



Degree Project in Technology

First cycle, 15 credits

# **Electrified Reforming of Biogas to Hydrogen for Industrial Furnaces with Negative Carbon Emissions: A Feasibility Study**

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# Abstract

The steel industry emits large amounts of carbon dioxide, the main emissions are produced in the process of heating up steel in industrial furnaces of electric arc furnaces (EAF). The purpose of this project was to propose and evaluate a process of reforming biogas to hydrogen to use as fuel for industrial furnaces and result in carbon neutral or carbon negative emissions. This has been done through a literature study reviewing current methods of reforming biogas to hydrogen gas, computer simulations in a program called Aspen Plus, thermodynamic calculations and a comparison with the combustion of pure methane. The study resulted in a process theoretically possible which would produce negative carbon emissions as a result of carbon capture and storage techniques. The proposed process is not as efficient as the process of burning pure methane, however, because it can offer carbon negative emissions it is still a more beneficial option environmentally.

# Sammanfattning

Stålindustrin släpper ut stora mängder koldioxid. Industrins huvudsakliga utsläpp produceras i processen där stål värms upp i industriella ugnar, exempelvis ljusbågsugnar (EAF). Syftet med detta projekt var att utvärdera och föreslå en process för att reformera biogas till vätgas. Detta för att kunna användas som bränsle för industriella ugnar och resultera i koldioxidneutrala eller negativa koldioxidutsläpp. Projektet har utförts genom en litteraturstudie som granskat nuvarande metoder för reformering av biogas till vätgas, datorsimuleringar i Aspen Plus där termodynamiska beräkningar och en jämförelse med förbränning av ren metan utfördes. Studien resulterade i en process som är teoretiskt möjlig, och som skulle ge negativa koldioxidutsläpp till följd av tekniker för avskiljning och lagring av koldioxid. Däremot är den föreslagna processen är inte lika effektiv som processen att bränna ren metan, men eftersom det kan ge negativa koldioxid utsläpp är det fortfarande ett fördelaktigt alternativ med hänsyn till miljöaspekter.

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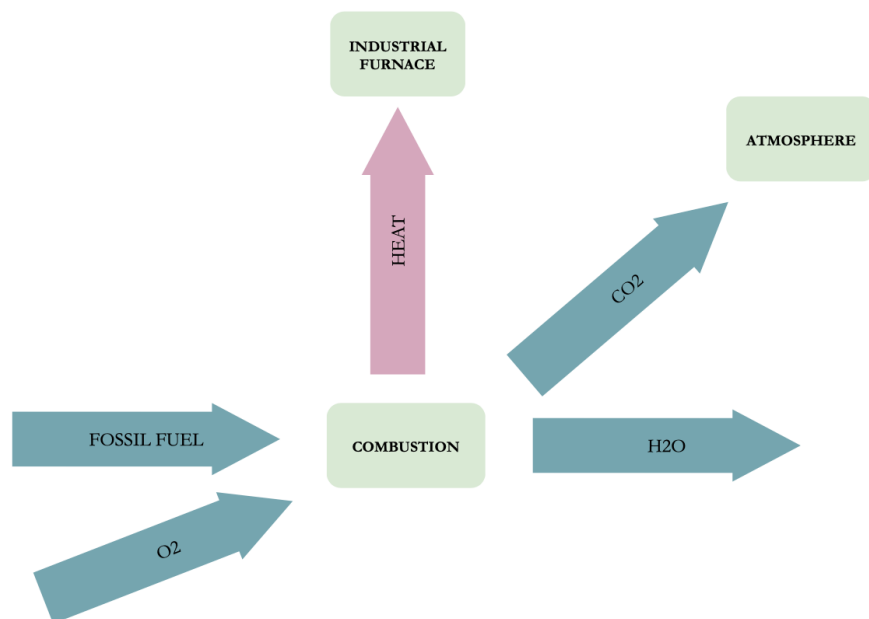
# 1 Introduction

As reducing carbon dioxide emissions become increasingly important the steel industry's demand for sustainable fuel increases. An electric arc furnace (EAF) uses heat through electrodes from an electric arc to reduce iron from iron ore, a process consuming high amounts of energy, approximately 425 kWh of energy per tonne of steel [1]. Currently, the fuels for heating furnaces are mainly fossil fuels such as natural gas and coal as shown in figure 1. Therefore, finding and using renewable sources of energy and carbon neutral or even negative processes are of great interest.

Hydrogen is one of the options available and is being evaluated by for example H2 green steel and Hybrit although their research and work deal with broader subjects and studies. Issues with using hydrogen as fuel include reforming and combustion of hydrogen are not as energy efficient as burning fossil fuels as well as hydrogen being difficult to store.

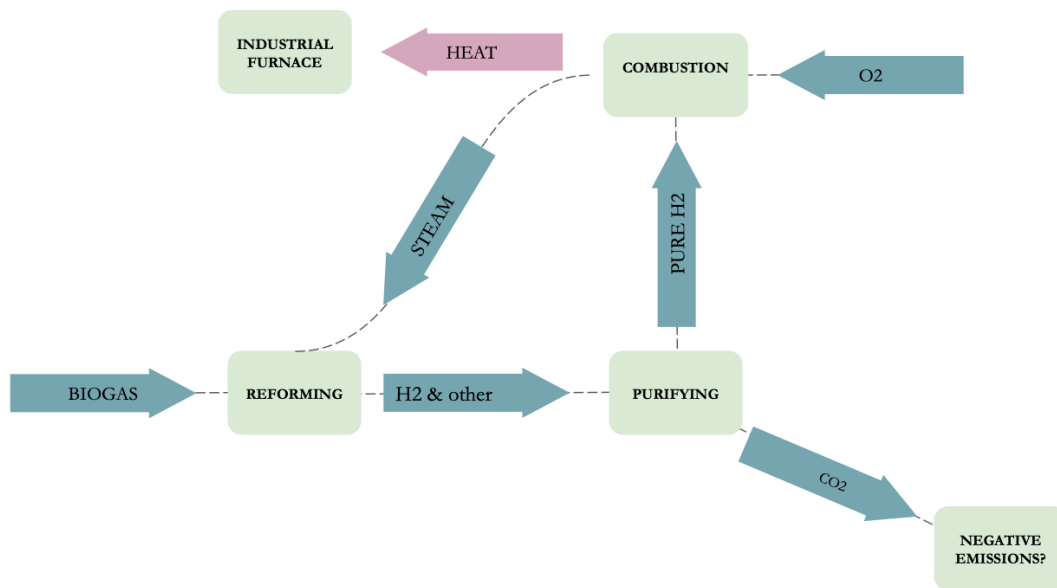
Hydrogen produced from biogas has the possibility to lower the carbon released into the atmosphere and perhaps even result in carbon negative emissions. This is possible by using carbon capture and storage techniques in combination with renewable fuel where biogas is reformed to hydrogen as shown in figure 2. In this report, the energy efficiency of producing and using hydrogen, steam-reformed from biogas will be evaluated and compared to the conventional method of burning pure methane with the purpose of lowering carbon dioxide emissions produced from heating steel [2].

## 1.1 General combustion of fossil fuel flowchart:



*Figure 1 General Methane Powered Process*

## 1.2 Hypothesis reformation to, and combustion of hydrogen flowchart:



*Figure 2 Hypothesis Hydrogen Powered Process*

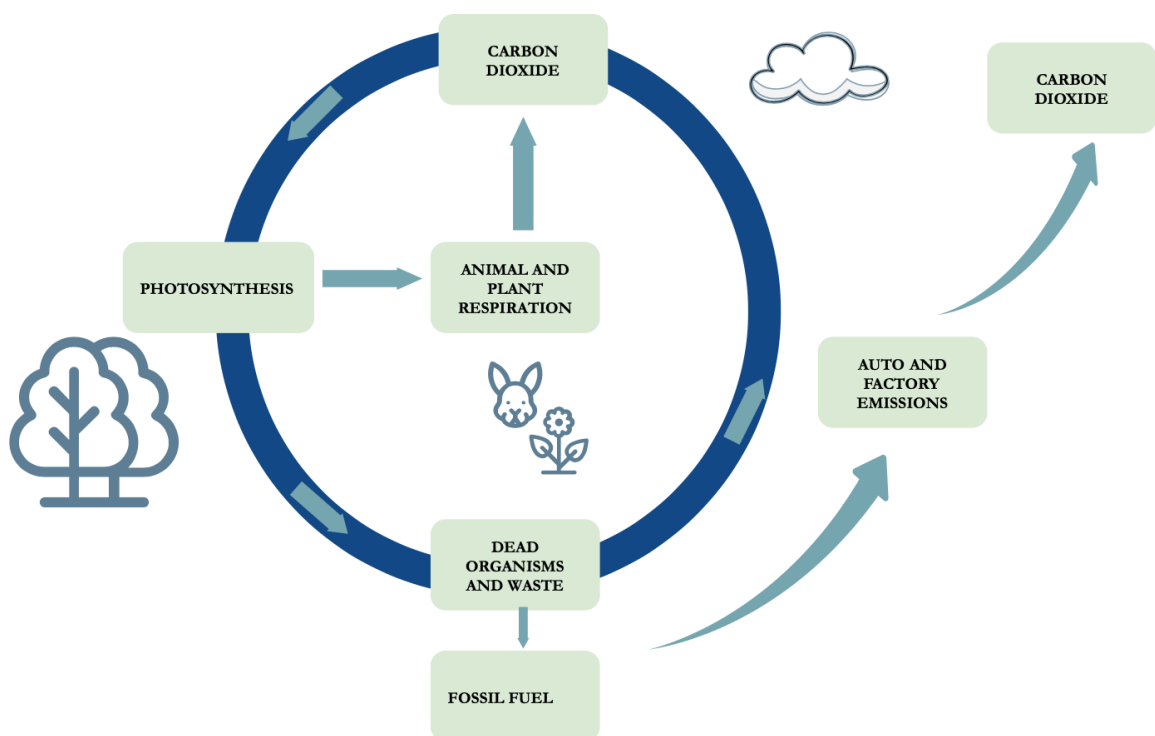
## 2 Theory

### 2.1 Biogas

Replacing fossil fuels in industrial furnaces is possible by reforming biogas to hydrogen gas ( $H_2$ ) and using combustion of hydrogen as an energy source. Biogas is a renewable fuel and contains approximately 60 percent methane ( $CH_4$ ) and 40 percent carbon dioxide ( $CO_2$ ) as well as very small amounts of other gases not referred to in this project. Biogas is produced from biological mass, for example food waste or sewage, and through an anaerobic process is broken down by microorganisms due to the lack of oxygen. The anaerobic digestion occurs naturally in landfills, livestock manure handling systems and nature. To optimise the process, it may be done in an oxygen-poor environment since this benefits the digestion and increases its control of the anaerobic process. The gas must be stored to be able to be utilised in later stages [3].

Biogas is renewable because it is made of food- and other biological waste that is part of the natural carbon cycle. This means that the carbon released from biogas results in neutral carbon emissions, due to the biological mass that previously had absorbed the amount of carbon which is then released when burned or biologically broken down [4]. This is what differentiates biogas from, for example, natural gas or oil which is not considered a renewable source since it is not included in the natural carbon cycle, see figure 3.

This process turns waste into a renewable source of energy which means it also contributes to a circular economy [5] because the usage of material otherwise considered to be waste.



*Fig (3) The Carbon Cycle*



## 2.2 Steam Methane Reforming

The reforming of biogas to hydrogen is in theory a simple reaction where methane is split into carbon and hydrogen. Today there are several ways of reforming methane into hydrogen. The most commercially used is steam-methane reforming (SMR) in which steam reacts with the methane in the biogas at high temperatures with a catalyst present. This reaction produces hydrogen, carbon monoxide and carbon dioxide [6]. There are more efficient ways than SMR to reform biogas, for example using a membrane reactor, but it is not yet economically comparable to the SMR process and therefore not included in this project [7].

In the SMR reactor inputs are biogas along with steam and it reacts via a catalyst and following stoichiometric reactions occur, see equations 1,2 and 3 [8]:



*Stoichiometric reactions of biogas reacting with steam creating hydrogen in the SMR process*

By reactions occurring, see equation 4 and 5;



*Byreactions which occur during the SMR process*

A catalyst is needed to achieve efficient production of hydrogen gas. The most used catalysts in SMR today are nickel-based impregnated with different reactive metal powders. The most efficient one for conventional SMR is (7%)Ni-(1%)Au/Al<sub>2</sub>O<sub>3</sub> which has a conversion of methane of 84 percent [8].

One issue with using a nickel catalyst is a build-up of coke which eventually stops the catalytic reactions. This leads to the catalyst needing to be exchanged which hinders a continuous reaction. There are catalysts less prone to coke build-up, for instance, ones using more noble metals such as ruthenium, platinum, and rhodium. They have previously shown to be successful in this category of reactions [9]. Though noble metals are effective, the supply is uncertain, and they are expensive. Therefore, the most appropriate alternative metal for the catalyst today is nickel.

When conducting this reaction, it is recommended to have a high steam to carbon ratio. Steam to carbon ratio (S/C) is the ratio between water steam and carbon, in this case, methane. It needs to be high to ensure that as much methane as possible reacts with the steam. Having a high S/C ratio also assists in reducing the production of coke because more carbon reacts with the steam to carbon dioxide rather than coke [10].

## 2.3 Pressure Swing Adsorption & Negative Emissions

After the production of hydrogen, the gas mixture needs to be purified of byproducts such as carbon monoxide and dioxide and other residues. This is done in a Pressure Swing Adsorption (PSA). In the process, gas molecules are bound to adsorbent material as a result of pressure changes. Gas molecules are more likely to be absorbed under higher pressure and the properties of the molecule dictate how likely it is to be absorbed. This is the reason this method is used to separate different molecules and gases from one another. The adsorption also depends on the polarity of the gas, the less polarity and volatile the gas molecule is the less likely it is to be absorbed. Hydrogen is low in both polarity and volatility while carbon dioxide and monoxide are a lot more polar and volatile [11].

The gas goes through the PSA and pressure is applied to absorb the carbon monoxide and carbon dioxide as well as other residue gases. When the hydrogen has passed through the pressure is reversed back to normal and the adsorbed gases are released, which enables the gases to be contained or released [12].

The adsorbent material can be silica gel or active carbon for example. This process is used in the industry because it is efficient, the PSA recovery of hydrogen for Linde is 99,99 percent [13]. Linde purifies hydrogen at about 400 degrees Celsius [14].

The PSA removes carbon dioxide and other unwanted gases and enables them to be stored underground meaning it does not contribute to carbon dioxide emissions. This contributes to carbon capture and storage (CCS), which is essential to achieving carbon negative emissions [15]. Negative emissions in the proposed process are possible because, as stated previously, burning biogas would result in a carbon neutral process. If the carbon from the biogas is instead stored and not released into the atmosphere it would result in carbon negative emissions.

Using a PSA device to capture carbon dioxide is an efficient way to do it compared with trying to catch it during or after combustion although it is possible to do it after combustion [16].

## 2.4 Aspen plus

Aspen plus is a computer program used to simulate chemical processes. It is used to foresee the result of a chemical process where parallel reactions are occurring and affecting each other. Aspen Plus uses mathematical and thermodynamic models to predict the outcome of a given process. The user chooses the conditions of the process including temperature and pressure during the inlets and reactor in the process. There is also the choice of reaction conditions for example common and ideal [17].

Aspen Plus was used for the mass balance in the project, specifically methane reforming and combustion of methane which have parallel reactions.

## 2.5 H<sub>2</sub> combustion

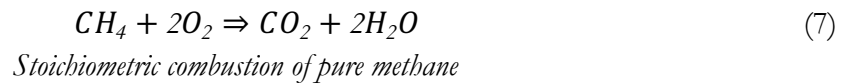
The combustion of hydrogen is from where the energy to the industrial furnace will be supplied. The reaction is stoichiometrically simple where hydrogen gas reacts with oxygen to create water, see reaction 6. This reaction is exothermic meaning it will result in excess energy in the form of heat. Energy will be released because breaking covalent bonds yields energy while forming them requires energy and the bond between two hydrogen atoms holds much more energy than the energy needed to create a water molecule.



In practice hydrogen will react with air which is approximately 79 percent nitrogen gas (N<sub>2</sub>) and 21 percent oxygen gas (O<sub>2</sub>). As nitrogen gas is not reactive it serves the purpose of diluting the reaction mixture as hydrogen is very reactive and using too high of a concentration would be unnecessarily perilous [18].

## 2.6 Methane combustion

Pure methane is one of the fuels used to heat industrial furnaces today according to Linde [2]. This is done by combustion of pure methane at high temperatures, and this is the stoichiometric reaction, see reaction 7.



This is an exothermic reaction meaning it releases the excess energy in the form of heat. In reality, the methane reacts with air which adds nitrogen to the mix but as the nitrogen does not react it only acts as dilution in the reactor.

## 2.7 Energy Equations

To calculate the energy balance and the possible amount of energy to obtain, the following thermodynamic equations were used [19].

$$E = HHV \cdot \widehat{m} + Cp \cdot \widehat{m} \cdot \Delta t \quad (8)$$

*General energy balance equation*

E = Energy (kW)

HHV = Higher heating value (kJ/kg) - (energy per mass of fuel)

$\widehat{m}$  = Mass flow (kg/s)

Cp = specific heat capacity (kJ/kg)

$\Delta t$  = Temperature °C

Equation 8 is used to calculate the components' energy in kilowatts. Specific heat is taken from this source [20].

For steam, the equation is slightly different because specific enthalpy h is used instead of specific heat capacity. This is because the energy content of the steam is decided by both partial pressure and temperature [21].

The partial pressure of steam is provided by Aspen Plus with the use of equation 9 where n is mole and p is the pressure which is based on the following equation:

$$\frac{n_{tot}}{n_{H2O}} = \frac{P_{tot}}{P_{H2O}} \quad (9)$$

*Partial pressure*

n = mole

P = partial pressure

The specific enthalpy (h) is a table value taken from this source [22].

This formula is used for steam where h is specific enthalpy:

$$E = h \cdot \widehat{m} \quad (10)$$

*Energy balance equation specific to steam*

h = Specific enthalpy (kJ/kg)

## 2.8 Circular process

When discussing sustainability a widely used concept is circularity, which is a concept where the goal is to go from a consumer type of community to a circular one where ideally nothing goes to waste but is used in some other way. This can be done by using materials that otherwise would have been wasted or finding ways to conserve energy that would otherwise have been lost for example.

## 2.9 Flowchart

A flowchart is a way of displaying where the energy and mass come from and end up and where energy needs to be added to the process, where it is lost. The purpose of this is to get an overview of how efficient the process is throughout the whole process and where improvements can be made.

### 3 Method

The method consists of a literature study, simulations, and thermodynamic calculations. The literature study consisted of reviewing hydrogen as fuel compared to the combustion of methane as well as all the parts surrounding the process. Aspen Plus was used to simulate the chemical exchange in the reactions and provide a mass balance for the process. Thermodynamic equations and Excel were used to calculate the energy balance for the combustion of hydrogen, methane reformation and methane combustion. After that, a comparison was made.

Different types of steam methane reformation techniques were compared to result in the best and most efficient method. The most efficient one used industrially is the SMR process using a nickel catalyst with a conversion of 84 percent [8]. Different ways to purify the hydrogen after the reformation were also researched resulting in the PSA process which is industrially used and efficient [13].

To propose a way of using hydrogen as a fuel for industrial furnaces the first step was to find out how much energy would be needed to make the process work. When that had been calculated that information was used to work out how much hydrogen would be needed to produce that amount of energy, see equations 1 and 3. This was done in excel where full combustion of hydrogen was simulated to calculate partial pressure and the rest of the input. This information was then used to complete the energy and mass balance for the SMR conversion of biogas to hydrogen calculated in Aspen Plus. This resulted in the amount of biogas needed to produce hydrogen enough to fuel an industrial furnace. Because the different processes affect one another the input needed to be adjusted to the different outputs several times until the desired energy was achieved in an optimised process.

The simulation of biogas reforming in Aspen Plus was done with 2 inlets, one with the biogas at 25 degrees Celsius and the other with steam and nitrogen at 800 degrees Celsius. It reacts in a Gibbs energy reactor at 1 atmosphere (atm) and 800 degrees Celsius at ideal conditions and then the output is analysed. The mass flows out and in, and the temperatures and the partial pressure are used in the energy balance.

Pure methane was evaluated as fuel for heating an industrial furnace to be able to make a comparison. This was done by calculating how much pure methane would be needed to achieve the same amount of energy as well as how much carbon dioxide the process produced. The Aspen Plus simulation of methane was performed similarly to the simulation of biogas reformation. Pure methane was used in one inlet at 25 degrees Celsius and air at 25 degrees Celsius in the other inlet. The reaction occurs in a Gibbs energy reactor also at 800 degrees Celsius and the outlet was analysed and used in an energy balance.

Combustion of pure methane, as well as combustion of hydrogen, is considered to reach full combustion resulting in all the fuel being used up in the reaction. The combustion of hydrogen is simulated in excel since there is only one possible result of the reaction and it is very reactive. The combustion of pure methane is simulated in Aspen Plus since parallel reactions are occurring.

One of the objectives of this process is to produce a circular process. This was done using the hydrogen combustion output, steam, and nitrogen, as input in the SMR reformation. In the first part of the hydrogen process, carbon monoxide and dioxide, as well as some methane, steam, and nitrogen, are produced. This is then purified in the PSA resulting in 99 percent pure hydrogen going into the third part of the process which is the combustion of hydrogen. Air is added and oxygen reacts with the hydrogen at a high temperature resulting in the energy needed to heat an industrial furnace and steam that goes back into the first part of the process of Hydrogen Powered Process.

Two flow charts were made to visualise the process and the energy balance of the proposed process and the combustion of methane to compare. Tables containing the information on the energy and the mass flow were made. The energy added and lost were calculated by the energy equations using the mass of the system and temperature changes along the way.

## 4 Results

The project resulted in a process for reforming biogas to hydrogen with the ability to fuel an industrial furnace, a Hydrogen Powered Process (HPP). A Methane Powered Process (MPP) was also simulated and compared to the HPP. Flowcharts offer an overview of the processes, mass and energy flows. The mass and energy balance of the simulated reactions and a comparison of the fuels evaluated are shown in table 1. For the HPP, see figure 4 and figure 5. For the MPP, see figure 6 and figure 7. In appendix A, B and C show detailed in and out data of the calculations made.

In the flow charts the blue arrows represent mass flow, the pink arrows represent energy flow and the green squares represent a process step.

### 4.1 Hydrogen Powered Process (HPP)

#### 4.1.1 Energy Flowchart

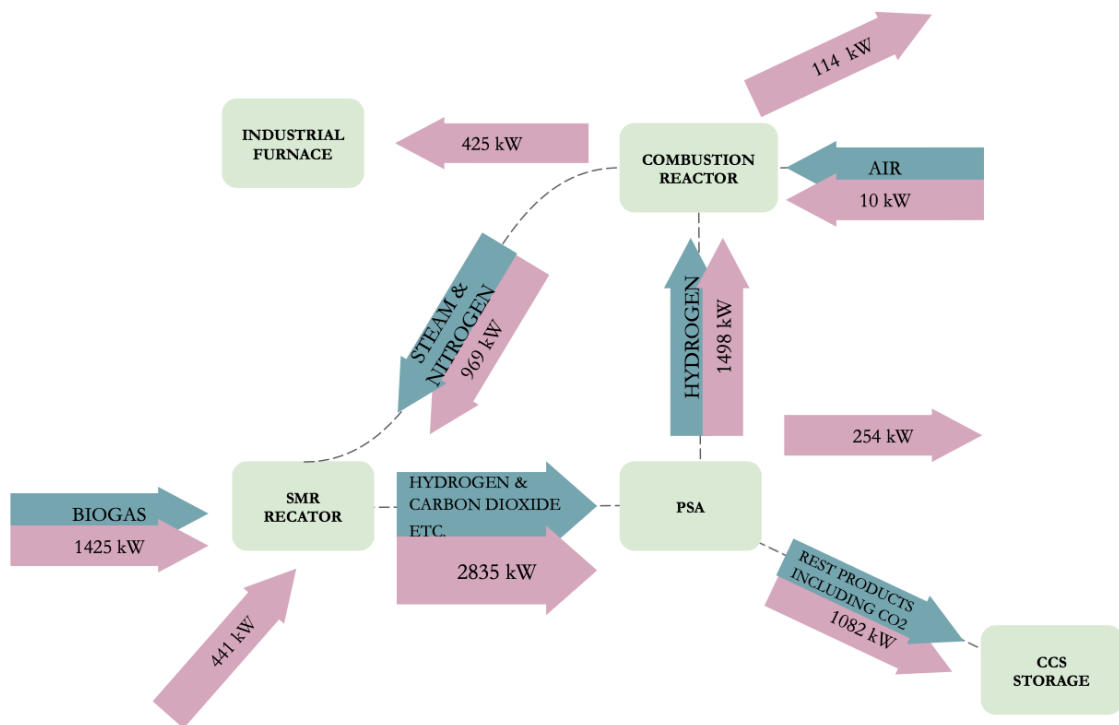
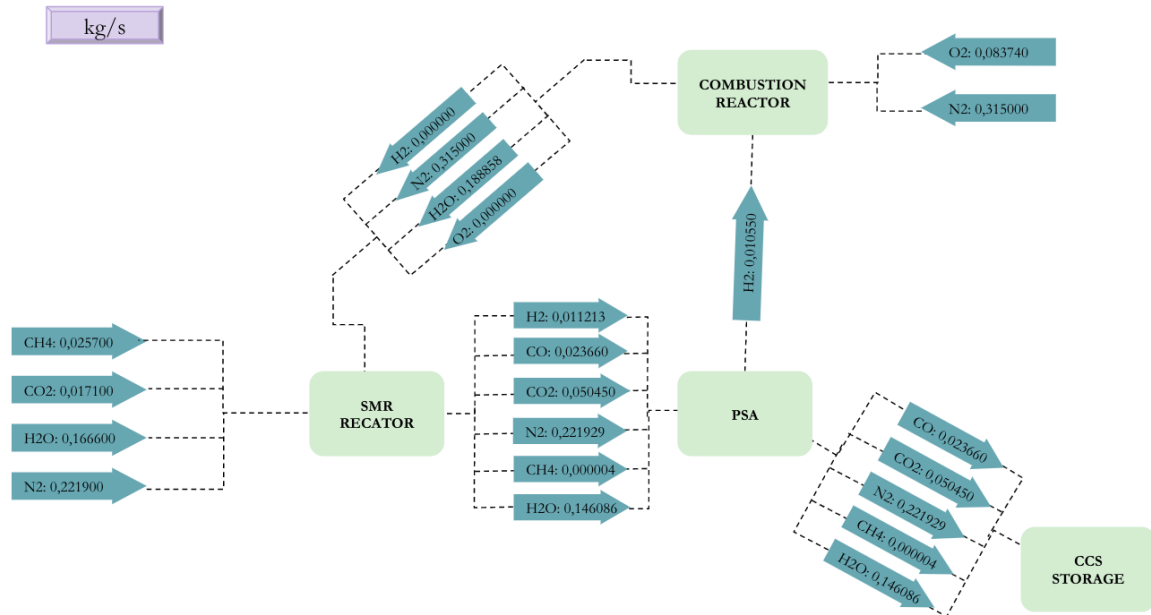


Fig 4 Hydrogen Powered Process energy flowchart



#### 4.1.2 Mass Flowchart

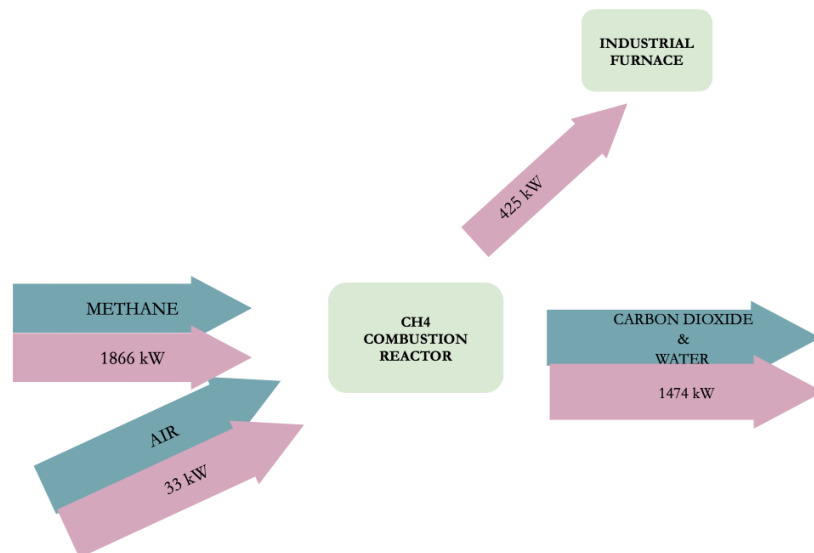


*Fig 5 Hydrogen Powered Process mass balance flowchart*

The energy output of 425 kWh is achieved with 0,01055 kg/s of hydrogen. With a catalyst conversion of 84 percent that results in 0,01256 kg/s of hydrogen needed to be produced by the HPP. This results in 0,0257 kg/s of biogas being needed. Because of the PSA process, these reactions have a carbon dioxide emission of negative 0,05045 kg/s after purification and CCS is applied. In the reforming of biogas to hydrogen, the steam to carbon ratio was 6,5 as a result of the steam and nitrogen from the hydrogen combustion.

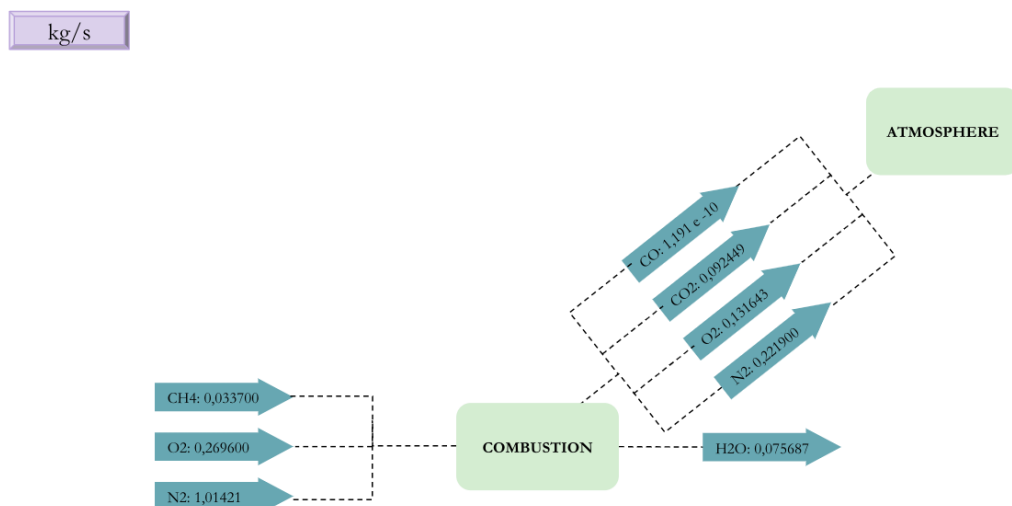
## 4.2 Methane Powered Process (MPP)

### 4.2.1 Energy Flowchart



*Fig 6 Methane Powered Process energy flow chart*

### 4.2.2 Mass Flowchart



*Fig 6 Methane Powered Process mass balance chart*

Combustion of methane shows that 0,0337 kg/s methane is needed to receive an energy output of 425 kW. The combustion of methane emits 0,09245 kg/s of carbon dioxide disregarding any possible capture after the process has occurred.

### 4.3 Results Hydrogen- and Methane Powered Processes

Table 1. Results HPP and MPP

	Hydrogen Powered Process	Methane Powered Process
Fuel type	Biogas	Methane
Amount of fuel kg/s	0,0428	0,0337
Energy derived kW	425	425
CO2 emissions kg/s	-0,05045	0,026841
Process steps	3	1
Amount ch4	0,0257	0,0337

## 5 Discussion

### 5.1 Comparison of processes

The proposed process of reforming biogas to hydrogen for fuelling industrial furnaces is possible and not unrealistic compared to the combustion of pure methane. The process is longer and contains more process steps than the combustion of methane. It is easier to hinder the release of carbon dioxide into the atmosphere in the reformation process using a Pressure Swing Adsorption (PSA) in comparison to the alternative of catching carbon dioxide after combustion. Using the process including hydrogen means that the carbon dioxide elimination is included in the process, compared to the pure methane process where it is implemented individually. The use of hydrogen to fuel industrial furnaces is already implemented, although on a small scale, thus showing it is feasible.

Comparing the different processes' efficiencies, one can see that the same amount of generated energy requires two times as much biogas as is needed comparing to the methane and air mixture needed. This means that the efficiency of the Hydrogen Powered Process (HPP) is much lesser than the Methane Powered Process (MPP). This could be because the methane is diluted with carbon dioxide and therefore not as efficient as pure methane is. It could also be because more steps are included where energy is lost. To compare the efficiency of the HPP if pure methane was used instead of biogas would prove if dilution, the process steps or a combination of the two is the issue.

However, over time, the difference in efficiency concerning MPP as well as HPP becomes less and less relevant. New sources are vital to fuel industrial processes due to the natural supply of fossil fuel running out.

### 5.2 Pressure Swing Adsorption

One of the intentions of this project was to examine whether a process like this could result in carbon negative emissions. Because of the PSA process, all the carbon mon- and dioxide are absorbed and can thanks to the CCS technique be stored instead of released. This results in a carbon negative process because a renewable fuel, biogas, is used. If CCS had not been applied the process would have resulted in a carbon neutral process instead.

If a fossil fuel such as methane would have been used in the process and CCS would have been applied, it would result in neutral emission of carbon-di and monoxide rather than a negative.

The calculations show that with CCS applied, the HPP results in a negative emission of CO<sub>2</sub> by 0,05045 kg/sec, while the current usage of MPP (without capturing the CO<sub>2</sub>) emits approximately 0,026841 kg/sec of CO<sub>2</sub>.

The PSA process requires a lot of energy to fuel it which is not necessarily a problem but for this entire process to become carbon negative the electricity being used in the processes around it needs to be from a sustainable source. If for example coal burning would be used to fuel it this would be back to square one. This is constant throughout the process; energy is needed to fuel the process and if that energy is not supplied from a sustainable source we might as well combust the fossil fuel directly.

It is also notable that the PSA is an extra step in the process, going from biogas which is mostly methane to reforming it to hydrogen and purifying it are steps that the combustion of pure methane does not have. These steps lead to losses and possible complications during the process which are downsides to the hydrogen process.

The energy needed to fuel the PSA and the methane reformation processes are not accounted for, only the energy needed for the mass in the system which gives an indicator of how much energy is needed but is not a complete analysis.

### 5.3 Biogas and Its Possibilities

Biogas is, as stated in the background, made from biological waste such as food waste and other biological waste. Today there is no shortage of biological waste however the supply of biogas. However, access to biogas is possibly an easy fix since as mentioned it produces various resources such as food waste, feedstock and more. And an increase in the production of biogas would mainly require a larger utilisation of waste.

### 5.4 Possible Issues

One of the issues with HPP is that the catalyst being used in the process needs to be replaced every so often which leads to an in-continuous process resulting in the process being less efficient and economically unfeasible. There is research on another way of reforming biogas and methane to hydrogen through a membrane reactor, but it is not yet implemented on an industrial scale. There may also be better catalysts to be explored to elongate the time it can be functional in the process.

Using hydrogen as a fuel is not easy to manage. Because it is highly reactive it needs to be contained in a very sealed and secure way. In this process, it is suggested that hydrogen is used as soon as it is produced. Though, notably, complications relating to using hydrogen may occur. For example, if a leak occurs there could be an explosion because hydrogen explodes when in contact with oxygen.

Using Aspen Plus to simulate the chemical reactions is theoretically a good way to estimate the results of the reaction but the results would be more realistic if an experiment could be performed to ensure what the output would be. Ideal conditions were used in the simulations and full combustion was assumed. Ideal conditions usually do not apply in reality because of bad exchange, small leaks and other small imperfections resulting in less-than-ideal conditions. This means that the results for both processes could produce less energy.

## 5.5 Sustainability and Ethics

Because sustainability and lowering carbon dioxide emissions are very central and even a necessity today, it is a good investment to choose the more sustainable option rather than the more efficient option to fuel industrial furnaces.

Today the industry is driven almost exclusively by profit and in that scenario, the methane powered process is preferred due to its efficiency of it. But in a society where more taxes are being applied to carbon dioxide emissions and the prices of fossil fuels only rise, it is a possibility that putting extra resources into creating and using a more sustainable fuel will prove beneficial in the long run, not only environmentally but also economically. There is increasing pressure from customers to supply environmentally sustainable products. In this case, the hydrogen process is better despite the possibility of capturing carbon dioxide after the combustion of methane.

If biogas was combusted instead of pure fossil methane it still means that the best that process can result in is being carbon neutral while using biogas in the SMR results in carbon negative emissions with CCS applied. However, combusting biogas is a better alternative than the combustion of fossil methane.

Aspects of circularity are achieved in the hydrogen process where biogas derived from waste is used which is circular on a big scale. The combustion of hydrogen also results in nitrogen and steam that is used in the biogas reformation which is a great way to make use of mass that is the by-product of one reaction and necessary in another. The steam and nitrogen also come in at 800 degrees Celsius meaning that not as much energy needs to be added when the reactants are heated in the SMR reactor.

Although the HPP is less efficient than the conventional MPP it should be considered a potential alternative since there is the potential to dramatically decrease the steel industry's carbon dioxide footprint, creating achievability for long-term sustainability both socially and ethically.

## 6 Conclusions

In conclusion the Hydrogen Powered Process (HPP) is an appropriate alternative to the combustion of methane for fuelling industrial furnaces and simultaneously achieving negative carbon emissions. Although the HPP is less energy efficient and has more process steps than the Methane Powered Process (MPP), the hydrogen process achieves negative carbon dioxide emissions thanks to the Pressure Swing Adsorption (PSA) and carbon capture and storage (CCS) methods. In the hydrogen process, it is possible to achieve circular elements. For example where biological waste is turned into biogas and where the steam produced in the combustion of hydrogen is used in the SMR process.

Although further energy is needed to fuel the SMR and PSA processes of biogas it is still beneficial considering environmental aspects. However, solely if the electricity used to fuel the process is derived from a renewable source. If for instance pure methane is combusted to produce energy for the biogas reformation process it would be better to simply use the combustion of methane for the industrial furnace.

In conclusion, the HPP is beneficial to reduce the carbon emissions that the steel industry emits. However, future research referring to the HPP, such as experimental work is found to be necessary.

- HPP is less efficient, even so a potential fuel for EAFs due to its ability to create negative carbon emissions.
- Further research including experimental research is essential.

## 7 Recommendations

The Hydrogen Powered Process (HPP) would benefit from being performed in a laboratory to ensure it would be as efficient as the results of the simulations. There are also a few changes that could be done to improve small inefficiencies to improve the entire process, such as finding a better catalyst to keep the coke production at a minimum. To get a better overview of the comparison it would be beneficial to do a full economic analysis.



## 8 Acknowledgements

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# Appendix

## A, Biogas Reformation Energy Balance

	Input	Input	Input	Input	Output	Output	Output	Output	Output	Output
	CH4 BIO	CO2 BIO	H2O	N2	H2	CO	CO2	CH4	H2O	N2
t ©	25	25	800	800	800	800	800	800	800	800
Cp (kJ/kg)	2,21	0,846		1,04	15,105	1,1985	1,253	4,6515		1,18
h (kJ/kg)			4160,0						4160,1	
HHV (kJ/kg)	555384				141700	9211		555384		
$\hat{m}$ (kg/s)	0,0257	0,0171	0,1666	0,2219	0,01256	0,02366	0,05045	0,000004 08077	0,12411	0,221929
E (kW)	14273	0,3624	693,05	184,64	137,0851	240,615	50,5711	2,28158	516,285	209,5010
Tot E	12409									

## B, Combustion Hydrogen Energy Balance

	Input	Input	Input	Output	Output	Output	Output
	H2	O2	N2	H2	O2	H2O	N2
t ©	25	25	25	800	800	800	800
Cp (kJ/kg)	14,31	0,918	1,04	15	1,01		1,18
h (kJ/kg)						4160,02	
HHV (kJ/kg)	141700			141700			
$\hat{m}$ (kg/s)	0,01055	0,08374	0,315	0	0	0,18858	0,315
E (kW)	1498,71	1,922	8,191	0	0	784,497	297,381
Tot E	424,944						

## C, Combustion Methane Energy Balance

	Input	Input	Input	Output	Output	Output	Output	Output	Output
	CH4	O2	N2	H2O	CO2	CH4	O2	CO	N2
t °C	25	25	25	800	800	800	800	800	800
Cp (kJ/kg)	2,21	0,918	1,04		1,253	4,595	1,01	1,1985	1,18
h (kJ/kg)				4159,07					
HHV (kJ/kg)	55384					55384		9211	
$\widehat{m}$ (kg/s)	0,0337	0,2696	1,0142	0,07569	0,09245	0	0,13564	0	1,0142
E (kW)	1868,30	6,1873	26,369	314,788	92,67045	0	109,213	0	957,414
Tot E	425,479								

