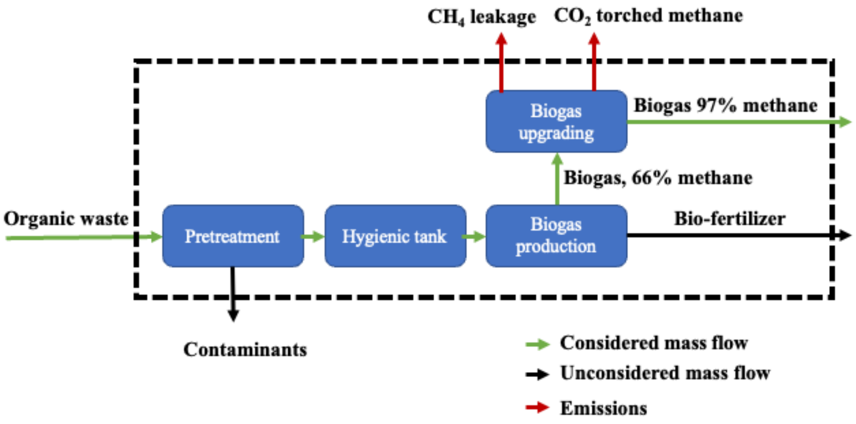

Figure 3: System description Uppsala Biogas plant

At the biogas plant, organic waste is separated into two different categories upon arrival. These two categories have separate pre-treatment before being added into the hygienic tank. The first category is organic waste from households and businesses. The second is organic waste from industry and slaughterhouses (*Uppsala Vattens Biogasanläggning* 2021).

In the first pre-treatment step for household waste, metal, plastic and other contaminates are removed for separate processing. Then the substrate goes through a grinder and a strainer making the consistency more fluid. From here the household waste is combined with organic waste from industry and slaughterhouses and heated to 70 degrees in the hygienic tank. This process kills off contaminating microorganisms. Heat for this process is recycled from existing material and put back into substrate entering the tank using a heat pump. Any additional heat required is provided from a pellet boiler (*Uppsala Vattens Biogasanläggning* 2021).

Following the hygienic tank, the anaerobic digestion process can begin. It is in this step that the biogas is produced. The biogas facility contains three anaerobic digestion tanks with a combined volume of 8 600 cubic meters. The substrate is continuously feed through these tanks spending 30 days in an anaerobic environment at 52 degrees Celsius. Here biogas and biofertilizer is produced. From this stage the biogas consists of two thirds methane and one third carbon dioxide (*Uppsala Vattens Biogasanläggning* 2021).

To be used as vehicle fuel, the biogas is upgraded so that it contains 97% methane. This is done by pushing the gas through a tube of water. The carbon dioxide then dissolves in the water and is washed away. From this process some methane can leak with the water. To reduce the amount of methane entering the atmosphere it is flared. Despite this about 1.4% of the methane leaks away. Finally, the upgraded biogas containing 97% methane is pressurized to 250 bars and delivered to filling stations for biogas vehicles. The remaining substrate can be used as bio-fertilizer for agricultural purposes (*Uppsala Vattens Biogasanläggning* 2021).

3.2 Steam methane reforming

The system boundaries, shown in figure 4, show what processes and sources of emissions and costs are included. Emissions from the biogas plant are included and will also be calculated based on data from current energy and material demand. Methane leakage from biogas upgrading is also part of the existing biogas plant and is included as a source of GHG emissions.

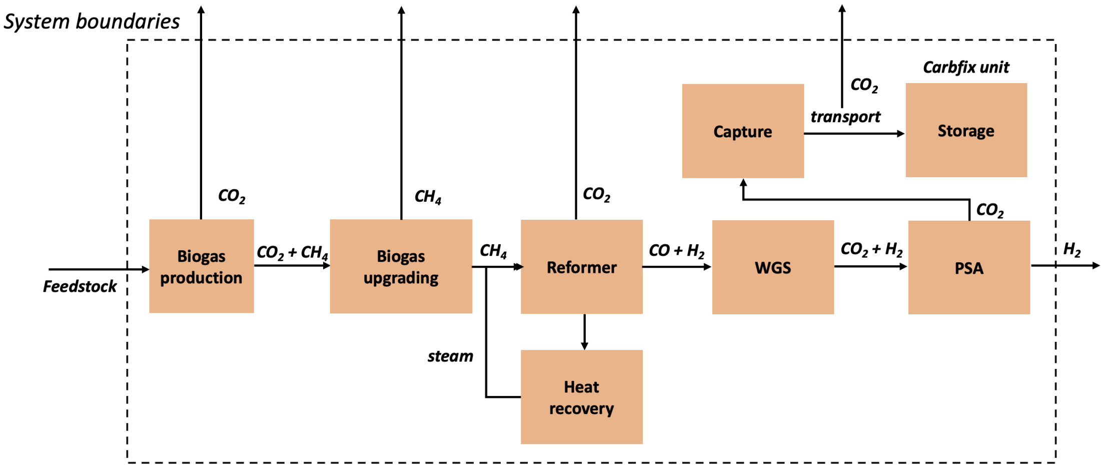

Figure 4: System description SMR biohydrogen

SMR takes place in the reformer, turning water and methane into carbon monoxide and hydrogen. Heat is provided by biogas incineration. No heat loss is considered meaning the heat recovery is assumed to be 100%. Carbon dioxide from heat production is not captured. Next is the WGS, an exothermic reaction where carbon monoxide and water form carbon dioxide and hydrogen. Since this process does not require energy, no additional sources of emission are introduced. Finally, carbon dioxide and hydrogen are separated using PSA. This is an energy intensive process powered by electric compressors (Simpson & Lutz 2007). Because of additional electricity use, this step is a source of added emissions.

Captured carbon dioxide is pressurized and transported on trucks to the closest site with suitable geology for carbon storage. Two additional sources of emissions are then introduced, electricity for pressurizing gas and fossil diesel to power the trucks.

Final use of the produced hydrogen is placed outside of the system boundaries. Combustion of hydrogen does not produce any carbon dioxide and is not considered in the GHG emissions analysis.

3.3 Pyrolysis

The methane pyrolysis system considered in this thesis is shown in figure 5. Like the SMR hydrogen system, emissions from the current biogas plant are considered. The produced methane is then processed in a plasma reactor. The plasma reactor, powered by electricity from the Swedish green electricity mix thermally decomposes methane in the absence of oxygen forming solid carbon and hydrogen. The pyrolysis reactor introduces GHG emissions from using electric power.

In pyrolysis most of the mass entering the system is converted to solid carbon. The produced carbon is transported and sold to the industrial sector. In this thesis, carbon black is assumed to be sold to tire production factories in Gothenburg. This adds a source of fossil emissions from transportation and an income from the sold carbon black.

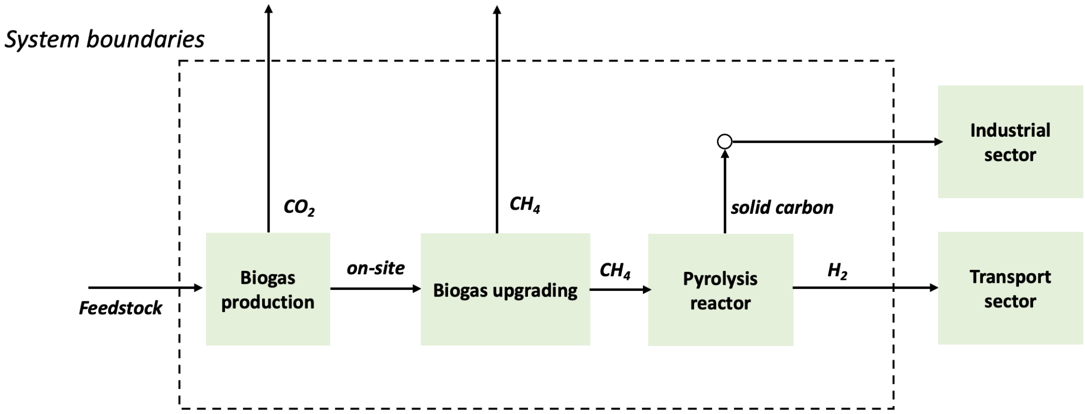

Figure 5: System description Pyrolysis biohydrogen

For the carbon black produced, a market value of 300 - 700 €/tonne is assumed based on Timmerberg et al. (2020). The market size for carbon black is also assumed to be large enough to be unaffected by the additional production introduced to the market.

3.4 Dark fermentation

In the case of dark fermentation, the current biogas plant is not a part of the system but replaced by an acidogenic and a methanogenic reactor as shown in figure 6. These two reactors replace the rot process in the existing biogas plant. This system outputs methane, hydrogen, and carbon dioxide. The CO_2 from the acidogenic reactor is captured for storage and methane goes to the transport sector.

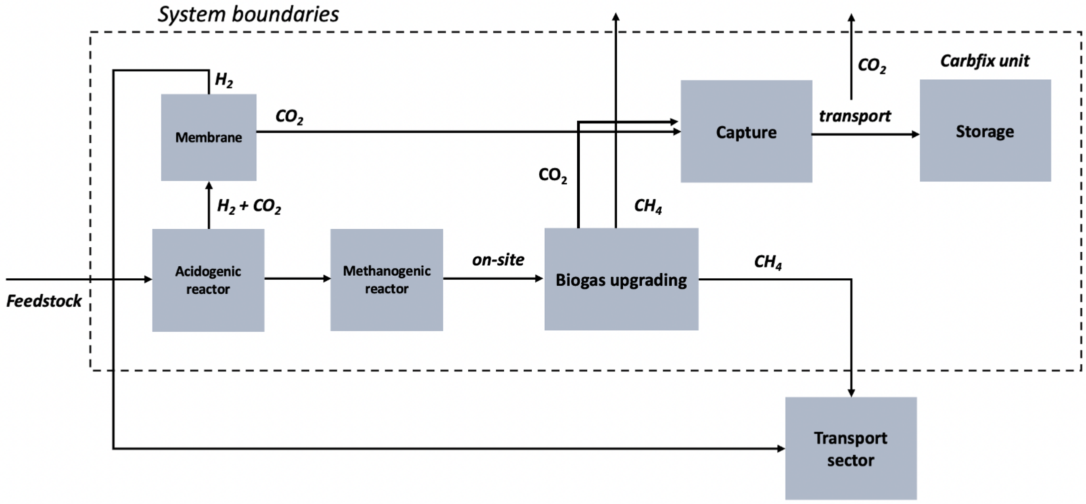

Figure 6: System description Dark fermentation hydrogen

The process has several steps producing different products, see figure 6. In the acidogenic reactor a mix of gaseous H_2 and CO_2 is produced and separated from the substrate. This gas is then separated by a membrane resulting in production of pure H_2 and CO_2 that can be captured and stored. The remaining substrate generates biogas consisting of CH_4 and CO_2. These gases are then also separated and used for fuel and stored respectively. Some CH_4 leakage occurs during biogas upgrading as illustraded in figure 6. Electricity use in the acidiogenic reactor is set at $0,0128kW/m^3$.

Since production efficiency varies with the composition of the substrate it is also necessary to investigate what efficiency can be expected in Uppsala with the substrate currently in use at the biogas plant. A substrate with a mix of household organic waste and slaughter house waste yields between 25 - 85 cm^3H_2 per gram substrate (Lukajtis et al. 2018).

3.5 Carbon Capture and Storage

The CCS method used by Carbfix relies on two mechanisms for trapping CO_2. Firstly, the dissolution of gaseous CO_2 into water before injection. This provides an intermediate storage through solubility trapping. As the solution is pumped into basaltic host rock. The host rock then releases two positive ions and so binds CO_2 forming a solid mineral. Through these steps permanent storage is achieved with a mineralization degree of > 70-95 %. (Ratouis et al. 2022).

The closest suitable rock formations to Uppsala are found in Bäsingen, according to the mineral storage atlas at Carbfixs' website. This site is located 104 km from Uppsala.

3.6 Reference hydrogen production

To evaluate the economics and emissions of produced bio-hydrogen, a reference production method is used. The dominant method for hydrogen production is SMR using natural gas as feedstock. Using this method, the cost of hydrogen production in Europe is 1.6 euro/kgH_2 in 2018, and the associated CO_2 emission is 10 kg CO_2/kgH_2 (Birol 2019). Since 2018, the price of natural gas has increased by a factor of four (*EU natural GAS* 2022). With this price increase, production of fossil hydrogen using SMR will also increase.

4 Method

In this section, calculations for economical costs and GHG emissions are described and presented. in the first step, mass and energy balances were calculated. Secondly different emissions sources are categorized and shown in production chain overviews. Emissions and costs per kilogram of produced hydrogen are calculated based on current specific production at the biogas plant in Uppsala and the mass balances. Finally, a sensitivity analysis was carried out.

4.1 Assumptions and limitations

- Biogas production for dimensioning is equal to reference year 2019.
- A green energy mix with emissions of 4 gCO_2/kWh is used.
- Captured carbon storage site is at Bäsingen, 104 km from Uppsala.
- Black carbon is sold to Gothenburg 464 km from Uppsala.
- Black carbon produced from pyrolysis is not combusted.
- The plant is assumed to operate for 24 h each day.
- Calculations assume no heat loss.
- Weighted average cost of capital (WACC) is assumed to be 5 % annually.

4.2 Life cycle assessment

The LCA will have the functional unit 1 kg of produced H_2. System boundaries are defined at the beginning of the project and dictate what data is gathered in the literature review. To have correct structure in the LCA and to ensure the results are credible, the ISO 14040 and ISO 14044 international standards were followed, including four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation.

4.3 Life Cycle Inventory

In this section, the climate impact for the different production paths of hydrogen are assessed. The emissions are evaluated according to their GWP_{100} emission values. Emissions from biogenic and fossil sources have different global warming potential and are therefore weighted differently according to table 1 (EPA 2023).

4.3.1 Uppsala Vatten Biogas plant

Current material flows at Uppsala Biogas plant are presented in table 2. Materials used as well as in what quantity is presented in *Miljörapport 2018 Biogasanläggningen vid Kungsängens gård* (2018). Data for GWP_{100} were found in the database ecoinvent.

The presented values for mass are given on an annual basis and are used in the production of 3 800 100 kg of biogas. Factored with GWP_{100} emission values from ecoinvent, annual emissions from each material was calculated. To obtain emissions per kg of produced biogas, the sum of the total emissions was divided by annual production.

Table 2: Emission in current biogas production in Uppsala

Material	**Mass or Energy**	**GWP_{100} [$kgCO_2$-eq/kg(kwh)]**	**Total emissions [$kgCO_2$]**
Electricity	1 522 000 [kWh]	0.004	6 088
Pellets	2 989 000 [kWh]	0.0053	15 777
Ironcloride	133 000 [kg]	0.48543	64 562
Diesel	2 624.8 [kg]	0.53703	1 410
Glycol	88.8 [kg]	2.9126	259
Asepto	45 [kg]	1.495985	67
Hydraulic Oil	3 975.7 [kg]	0.925	3 678
Biogas	**3 800 100 [kg]**	**0.0242**	**91 840**

From table 2 and calculated values for total emissions for biogas, the results showed that every kilogram of biogas has a carbon footprint of 24.2 gCO_2-eq/$kgCH_4$.

4.3.2 Electricity mix emissions

In this study electricity is assumed to be sourced from a fossil free energy mix. Because of the green profile of the hydrogen production facilities a choice of green energy seems likely. In an LCA perspective of the fossil free energy mix in Sweden, the GHG emissions are 4 gCO_2eq/kWh (*Ursprungsmärkning och Miljöpåverkan på vår el* 2021). Emissions from electricity production varies a lot depending on the production source, in the residual mix, emissions are as high as 365.27 gCO_2eq/kWh (*Nu Finns information om residualmix för* 2020).

4.3.3 Transportation emissions

Transport emissions are considered for the captured CO_2. The calculations of emissions produced are based on truck emission/km and total kilometers driven. A round trip from Uppsala to selected storage site is 208 km and the load capacity per truck is 60 tonnes. CO_2 emissions for truck is 730gCO_2eq/km Trafikverket (2023).

4.3.4 Compression of produced gas

Produced H_2, CO_2 and CH_4 is assumed to be pressurized after production. CO_2 is assumed to be pressurized to 15 bar and CH_4 to 200 bars. The pressurization of gas consumes electric power in the form of a compressor. This process requires 0.185 $kWh/kgCO_2$ and 0.34 $kWh/kgCH_4$ (Janke et al. 2022). Hydrogen is assumed to be pressurized to 500 bar since the range for storage in vehicles is 350 - 700 bars (IEA 2023). The energy required to compress hydrogen to 700 bars from 1 bar is between 4.31kWh/kgH_2 and 6.46kWh/kgH_2 (Knop 2016). For calculations in this study, 5kWh/kgH_2 is used.

4.3.5 Material flows and mass balance

In this section the method for calculating production for each system producing biohydrogen is presented.

Basis for calculations

Calculations of the mass flows were based on 1 kg of methane entering the SMR and pyrolysis production pathways. This was done to estimate the quantity of hydrogen that would be possible to produce in Uppsala using the different methods. Current production of 3 800 100 kg biogas results in 3 206 900 kg of methane after losses to torching and heating. In the case of dark fermentation, the calculations were based on retaining current flow of organic waste.

Steam Methane Reform

Putting the reaction formulas shown in equation 1 and 2 together, we get a total reaction for the SMR process shown in equation 5. The reaction formula shows the molar balance between the input material, methane and water, and the output, hydrogen, and carbon dioxide.

$$CH_4(g) + 2H_2O \longrightarrow CO_2 + 4H_2 \tag{5}$$

Using 1 kg of methane as a reference, the mass flow is calculated using the reaction formula shown in equation 5 and equations 6 - 10.

$$m(CH_4) = 1\,kg \tag{6}$$

$$n(CH_4) = \frac{m(CH_4)}{mw(CH_4)} \tag{7}$$

$$m(CO) = n(CH_4) * mw(CO) \tag{8}$$

$$m(CO_2) = n(CH_4) * mw(CO_2) \tag{9}$$

$$m(H_2) = 4 * n(CH_4) * mw(H_2) = 0.5037\,kgH_2/kgCH_4 \tag{10}$$

Additional methane is used to provide heat for the reaction shown in equation 1. The reaction consumes 0.251 MJ/mol CH_4 and the energy content of methane is 50 MJ/kg (*World Nuclear Association* 2022). To produce 0.5037 kg of hydrogen according to equation 10, an additional amount of 0,3130 kg of methane is consumed. This reduces the hydrogen yield to 0,3836 $kgH_2/kgCH_4$.

Pyrolysis

The method used for SMR is also used here. The complete reaction formula is shown in equation 11

$$CH_4 \longrightarrow C + 2H_2 \tag{11}$$

Using 1kg of methane as a reference, the mass balance of the system was calculated using equations 12 - 14

$$n(CH_4) = m(CH_4)/mw(CH_4) \tag{12}$$

$$m(C) = n(CH_4) * mw(C) = 0,748\, kgC/kgCH_4 \tag{13}$$

$$m(H_2) = 2 * n(CH_4) * mw(H_2) = 0,252\, kgH_2/kgCH_4 \tag{14}$$

Dark fermentation

Production yield with current substrate amount received daily at the biogas plant in Uppsala was calculated according to table 3. Data for calculations presented in the table was sourced from Yeshanew et al. (2018).

Table 3: Dark Fermentation mass calculations

120	ton/day	Daily amount of fresh bio waste treated
33%	-	Fraction of total solids (TS)
85%	-	Fraction of volatile solids (VS)
3,3	days	HRT of dark fermentation reactor
390	m^3	CSTR volume with 33% TS
860	m^3	CSTR volume with 15% TS
260	ton/day	Total input bio waste + recirculation water
117,8	ton/day	Daily amount of VS
39	ton/day	Daily amount of TS
43	LH_2/kg VS	H_2 yield during dark fermentation
130	LH_2/kg TS	H_2 yield during dark fermentation
167	LCH_4/kg VS	CH_4 yield during dark fermentation
510	LCH_4/kg TS	CH_4 yield during dark fermentation
0,1	kg/m^3	H_2 density at STP
0,7	kg/m^3	CH_4 density at STP
11	gH_2/kg TS	H_2 yield during dark fermentation (2.02 g/mol)
11	g/gH_2	CO_2 yield during dark fermentation (44.01 g/mol)
450	kgH_2/day	Daily amount of H_2 (dark fermentation)
4,9	tonCO_2/day	Daily amount of CO_2 (dark fermentation)
14	tonCH_4/day	Daily amount of CH_4 (2nd stage)

To get annual production, daily values were multiplied by 365.

4.4 Economic analysis

The economic analysis was done to find levelized cost and CO_2 abatement cost for produced biohydrogen. Investment costs are adjusted to account for a plant lifespan of 30 years and running costs are based on the production rate of hydrogen. To make the results relevant to Uppsala, the capacity of hydrogen production for each method corresponds to utilizing all the upgraded biogas the plant currently produces to make hydrogen.

The economic model used is based on the method used by Timmerberg et al. (2020) in the report "Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas – GHG emissions and costs". The levelized cost of hydrogen (LCOH) was calculated using equation 15. In this method the investment cost of the production plant C_p, cost of energy powering the hydrogen plant C_e and the costs for maintenance C_{om} are considered. In addition to this, any additional income is added as a negative term in the numerator. The investment cost is used together with WACC to distribute investment capital cost over the lifespan of the plant.

Abatement costs for CO_2 (CO_{2aci}) in each hydrogen production processes is derived from levelized costs and GHG emission estimations ($\mathrm{GHG_i}$) compared to reference fossil hydrogen production cost ($\mathrm{COH_{ref}}$) and GHG emissions ($\mathrm{GHG_{ref}}$) according to equation 16.

$$LCOH = \frac{\frac{C_p}{\sum_{n=1}^{N} \frac{1}{(1+WACC)^n}} + C_e + C_{om}}{p_h} \tag{15}$$

$$CO_{2aci} = \frac{LCOH - COH_{ref}}{GHG_{ref} - GHG_i} \tag{16}$$

4.4.1 Investment & running cost inventory

Economic parameters for the production methods of biohydrogen are shown in table 4. Data for SMR and Pyrolysis investment cost was sourced from Timmerberg et al. (2020). Dark Fermentation investment cost was sourced from Janke et al. (2017).

Table 4: Economic parameters for the production methods.

Biohydrogen production method	**SMR**	**Pyrolysis**	**Dark fermentation**
Investment cost [€/(kgH$_2$/h)]	24 850	27 750	16 566
Electricity consumption [kWh/kgH$_2$]	0.32	5.07	0.58
Annual O&M cost [% of investment]	5	5	5
Byproduct income [€/kgH$_2$]	na	2.08	46.91
WACC [%]	5	5	5
Investment lifetime [years]	30	30	30

To transport CO_2 the gas needs to be pressurized. This process adds an additional cost of 13-25 $/ton (Baylin-Stern & Berghout 2021). The overall cost of the gas mixture capture, transport and storage is 24.8 $/ton. This number consists of capture at 21.3 $/ton, transport of 1.5 km is 1.3 $/ton, injection of CO_2 into the ground is 1.3 $/ton and finally monitoring costs 0.9 $/ton (Gunnarsson et al. 2018).

Since transport distance in this case is further than the 1,5 km used by Gunnarsson et al. (2018), the transportation costs were calculated separately. The cost of truck transport differs depending on the type of load. In this case the loads considered are either pressurized gas or solid carbon respectively. The cost of transport for pressurized gas is 0.127 €/km*ton and for solid carbon it's 0.366 €/km*ton (Meulen et al. 2020).

4.5 Sensitivity analysis

In the sensitivity analysis the uncertain values are varied to examine their impact on the overall results.

The varied values are carbon capture ratio, price of carbon black and the fraction of methane leakage. The capture ratio is set at either 54 % or 90 % in the SMR process and the investment cost is adjusted according to Timmerberg et al. (2020). Price of sold carbon black in pyrolysis is varied between 300 - 700 €/tonne according to current market price (Timmerberg et al. 2020). Methane leakage is removed from dark fermentation in the sensitivity analysis.

5 Results

In this section results from the literature study and from calculations are displayed. The results are divided into mass balance, emissions, economics and finally sensitivity analysis.

5.1 Mass balance

First in this section, results of production calculations based on 1kg of methane are shown for each production method. Secondly the annual production is calculated based on current upgraded biogas production at Uppsala biogas plant.

5.1.1 Steam methane reform

In the SMR process, 1kg of methane, in the ideal case can with water be converted into 0.503 kg of H_2 and 2.74 kg of CO_2 according to the calculations. The mass flow of this process is shown in figure 7. To provide the necessary energy an additional amount of 0.31 kg of methane is combusted. In total 1.31 kg of methane is required to produce 0.503 kg of hydrogen. This is equivalent to 1 kg of methane yielding 0.38 kg of H_2.

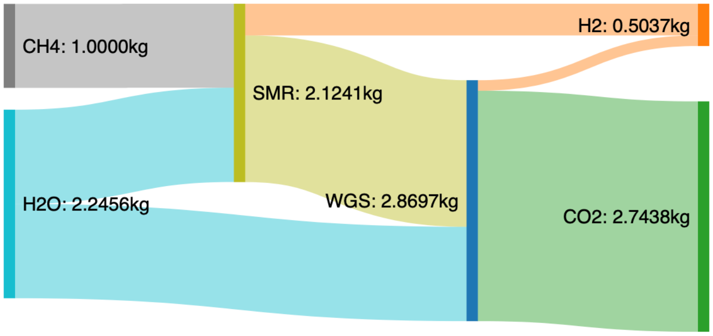

Figure 7: Mass flow for SMR bio-hydrogen

5.1.2 Pyrolysis

For methane pyrolysis, the ideal case 1 kg of methane can be converted into 0.748 kg solid carbon, and 0.251 kg of hydrogen. The mass flow of this process is shown in figure 8

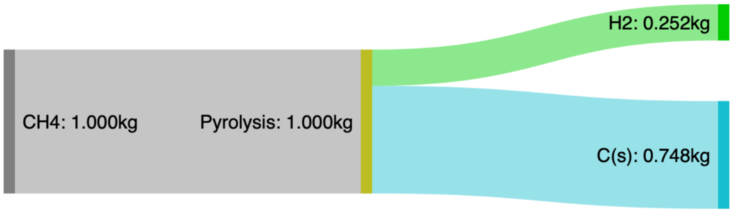

Figure 8: Mass flow for Pyrolysis bio-hydrogen

5.1.3 Dark Fermentation

In the case of Dark Fermentation, the existing anaerobic digestion process is replaced. For this reason, the mass flow shown in figure 9, displays H_2, CH_4 and CO_2 yield for 1kg of VS substrate.

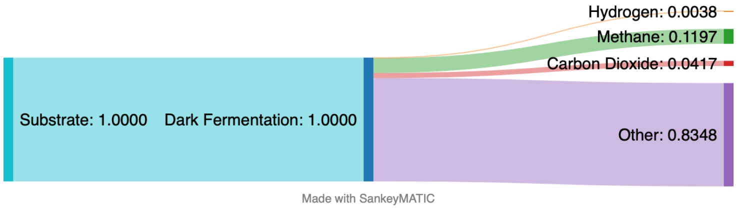

Figure 9: Mass flow for Dark Fermentation biohydrogen

5.1.4 Annual production

Combining production values from Uppsala Biogas plant and the presented mass flows, total production for each method was calculated and presented in table 5. The results show the highest hydrogen yield from SMR and the lowest for Dark Fermentation. Captured CO_2 represents emissions that have been mineralized and permanently stored.

Table 5: Annual production from existing substrate flow

Production method	H_2 [kg]	**Captured** CO_2 [kg]	C [kg]	CH_4 [kg]
SMR	1 230 300	4 513 900	0	0
Pyrolysis	808 140	0	2 398 800	0
Dark fermentation	164 615	967 760	0	5 147 960

5.2 Emissions

In this section the results from GHG emission life cycle assessment are presented for the bio-hydrogen production methods.

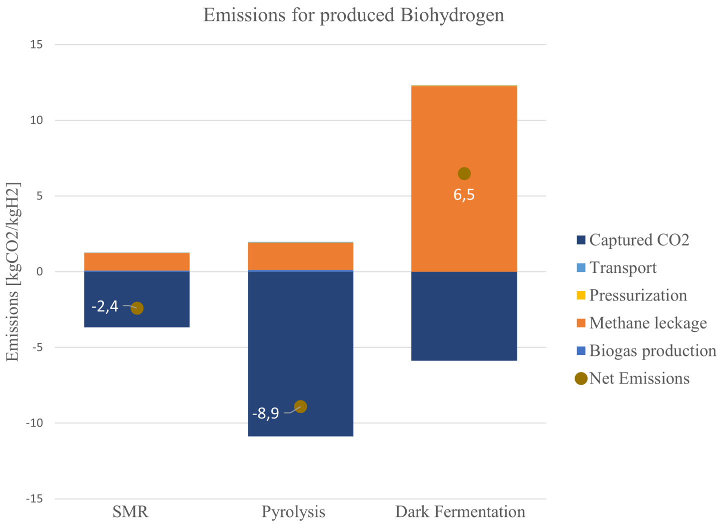

Figure 10: Emissions affecting climate change distribution

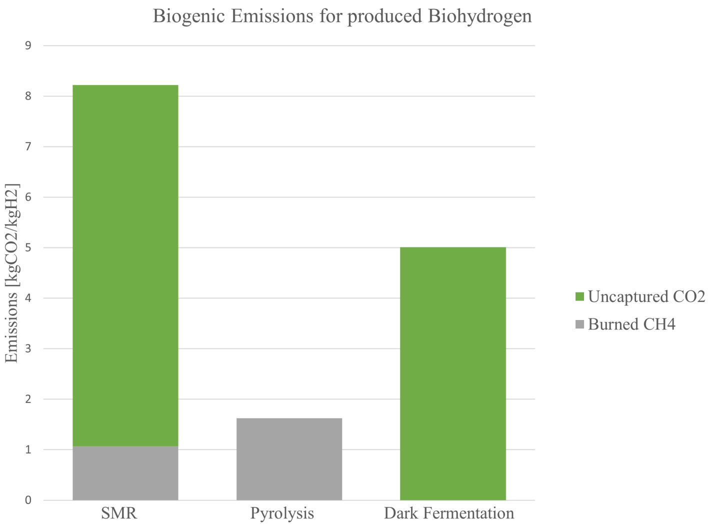

Figure 11: Biogenic CO_2 emissions with no impact on climate change

5.2.1 Steam methane reform

Detailed results for GHG emission calculation for SMR biohydrogen are presented in figure 10 and 11. In these results a capture efficiency of 54 % and a mineralization factor of 95 % were used. The main portion of GHG emissions is biogenic and has no negative effect on climate change. These emissions are shown in figure and 11. Included here is CH_4 that has been flared, used for heating, or burned to power the SMR-reaction. Also included is CO_2 leakage in the mineralization stage. These emissions are from carbon absorbed from the atmosphere by the substrate and therefore does not introduce additional CO_2 into the atmosphere like fossil emissions do. The large portion of emissions affecting the climate comes from methane leckage.

5.2.2 Pyrolysis

Detailed results for GHG emission calculations for methane pyrolysis are presented in figure 10 and 11. For pyrolysis, the main portion of emissions are from biogas upgrading and flared CH_4. Negative emissions is stored in the form of carbon black. Since this carbon is not mineralized, long term storage and therefor emissions are more uncertain.

5.2.3 Dark Fermentation

Detailed results for GHG emission calcualtions for Dark Fermentation hydrogen are presented in figure 10 and 11. The largest portion of emissions are from methane leakage in the biogas upgrading.

5.2.4 Annual and specific emissions

In table 6 calculated annual hydrogen production, GHG emissions and specific emissions per kg of hydrogen is presented. Pyrolysis captures the most CO_2 per kg of H_2, however SMR captures more in total due to higher general production. Dark fermentation does not achieve net negative emissions.

Table 6: Annual hydrogen productions and total emissions for the biohydrogen production methods.

	SMR	**Pyrolysis**	**Dark Fermentation**
Annual production [tonnes]	1 230,3	808,14	164,62
Emissions [tonnes/year]	-3 194,5	-7 204	1 061,9
Specific emissions [kgCO2/kgH2]	-2,40	-8,91	6,45

5.3 Economics

In this section results from the economic calculations are presented and compared to the dominant production method of fossil hydrogen.

5.3.1 Levelized costs

The levelized cost for producing biohydrogen with SMR, pyrolysis and dark fermentation respectively is shown in figure 12. It is shown that Dark fermentation has a negative cost meaning there is a profit in the production chain before the biohydrogen has been sold.

Another result is that SMR is a cheaper production method of biohydrogen than pyrolysis while the price of carbon credits is 440 € or lower. At higher prices of carbon credits pyrolysis is less expensive due to lower emissions shown in section 5.2.

Where the levelized cost of biohydrogen crosses the line for the price of reference hydrogen shows the break even point for the different production methods. For SMR this happens at 350 €, for pyrolysis 400 € and dark fermentation is cheaper at all times in the results.

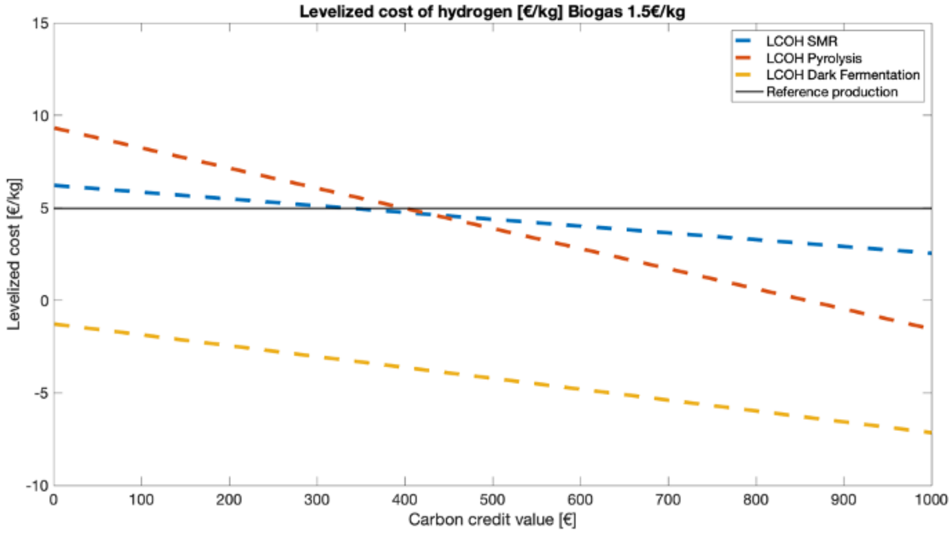

Figure 12: Levelized cost Biohydrogen

The levelized cost was also calculated at three different market values for biogas, shown in figure 13. Each production method is assigned a color and the three lines correspond to a different cost of biogas.

From the graph, sensitivity to cost of biogas can be deduced. The closer the lines are together, the less dependency on biogas cost for that production method. From this it is shown that pyrolysis is most dependant on biogas cost, then SMR and dark fermentation has the lowest.

Another result is that for both SMR and dark fermentation, a higher cost of biogas corresponds to a higher levelized cost, the opposite is the case for pyrolysis.

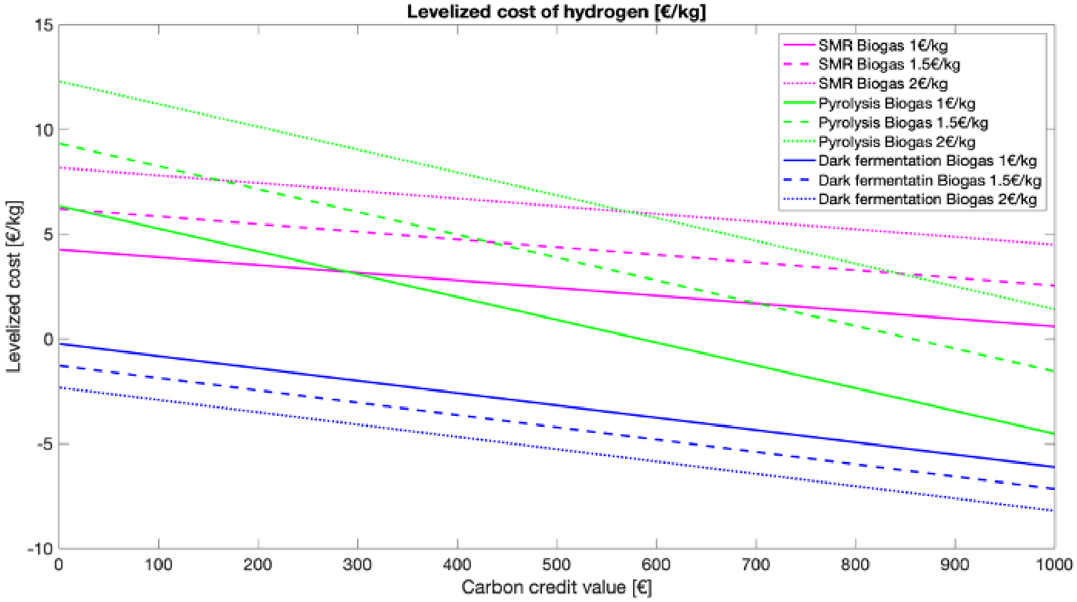

Figure 13: LCOH of Biohydrogen with varied biogas value

5.3.2 CO_2 abatement cost

Figure 14 shows the abatement cost per tonne of CO_2 as a function of the carbon credit value. Negative abatement costs indicate that the production of bio-hydrogen is cheaper than the fossil reference. A lower abatement cost is therefore more beneficial.

From the results in figure 14 we can see again that hydrogen produced using SMR and pyrolysis is profitable when the value of carbon credits exceed 350 € and 400 € respectively.

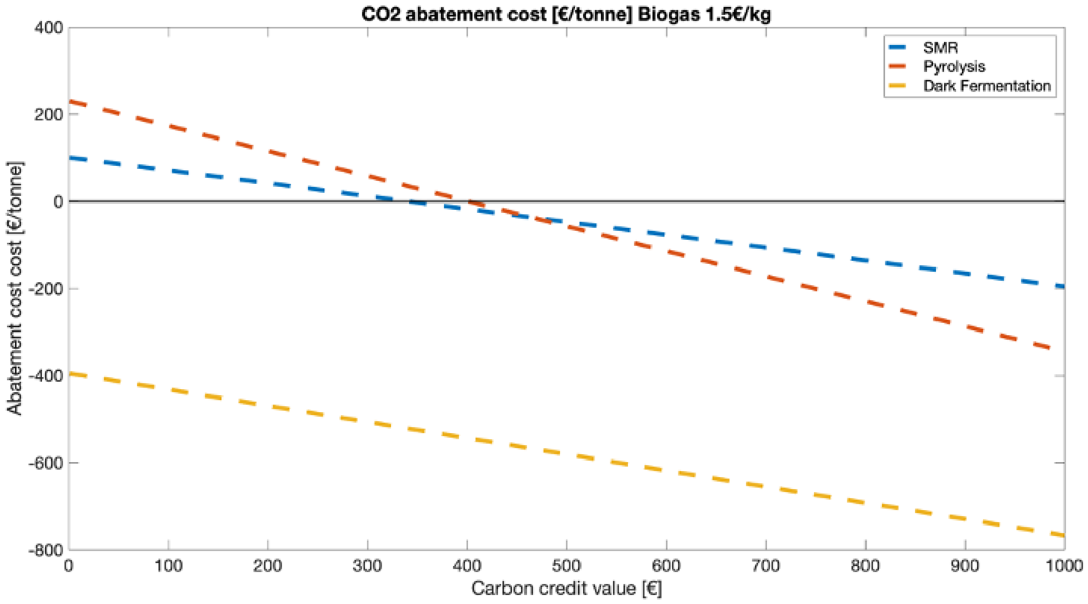

Figure 14: CO_2 abatment cost for Biohydrogen

In figure 15 the same result is shown as in figure 14 but with varied cost of biogas. The results show that the point where pyrolysis becomes less expensive than SMR is only dependant on the value of carbon credits and not the value of biogas.

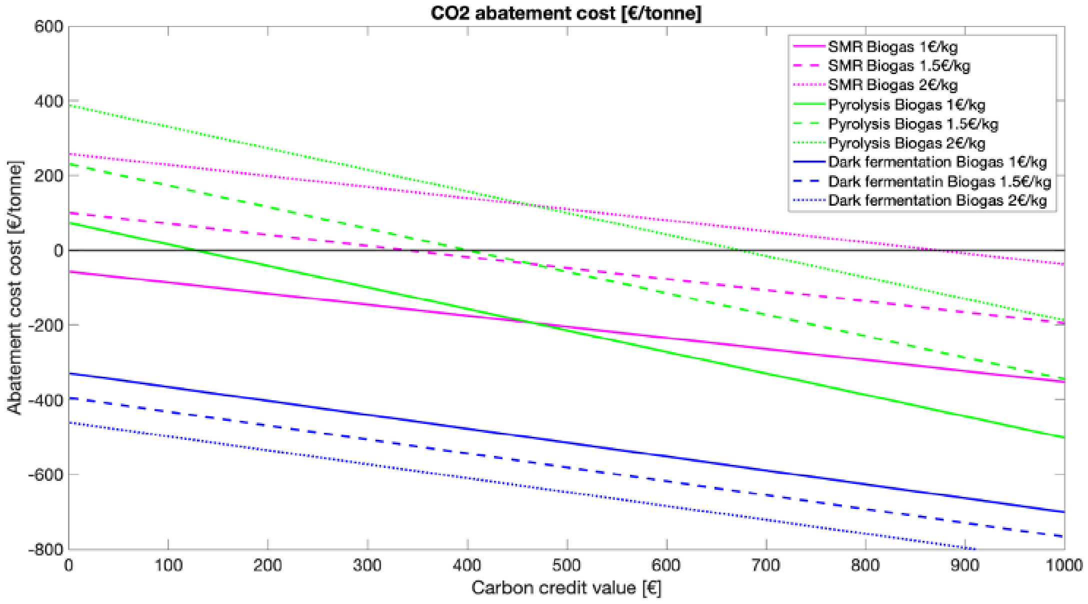

Figure 15: CO_2 abatment cost for Biohydrogen with different prices of Biogas and Carbon Credit

5.3.3 Cost distribution

The results of the cost distribution for producing hydrogen using SMR is shown in figure 16. The cost of biogas is shown to be the dominant factor for SMR biohydrogen production.

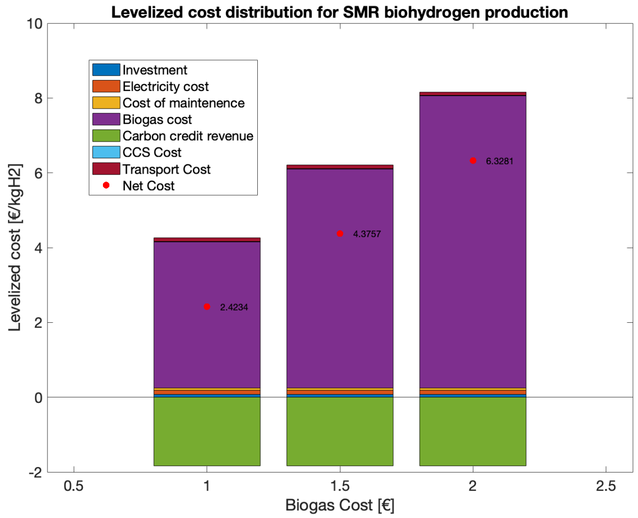

Figure 16: LCOH distribution of SMR Biohydrogen

For pyrolysis the cost of biogas is also the dominating factor. However, as shown in figure 17, revenue from carbon black and transport costs are also significant.

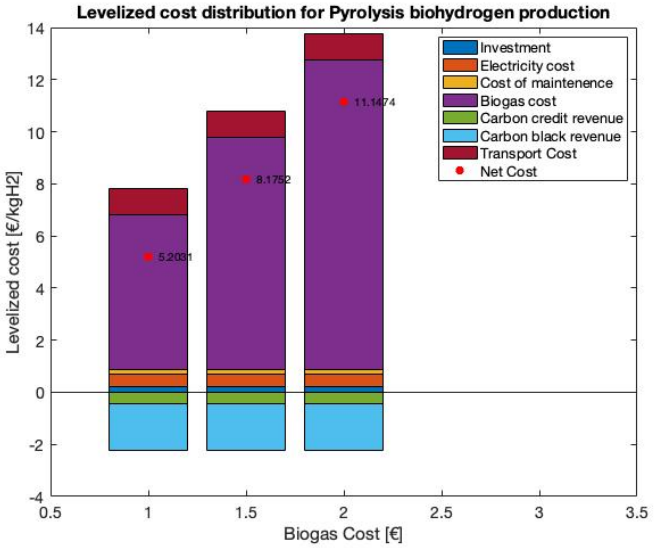

Figure 17: Levelized cost distribution for methane pyrolysis

In the case of dark fermentation, the production of biogas at Uppsala biogas plant is increased. This means the income from produced biogas is always higher than lost income causing a negative cost for biohydrogen as shown of the results in figure 18 The value of biogas is the dominant factor for dark fermentation biohydrogen.

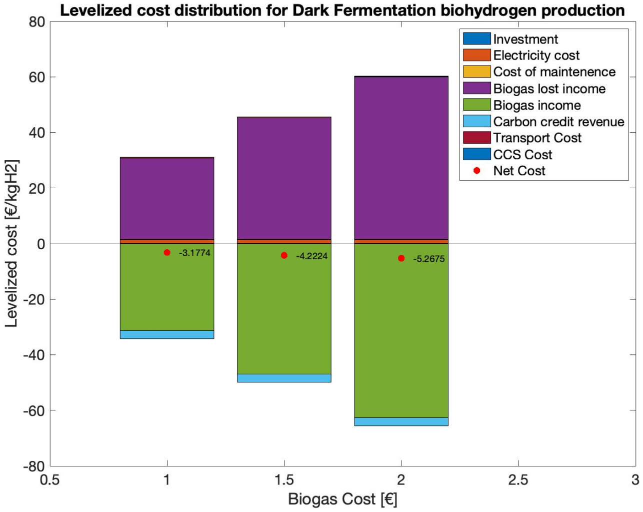

Figure 18: Levelized cost distribution for Dark Fermentation hydrogen

5.4 Sensitivity analysis

In this section, some input parameters to the systems were varied to see how different system configurations would impact the results.

5.4.1 Carbon capture ratio SMR

In the primary results, a capture rate of 54 % is used. In this variation the capture rate was increased to 90%. A system with this capture efficiency is associated with a higher investment cost of 24 850 €/kgH_2/h (Timmerberg et al. 2020). This represents an averaged investment cost for systems with this capture efficiency.

Figure 19 shows the updated emission distribution with a capture rate of 95 %. As a result of more CO_2 getting captured, the net emissions are lower than with 54 % capture rate.

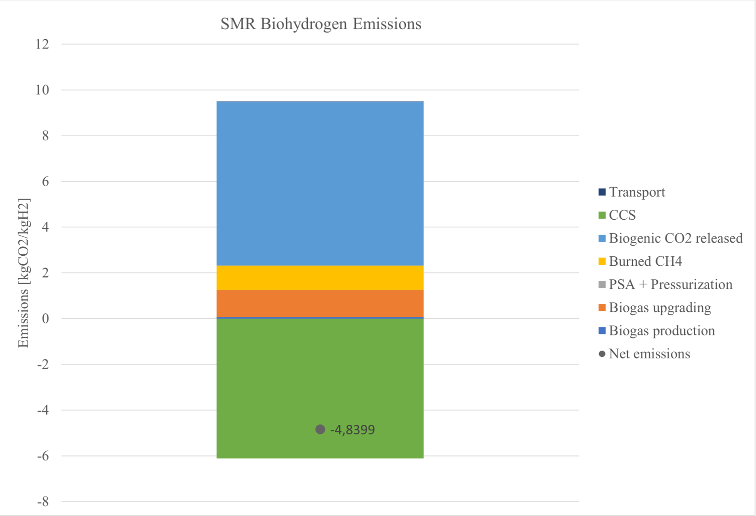

Figure 19: Emissions of biohydrogen production using SMR with a carbon capture ratio of 95 %

The levelized cost of hydrogen is shown in figure 20 and is slightly higher than before. Because of the relatively low impact of carbon credits, it is the higher investment cost that has the greater impact on levelized cost.

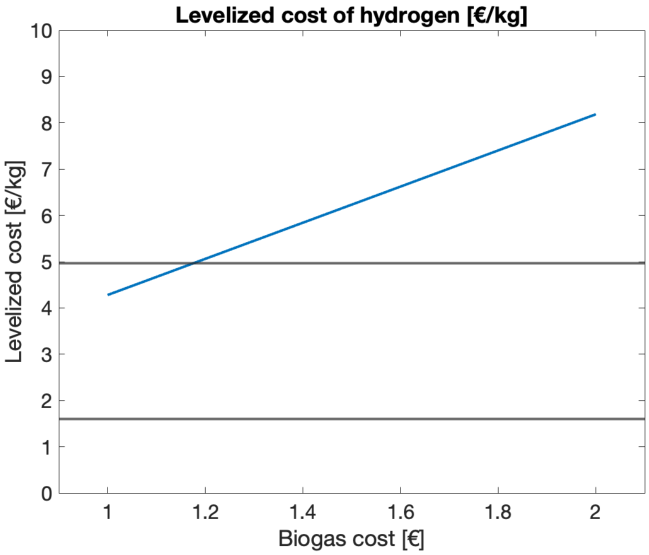

Figure 20: Levelized cost of biohydrogen production using SMR with a carbon capture ratio of 95 %

The lower emissions are not enough to offset the increase in price from a CO_2 abatement cost perspective as shown in figure 21. Even though more CO_2 is captured the cost per tonne is higher.

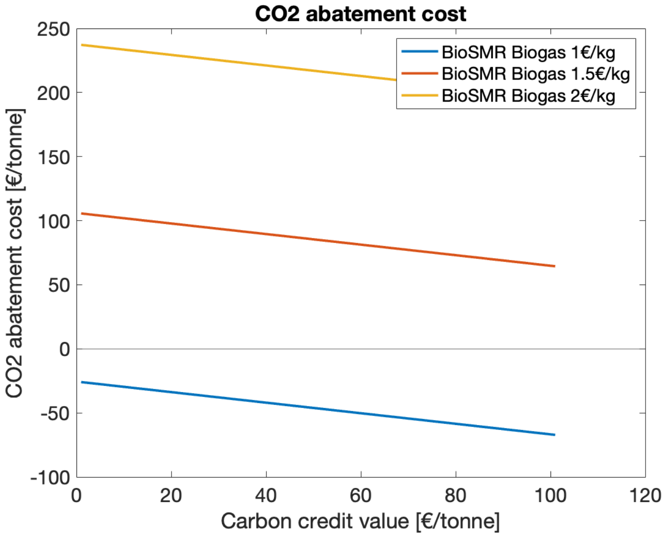

Figure 21: CO_2 abatement cost of biohydrogen production using SMR with a carbon capture ratio of 95 %

5.4.2 Carbon Black Cost

In the primary results, a carbon black cost of 700 €/tonne was used. In this variation, the lowest value from the span of 300 - 700 €/tonne was used.

In this case, the income from carbon black was reduced resulting in a higher levelized cost of hydrogen as shown in figure 22. The difference is about 1.2 €/kgH_2.

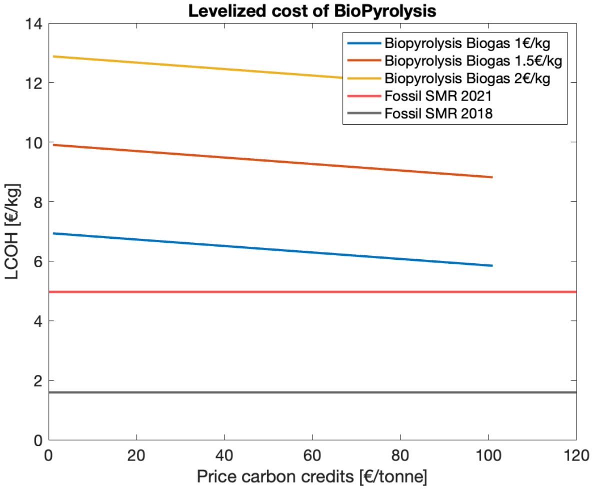

Figure 22: Levelized cost of biohydrogen produced with pyrolysis and with a carbon black price of 300 €/tonne.

The CO_2 abatement cost is also increased by the reduction in price for carbon black. In this case the abatement cost as shown in figure 23 is 70 € higher per tonne of CO_2 than in the primary results.

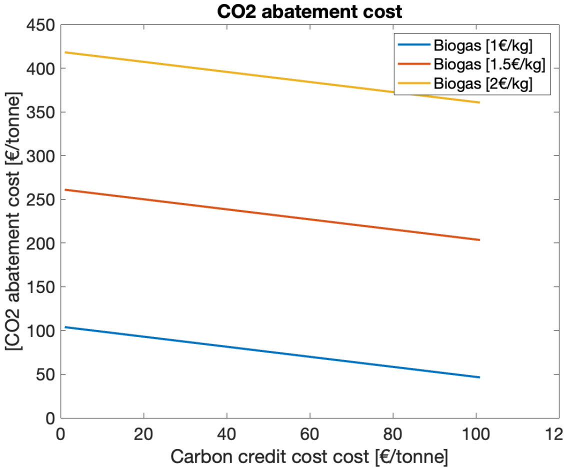

Figure 23: CO_2 abatement cost of biohydrogen produced with pyrolysis and with a carbon black price of 300 €/tonne.

5.4.3 Methane leakage Dark Fermentation

Methane leakage affects Dark Fermentation more than the other methods since a larger volume of methane is produced. Because of this, results are also calculated here without any methane leakage to see how large impact this has on emissions.

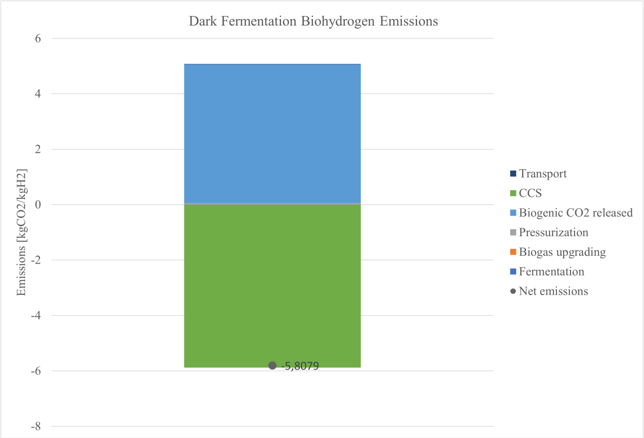

Figure 24: Emissions of biohydrogen production using Dark Fermentation with no methane leakage.

In Figure 24 we see emission results of -5,8079 $kgCO_2/kgH_2$. A reduction of 12,26 $kgCO_2/kgH_2$ compared to the standard case with 1,4 % methane leakage.

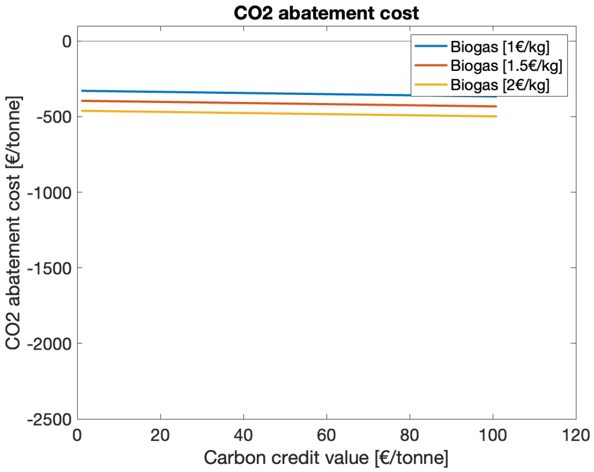

Figure 25: Levelized cost of biohydrogen production using Dark Fermentation with no methane leakage.

With the reduction of emissions, the CO_2 abatement cost is also drastically reduced. In this case a revenue of 329,5 - 498,9 €/tonne is generated.

6 Discussion

In this section the results are discussed with a basis in the research questions. Topics to be discussed are therefore, GHG emissions, LCOH and CO_2 *abatement cost. In addition, assumptions, potential sources of errors as well as suggestions for future studies are discussed.*

6.1 Greenhouse Gas Emissions

For greenhouse gas emissions, pyrolysis showed the strongest negative emissions per kg of produced H_2 as well as the highest negative emissions annually. However, the carbon is in this case made into rubber tires in Gothenburg. Compared to mineralizing carbon dioxide, this carbon sink is less certain to last over time. The implication of this is that some of this CO_2 or all of it, might get released back into the atmosphere reducing the effect of negative emissions in the hydrogen production process. The SMR process however provides more hydrogen while still giving negative emissions and storing these securely by mineralization. Dark Fermentation does not, in these results, manage negative emissions and is therefore not a NET. This is mainly due to the methane leakage of 1.4 % in biogas upgrading. In the sensitivity analysis as the methane leakage is set to 0, results show negative emissions. Since the leakage amount is uncertain and hard to measure, its large impact on the results makes the results more unreliable.

The main portion of emissions in SMR is biogenic CO_2, since this carbon was collected from the atmosphere by the substrate it does not contribute to climate change. In fact, the negative emissions from the substrate is equal in magnitude to biogenic CO_2 released and captured CO_2 (CCS). If the captured CO_2 is larger than fossil CO_2 released, the process will yield negative emissions. In pyrolysis however, the largest portion of emissions are from flared CH_4 and biogas upgrading. Since flared methane only produces biogenic emissions, these are compensated by the substrate. The main source of emissions is therefore methane leakage in biogas upgrading.

6.2 Economics

The levelized cost of hydrogen produced using these three methods was shown to depend largely on the price of producing biogas as shown in figure 13. As well as in the cost distribution figures 16, 17 and 18.

Hydrogen produced via SMR was cheaper than fossil SMR hydrogen 2021 if biogas cost 1 €/kg. Otherwise the levelized cost stayed over 5.9 €/kg despite of income from the carbon credits. In the case of pyrolysis, it was only when biogas was 1 €/kg and the price of carbon credits was over 78 €/tonne that is was cheaper than fossil SMR 2021. Dark Fermentation on the other hand, produces more methane than the current anaerobic digestion process at Uppsala Biogas Plant. This means that in this model, even before any hydrogen has been sold, the process has made a profit. The levelized cost is therefore slightly negative for the lowest price of biogas and more strongly negative as biogas gets more expensive. An inverse relationship to the cost of biogas than with the other two methods.

The CO_2 abatement cost showed a high sensitivity to the cost of biogas. The critical value is these graphs is 0, higher than this it is an economic loss to capture CO_2, and lower than this means it is done while making a profit. For biohydrogen produced via SMR, negative values for CO_2 abatement costs were achieved when biogas was 1 €/kg. Increasing the biogas cost to 1.5 €/kg, even the highest valued carbon credits did not yield a economically beneficial system. Pyrolysis had a slightly higher CO_2 abatement cost and so only managed to break even when biogas was 1 €/kg and carbon credits were 60 €/tonne or higher. The main reason for this is the lower volume of hydrogen produced, causing less hydrogen to carry the economic loads. Dark fermentation has very strongly negative abatement costs. This is caused by the large biogas production.

6.3 Future studies

Since the LCA showed that climate impact was greatly affected by methane leakage, further studies could be conducted to quantify the leakage more precisely and what could be done to reduce it.

6.4 Sources of Error

Since this work contains many assumptions, several production steps and pathways, many sources of error are introduced. The largest impact on the results come from biogas cost and methane leakage.

Since enthalpies are used to calculate energy requirements to power the chemical reactions in this study, real life production would yield lower efficiencies in production causing higher costs and emissions.

7 Conclusions

Two of the examined production methods of biohydrogen were found to be viable NETs in Uppsala. The cheapest method and with the most secure carbon sink was SMR with CCS. This method also gave the highest hydrogen production.

The largest negative emissions came with Pyrolysis, annually producing -7 204 tonnes of CO_2-eq. This method was however shown to be expensive and was only cheaper than the reference hydrogen when the price of carbon credits was higher than 70 €/kg and carbon black could be sold for 700 €/tonne. Since the carbon captured in this case is stored in tires and not mineralized, the period for the carbon sink is also uncertain.

Dark Fermentation mainly produced biogas, this makes the results strange since they are based on a byproduct in the production chain. Annual hydrogen production was low and negative emissions were not achieved due to methane leakage. When the methane leakage was removed, Dark fermentation managed -5.8 $kgCO_2/kgH_2$. Even in this case annual negative emissions are still lower than for SMR and since production of hydrogen is also lower, SMR is judged to be a better option.

Each method is a different compromise. Dark Fermentation gives a low yield of hydrogen and does not manage negative emissions. Pyrolysis is expensive but with the highest negative emissions. SMR provides the highest amount of hydrogen, has a lower cost than pyrolysis and works as a NET unlike Dark Fermentation.

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