POWER TO GAS – BRIDGING RENEWABLE ELECTRICITY TO THE TRANSPORT SECTOR

Abstract

Globally, transport accounts for a significant part of the total energy utilization and is heavily dominated by fossil fuels. The main challenge is how the greenhouse gas emissions in road transport can be addressed. Moreover, the use of fossil fuels in road transport makes most countries or regions dependent on those with oil and/or gas assets. With that said, the question arises of what can be done to reduce the levels of greenhouse gas emissions and furthermore reduce dependency on oil? One angle is to study what source of energy is used.

Biomass is considered to be an important energy contributor in future transport and has been a reliable energy source for a long time. However, it is commonly known that biomass alone cannot sustain the energy needs in the transport sector by far.

This work presents an alternative where renewable electricity could play a significant role in road transport within a relatively short time period. Today the amount of electricity used in road transport is negligible but has a potential to contribute substantially. It is suggested that the electricity should be stored, or "packaged" in a chemical manner, as a way of conserving the electrical energy. One way of doing so is to chemically synthesize fuels. It has been investigated how a fossil free transport system could be designed, to reach high levels of self-sufficiency. According to the studies, renewable electricity could have the single most important role in such a system.

Among the synthetic fuels, synthetic methane (also called synthetic biogas) is the main focus of the thesis. Hydrogen is obtained through water electrolysis, driven by electricity (preferable renewable), and reacted with carbon dioxide to produce synthetic methane. The concept of the mentioned process goes under the name Power to Gas. The electricity to fuel efficiency of such a process reaches about 50 %, but if utilizing excess heat produced during the electrolysis and the reaction, the total process efficiency can reach much higher levels.

The economics of the process is as important as the technology itself in terms of large scale implementation. The price of electricity and biogas are the most important influences on the economic viability. The minimum "spread" between purchase and selling price can be determined to obtain a general perception of the economic feasibility. In this case biogas must be sold about 2.6 times higher than purchased electricity per kWh.

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List of Abbreviations

CAES - compressed air energy storage

CH_4 – Methane

CO_2 – Carbon dioxide

DME – Dimethyl Ether

FT – Fischer-Tropsch

H_2 – Hydrogen

HCNG – (Approx.) Hydrogen blended compressed natural gas

kWh – Kilowatt hour

MCFC – Molten carbonate fuel cell

MWh – Megawatt hour

NTP – Normal pressure and temperature (1 atm, 20 °C)

PEM – Proton exchange membrane

PHES – Pumped hydro energy storage

PWh – Petawatt hour (1 PWh = 1×10^{15} Wh)

SBG – Synthetic biogas

SOFC – Solid oxide fuel cell

UNFCC - United Nations Framework Convention on Climate Change

List of Papers

Appended

I. Erik G. Lindfeldt, Maria Saxe, Mimmi Magnusson, Farzad Mohseni, 2010. *Strategies for a road transport system based on renewable resources – The case of an import-independent Sweden in 2025* Applied Energy 2010:87;1836–1845

II. Farzad Mohseni, Mimmi Magnusson, Martin Görling, Per Alvfors, 2012. *Biogas from renewable electricity – Increasing a climate neutral fuel supply* Applied Energy 2012:90;11-16

III. Farzad Mohseni, Martin Görling, Per Alvfors, 2012. *The competitiveness of synthetic natural gas as a propellant in the Swedish fuel market* (In Press) Energy Policy 2012:xx;xx

Not appended

IV. Mimmi Magnusson, Farzad Mohseni, Martin Görling, Per Alvfors, 2010 *Introducing Renewable Electricity to increase Biogas Production Potential* International Conference on Applied Energy 2010.

V. Farzad Mohseni, Martin Görling, Per Alvfors, 2011. *Synergy effects of combining hydrogen and gasification for synthetic biogas* World Renewable Energy Congress 2011.

My contribution to the papers

Paper I: Equal responsibility between all authors regarding the different sections. I was main author together with Mimmi Magnusson.

Paper II: Main author and corresponding author. I was responsible for the section with the Sabatier process.

Paper III: Main author with responsibility in all sections together with co-writers.

Preface

After my undergraduate studies in 2007, I was fortunate enough to be introduced to Agrivind AB through a friend. Here I met people with a burning interest and a willingness to contribute their part in climate change mitigation. I was inspired by their ideas and visions and was (of course) interested in working as a research engineer at Agrivind when I got the offer. To make it possible for the project to move forward, by the beginning of 2008, a collaboration with the Division of Energy Processes (EP) at KTH was initiated where I started as an industrial licentiate student, thus beginning my PhD studies. For me, it was an excellent position where I got the opportunity to work with like-minded people with ambitions and interest to learn more and perhaps make a contribution to energy science.

During my time at EP I have gained valuable knowledge and experience, which is going to be useful for the rest of my life. I have got a broad technical understanding of many different processes and applications, which work as an excellent base and will hopefully facilitate for me in my future work.

In the presented papers, energy values have been displayed in various ways, both Watt hour (Wh) and Joule (J). However, in the thesis, the figures are consistently presented in Wh (In chapter 3 Joule is shown in parenthesis as well), due to convenience, habit from calculations and “way of thinking”.

1 Introduction

During the history of mankind, it has been shown that every step forward in development has always involved an increase in energy utilization. One significant breakthrough was the industrial revolution in the late 18th century, were many ground breaking technologies emerged, among others the steam engine was invented. Over the last two hundred years, energy usage has almost exploded compared to earlier development, since middle of 1960's until today the energy usage has increased enormously in absolute figures, from 46 PWh to 125 PWh in 2008 (BP Historical Data 2012, Swedish Energy Agency 2010a). To sustain such an escalation it is apparent that usage must become vastly more efficient and additionally the energy sources must be renewable to keep anthropogenic carbon dioxide emissions minimal. Net emitted carbon dioxide is recognized to be the main reason for increased mean temperatures due to the greenhouse effect, which in turn is presumed to be the cause of for example extreme climate conditions.

Besides climate effects, another issue is the increase in acidity in the oceans, caused by higher levels of atmospheric carbon dioxide. Increased acidity affects a considerable number of marine organisms such as corals, plankton and shellfish. Increased acidity in their habitats results in severe living conditions for these organisms, which puts whole aquatic ecosystems at risk (Turley 2008). In turn, many land-based ecosystems could be affected as well.

Today, most energy-utilizing processes, e.g. industrial equipment, furnaces, vehicles, power production processes etc, are developed to use fossil energy from sources like oil, coal and gas. Development has taken this path due to the accessibility of fossil energy in large quantities and concentrated form. As a consequence, most energy systems in a global perspective are based on fossil energy, making a switch to renewable alternatives very complicated on many levels, not to mention costly.

An important milestone regarding climate change and fossil energy usage was the "United Nations conference on environment and development" (also known as the "Rio conference") in 1992. Here, the UN's framework convention on climate change (the UNFCCC) was adopted, in which fundamental principles and guidelines for intergovernmental efforts were established. However, the convention was not legally binding on the part of the committed countries. In 1997 the Kyoto protocol was adopted (which to some extent leaned on the UNFCCC) and was primarily in "raw" form, hence it needed to be clarified and explained more in detail. The final edition became the Marrakesh Accords in 2001(UNFCCC 2). In 2005 it entered into force as a legal obligation for parties who were committed (UNFCCC 1). The Kyoto protocol goal is basically to lower greenhouse gas (GHG) emissions by 5.2% during 2008-2012 compared to 1990 levels.

Even though there are intergovernmental legislations and awareness among countries it takes time for society to adapt. Implementing changes in practice has proven to be difficult. Many obstacles must be overcome, e.g. technologies that are predicted to have a promising future are still novel and have to be tested and evaluated before being implemented on a large scale. Other constraints are lack of funding, difficulties in fulfilling economic feasibilities, lack of incentives, etc. In 2008 about 87.2 % (125 PWh) of the global primary energy supply was of fossil origin while the remaining 12.8 % (19 PWh) was from renewable sources. In comparison, the corresponding figures for 1990 were 87.3 % and 12.7 % respectively (Swedish Energy Agency 2010a).

Generally, there are two key paths to reduce the net contribution of carbon dioxide to the atmosphere: by using more energy-efficient processes or increasing the fraction of renewable energy in the primary energy supply. Dividing the energy usage over different sectors, the two sectors that need to be addressed are the transport sector, in which road transport is the main focus of this work, and the stationary sector.

Globally, transport accounts for 27 % of total energy utilization (IEA 2011) and is heavily dominated by fossil fuels. In contrast to the stationary sector with relatively few but large emission sources, road transport has a vast quantity of small emitting sources in the form of various types of vehicles. Hence, the main issue is how the GHG emissions in road transport can be addressed. Moreover, the use of fossil fuels in road transport makes most countries or regions dependent on those with oil and/or gas assets. With that said the question arises of what can be done to reduce the levels of GHG emissions and furthermore reduce dependency on oil? One angle is to study what source of energy is used.

This work presents an alternative where renewable electricity could play a significant role in road transport within a relatively short time period. Today the amount of electricity used in road transport is negligible but has a potential to contribute substantially, which will be demonstrated throughout the thesis. It is suggested that the electricity should be stored, or “packaged” in a chemical manner, as a way of conserving the electrical energy (in contrast, electricity must be used directly upon production). One way of doing so is to chemically synthesize fuels, which is an area that is gaining interest among researchers as well as various industries.

1.1 Background

It has been recognized that in order to eliminate the use of fossil energy in transport, several different energy sources, technologies and strategies need to be combined to meet the energy demands according to e.g. (Lindfeldt et al. 2010). Biomass is considered to be an important energy contributor in future transport and has been a reliable energy source for a long time. It can be used directly as fuel wood or as feedstock to produce propellants, e.g. via gasification. However, it is commonly known that biomass cannot sustain the energy needs in the transport sector by far (Biomass and its potential are more thoroughly discussed in chapter 3). Hence, it is likely that other renewable sources (e.g. wind, solar, hydro) will play a larger role in future transport.

Wind, solar and hydropower (mainly “run of river” technology or wave power) are intermittent and high shares in the grid of such power sources will be difficult to manage. When periods of excess electricity production occur, it would be beneficial to have a process that could convert electrical energy into a storable form for more appropriate use when needed. Access to relatively cheap electricity (due to excess production or off-peak periods) will be of importance when synthesizing the fuels. The possibility to store electrical energy is going to be a crucial issue when the mentioned renewable sources gain higher penetration in the electrical grid.

Fuel synthesis (in this case based on electricity) basically opens up the possibility to produce any fuel desired. Hence, synthetic fuels that are similar to today’s fuels are preferable since these will be possible to use in existing vehicles. In this work the focus has been on synthetic methane (also called synthetic biogas or SBG further on in the work). Hydrogen and synthetic methanol production are closely related to synthetic biogas production and have also been studied and taken into discussion briefly. Lately, the concept of using electricity to produce gaseous fuels has been labeled Power to Gas, and generally applies for the production of e.g. hydrogen or synthetic methane. In this work, however, Power to Gas refers to synthetic methane production from electricity.

Carbon dioxide is suggested to act as carbon source and hydrogen produced in water electrolysis (driven by renewable sources) should consequently act as energy carrier. The key steps in producing of synthetic fuels are described below.

- CO_2 capture – Carbon dioxide is abundant and relatively easy to access. Carbon dioxide could be taken from stationary industrial processes or even from the air. If recycling carbon dioxide from for example a biomass-fired combustion to form a “new” fuel, it could even be considered to have a negative impact on the net CO_2 contribution to the atmosphere. However, if carbon were recycled from a fossil-fuelled combustion, the carbon atom would be used twice before reaching the atmosphere. Hence, it would have

½ the effect compared to a non-recycled emitted carbon. In total, recycling carbon dioxide would replace the need of using additional fossil carbon which would contribute to the net emissions.

- Electrolysis – The past 10-15 years have seen a rapid expansion of renewable energy utilization (mainly wind power and solar power). However, power production at such plants is intermittent and to optimize the resource management, it is essential to make the most of the electricity produced during off-peak periods. Electrolysis is flexible and can be driven during times of excess electricity production to store the energy in form of hydrogen. In fuel synthesis hydrogen is an energy carrier and is essential when creating different types of hydrocarbons.

- Fuel synthesis – The actual forming of fuels occurs in this step. Basically all types of fuels could be synthesized depending on reaction pathway. Many synthesis reactions that are suggested (Lunde 1974; Specht et al. 1998, Karimi et al. 2012) have been known for a long time; however, it is only recently that they have become of interest in fuel production applications as a result of CO_2 mitigation discussions.

Due to the nature of the papers appended in this work, it is apparent to set the system boundaries around Sweden. However, the calculations are general and consequently applicable to different areas and regions.

1.2 Aim

This work has studied the possibilities to increase the share of renewable energy in the road transport sector by introducing renewable electricity. Today electricity is not implemented to any significant extent in road transport; it is mainly associated with track-bound applications.

The objective of the thesis is to present an alternative that could have a significant impact within a relatively short period of time. The synthetic routes presented in the thesis are known reactions and have been studied by many research teams. The applications of the reactions are however not studied to the fullest. This thesis presents alternatives where the reactions can be implemented to improve the transport sector's access to renewable fuels.

1.3 Thesis outline

The thesis sets the scene by briefly introducing the current energy and GHG situation, their goals and existing legislations in a global perspective. In Chapter 3 the thesis concludes a study which investigates the requirements for Sweden in order to create a self-sufficient transport sector; mainly by moving away from fossil energy (Sweden is considered an excellent example in this case since it is relatively rich in biomass). As one of many alternatives that will need to be implemented, electricity (preferably renewable) will play a significant role in the transport sector. The following chapters (chapters 4 and 5) present the alternative of using electricity in synthetic fuel production (mainly synthetic biogas) and its potential. In chapter 6 an indicative economic evaluation is made of the SBG production. Chapter 7 sums up, analyses and discusses the presented data from the previous chapters and the thesis is rounded off with concluding remarks in chapter 8.

2 Methodology

Studies and analyses of energy systems are a “common thread” throughout this work and have been its main focus. An energy system could be viewed as an interconnected network of sources and stores of energy. System boundaries are then used to define what the chosen energy system includes. The boundary is set to create a target area and a point of reference where studies and analysis can be performed. The technologies that are presented (mainly Sabatier) have been evaluated, not only as a single technology but as a potential integrated part of the surroundings or existing system. Even though the main area is energy systems, other aspects have been presented as well. This work also evaluates technical aspects and economic aspects to give a more extensive indication of how presented technologies would perform.

Backcasting is a method which is well suited during planning of complex systems (Dreborg 1996; Höjer and Mattsson 2000). It has a target-oriented approach and there are four main tasks that are done during a backcasting study. Firstly, long-term targets (one or many) are established which could represent for example an ideal future. In the following step, all targets are compared to the current situation, existing trends and the expectations regarding their development. The third step consists of creating and forming images that fulfill set targets. In the final step the images are analyzed taking various aspects into consideration, e.g. feasibility, and “road maps” of how to reach the set images are developed (Åkerman and Höjer 2006). Determining such targets leaves room for a flexible planning process where different paths can be identified. A backcasting study is implemented in Paper I, which investigates different strategies needed if a self-sufficient road transport sector is to be achieved by 2025.

An economic assessment of synthetic biogas production is made in paper III to establish the viability of the process from a commercial point of view. In order to perform the assessment some data and conditions had to be assumed according to existing trends; in a sense, the evaluation leans towards forecasting. The calculation was based on the annuity method of depreciation, which is a tool used to determine how the economic possibilities can be considered. The results are highly preliminary and are based on a case plant rather than presenting a general result. However, the method is applicable for different conditions and set-ups of the plants.

3 The road transport sector

In Sweden, the road transport sector is responsible for about 40 % of the total CO_2 emissions even though only 18 % of the energy is used (Swedish Energy Agency 2007a). Compared to the global status, with the corresponding figures of 26 % and 23 % respectively (Swedish Energy Agency 2007a), the Swedish CO_2 emissions from Swedish transport are quite high. The distribution is explained by the high share of renewable and CO_2 lean power production in the stationary sector, i.e. hydropower and nuclear power. Additionally, the heating sector uses a significant amount of biomass and waste for their combustion. By contrast, the road transport is heavily dominated by fossil fuels.

In 2009 the Swedish parliament approved different bills regarding transport political goals, one of which was that at least 10 % of the energy usage in the Swedish transport fleet must be of renewable origin by 2020. Additionally, in a longer perspective it should be totally independent of fossil fuels by year 2030 (planning target). As a comparison, in 2010 about 5.7 % was renewable (Swedish Energy Agency 2011a). However, with or without political goals road transport will need to move away from fossil usage.

This chapter refers to Paper I, which analyses and discusses possible measures that could contribute to the reduction of fossil energy usage in road transport. In turn, such measures could also lead to higher self-sufficiency; at best, complete self-sufficiency. The target horizon has been set to 2025. A “Business as usual” scenario is presented displaying the evolution of energy demand in road transport, published by the Swedish Energy Agency for 2025. If no unpredicted, radical changes take place, it adds up to 99 TWh (Swedish Energy Agency 2007b), which is used as the base for calculations. In 2009 the corresponding figure was almost 85 TWh (Swedish Energy Agency 2010b).

In addition two scenarios are presented, the “Attainable” scenario and the “Optimistic” scenario. As revealed in the labeling the Attainable scenario can briefly be explained as making more reserved interpretations of the results coming from the different assessment studies compared to the Optimistic scenario. In this chapter only the Attainable scenario is considered, since it presents a more pragmatic and realistic picture of the situation.

3.1 Strategies for an import-independent transport system

Until recently there has (un)fortunately been an abundance of relatively cheap fossil energy available for usage in the transport sector. This has inhibited the incentives to create a more energy-efficient road transport system based on renewable energy sources. Today, due to enlightenment about climate effects, energy limitations and economic aspects, such a system is most countries' ambition. At best, it would also be self-sufficient.

However, to obtain self-sufficient road transport based on renewable energy, there must be changes in the whole system, both in the delivery of energy (supply side) and the utilization of energy (demand side). In Paper I, extensive research was done which studied the present and future energy situation combined with present and future development of vehicles and their energy utilization, all within the borders of Sweden.

Section 3.1 briefly highlights different strategies and quantifies how much each strategy will contribute in terms of energy (TWh). Results for the Attainable scenario show that not only will it be necessary to use several strategies, but how much each strategy could contribute, which is presented in Figure 1.

3.1.1 Supply side – Renewable energy replacing fossil fuel demand

It is possible to obtain a wide range of different vehicle fuels from biomass (forest and/or agriculture), e.g. ethanol, dimethyl ether (DME), Fischer-Tropsch diesel, methanol and methane. Biomass is often brought up as a great alternative for replacing fossil fuels mainly due to its flexibility and accessibility. Obviously, depending on what fuel is sought, the processes will have varying energy efficiencies. In this work, the overall efficiency is assessed to be about 50 % regardless of type of fuel (Hamelinck and Faaij, 2002; Olah, Goeppert, and Prakash 2006). The efficiency is assumed to include the energy needed for production, harvesting and transportation of biomass as well as distribution of the fuel and excess heat (e.g. district heating). Many assessments have been made of the Swedish biomass potential and it lies between 156 – 222 TWh available for exploitation in 2025 (Swedish Government Official Report 1992; Swedish Government Official Report 2000; Swedish Government Official Report 2005). In 2006 the usage was "only" about 117 TWh (Swedish Energy Agency 2007a), which gives an increase of about 39 – 106 TWh of expected available forest in the future. Of this about 28 TWh is assumed to be available for biofuel production. Hence the resulting amount of fuel that could be obtained from biomass is about **14 TWh** in 2025. This corresponds to about 14 % of the total amount needed in 2025.

Crude biogas[1] is produced when organic material is degraded in the absence of air (digestion). Today the main sources in biogas production are sewage sludge, co-digestion and landfill gas where the end uses are mainly in vehicle purposes and heat production (Swedish Energy Agency 2011b). Other sources include for

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[1] Is described more thoroughly in 5.1

example the food industry, grocery stores, agriculture and forest residues. Interest in biogas as an energy source is increasing and many studies have tried to assess the total potential in Sweden. A source with high production potential has been shown to be waste from agriculture and is expected to grow substantially in the future. In 2010 the amount of biogas coming from agriculture reached less than 0.5 TWh (Swedish Energy Agency 2011b). The feasible potential from agriculture, however, is almost 8 TWh (Linné et al. 2008). It is estimated that biogas from all mentioned sources combined (excluding forest residues) could reach levels of about 11 TWh annually, where agriculture waste would account for the main part (Linné et al. 2008). This is in line with (Nordberg 2006) estimations. However, the feasibility of reaching such levels by 2025 is highly uncertain due to many different factors, e.g. changed energy prices, competition situations, political regulations etc, hence it is cautiously assumed that about **7 TWh** is possible to produce by 2025.

Due to goals and legislations set nationally and in the EU, Sweden is rapidly expanding its base of electricity production from wind power. In 2006 less than 600 MW was installed, delivering almost 1 TWh. In 2010 the installed effect was more than 2000 MW and delivered 3.5 TWh (Swedish Energy Agency 2011c). Due to the aggressive expansion, it seems reasonable to believe that the production goal of 10 TWh could be reached in 2015 and even the “planning” target of 30 TWh in 2020 does not seem unlikely. Paper I analyzed different wind power assessment studies for Sweden in 2025 and it was determined that there would be an excess electricity production of about **42 TWh** that could be used as energy source in for example road transport. Electric vehicles would be an attractive option if cheap, high-performance batteries become available. However, battery manufacturers still have some issues to deal with; hence the availability of such batteries is quite uncertain, which makes it necessary to study other alternatives as well. Other options are synthetic fuels. The electrical energy will be converted through different processes and stored chemically. However, these fuels will suffer from conversion losses, and will range between 50 % and 60 % electricity to fuel efficiency. The amount of renewable energy utilized in the road transport will thus be variable depending on what technology is used.

3.1.2 Demand side – Fuel demand reduction

In addition to increasing the renewable share in road transport, measures can be taken that reduce the demand for energy. These measures include for example decreasing road transport demand, technical improvements and non-technical improvements and are described below.

Firstly, decreasing the demand for road transport is possible to achieve mainly by two paths: making people change transportation means (e.g. by road pricing or regulations), or by encouraging decreased road transport using appealing alternatives. IEA and IPCC have estimated that measures such as infrastructure improvements, better transit systems and net meetings could reduce travel demands considerably, about 10 – 15 % (IEA 2003; IPCC 2007). Structural changes would also aid the reduction. When taking all aspects into consideration it is assumed that about 10 % of the energy demand in 2025 is reduced, which corresponds to about **10 TWh**.

Technical improvements will also have a significant effect in reducing the energy demand. In the business as usual scenario, however, an improved overall efficiency of about 26 % is pre-assumed for cars and about 5 % for lorries, which is taken into consideration (Swedish Energy Agency 2007b). A number of different measures can be implemented which could reduce demand significantly. Among these, hybridisation by using batteries and electric engines is a major improvement. Lower tyre resistance, improved aerodynamics and weight reduction are other factors that could contribute additionally. In such situation there is a probability of rebound effects where car owners could use their cars more due to cheaper km cost. Hence, to reduce that effect, fuel prices must be regulated to some extent (Robért and Jonsson 2006; Greening, Greene, and Difiglio 2000). The IPCC predicts that the fuel efficiency in Europe will be improved by 35 – 55 % in 2025 compared to 2001 and the IEA predicts a reduction of 40 % by 2030 (IEA 2001; IPCC 2007). Accordingly, in this work, an average of 40 % reduction for cars and 30 % reduction for heavy-duty vehicles is assumed. After subtracting the Business as usual improvements the energy reduction adds up to about **13 TWh.**

So called Eco-driving is a good example of a non-technical improvement. Studies show that less frequent stops during driving have a significant influence on fuel consumption (Granovskii, Dincer, and Rosen 2006; Ericsson 2000). Hence street and traffic conditions play an important role in reducing energy demand. Real time displays showing road conditions and traffic situations could help drivers find the optimal routes and avoid for example roads that are congested. Except for driving patterns, better maintenance would aid fuel savings. It must be emphasized that to some extent, there will be counteractions between non-technical and technical improvements. For instance, changed driving patterns to more “eco-friendly” driving will not be much more efficient if using a hybridized car compared to a conventional car. Hence, non-technical improvements are assessed to contribute with a modest 5 % for urban vehicles and 10 % for long distance vehicles (since they will not be affected by counteractions to the same extent). This corresponds to about **5 TWh** in fuel savings.

3.1.3 Combining supply- and demand-side strategies

Figure 1 presents how much each strategy would cover of the total energy demand in the Swedish road transport in 2025. An interesting aspect that is revealed in the figure is that biofuels from biomass, which were expected to form the "backbone" of energy supply, instead only contributes a minor part of the total need. When combining all strategies except renewable electricity, about half of the energy demand is covered. The highlighted part of Figure 1 shows how much energy is still needed and is presented separately in Figure 2.

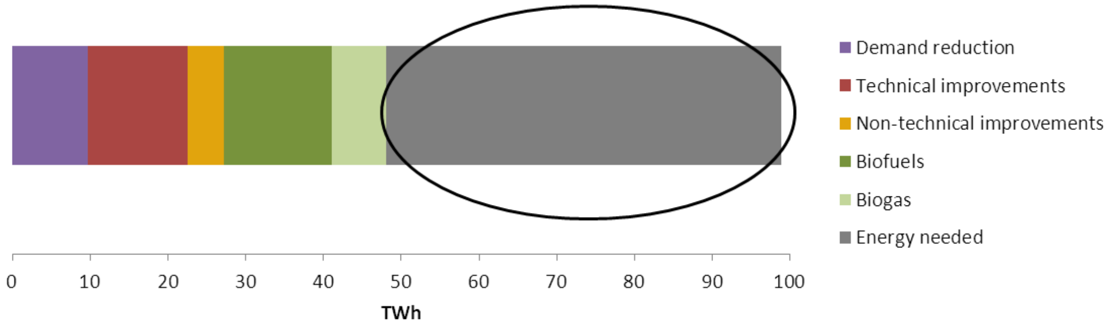

Figure 1 Presentation of how much each strategy would contribute to a future energy demand

Depending on what application is used for the available renewable electricity, the extent of its contribution will vary and it is shown by the variation in shading in Figure 2. As can be seen, there will be a deficit of energy even if all the electricity was to be used without conversion losses. However, it is clear that renewable electricity will play an important role in future road transport with a major potential of energy supply.

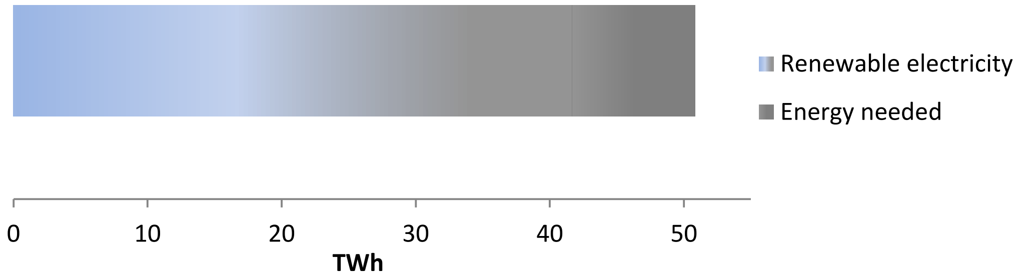

Figure 2 An undefined fraction of fossil fuels will still be left in road transport even after introduction of electricity

Table 1 presents a summary of the strategies from earlier sections and as can be seen there is a lack of about 8 TWh out of the total 99 TWh at the best. That energy demand would have to be met through external supply.

Table 1 Contribution of strategies

Total demand and strategies	Energy (TWh)
Total energy demand 2025	99
Decreased demand in road transport	10
Technical improvements	13
Non-technical improvements	5
Biofuels	14
Biogas	7
Remaining	50
Renewable electricity	42
Conclusion	**Deficit!**

4 Third-generation fuels – synthesizing hydrocarbons

There is no clear definition of the terms first, second and third generations of (bio)fuels. To my knowledge, these terms have been arbitrarily used in different contexts by the speaker or author when that person finds it suitable. However, one rather good indication could be to look at the level of synthesis/anthropogenic influence. First-generation fuels could be considered those fuels that are based on organic material and naturally degraded whilst the product is taken care of, e.g. ethanol from sugarcane, biogas from digestion etc. Fuels belonging to the second generation are originally from biomass as well. However, the biomass is treated to some extent chemically and/or thermally during the process to reach the products, e.g. ethanol from biomass through gasification or fermentation. Finally, third-generation fuels could be seen as fully synthetic and are not dependent on biomass (even though by-products from biomass processes could be used). The process is based on renewable energy sources to stay CO_2 lean. The production of e.g. synthetic biogas implies that the process belongs to the group of third generation fuels due to fully synthetic production.

4.1 *Carbon emission levels and CCS*

"Waste is what's left when imagination fails" – Unknown

One key reason why fossil fuels are held responsible for climate change is the net emissions of carbon dioxide when combusted. Carbon dioxide is one of many greenhouse gases, which basically keeps the heat from the sun within the atmosphere which in turn increases the average temperature on earth. Changes in temperature are expected to have major consequences; everything from rising sea levels to extreme weather conditions.

When biomass or any other "climate neutral" organic matter is combusted, carbon dioxide is emitted to the atmosphere as well. In this case however, there is the option of re-circulating the emitted carbon dioxide by for example planting a tree to replace the combusted one. If the biomass is not re-planted after combustion, the emitted carbon dioxide will cause the same climate effect as if a corresponding amount of fossil fuel were burned. Hence, the problem is due to the net addition of carbon dioxide.

To keep fossil combustion processes CO_2 lean an alternative is CCS (carbon capture and storage). In terms of climate change mitigation expectations are high regarding CCS. According to IPCC (Intergovernmental Panel on Climate Change) scenarios, CCS will potentially be able to reduce up to half of the CO_2 emissions' role when trying to reach goals of keeping carbon dioxide below 750 ppm by 2100 (IPCC 2005). The European Commission states that it is not possible to reduce CO_2 levels by 50 % by 2050 without CCS. Consequently they have allocated large amounts of funding for its research and development over a given period. The United States is also committed to conduct research on CCS (Hansson and Lind 2009; IPCC 2005).

Potential carbon sources are basically any CO_2 emitting processes. However, some flue gases/emission sources are more preferable than others. High concentrations of carbon dioxide in the flue gas make the separation cheaper than those streams with low concentration. In for example conventional combustion, which is done with air, the flue gases contain large amounts of nitrogen together with the carbon dioxide. Until recently, there has not been any interest in the industry to separate these gases since they naturally exist in the atmosphere and can be emitted in that mixture. The availability of CO_2 separation equipment is therefore scarce.

In principle there are three different CCS methods: post-combustion, pre-combustion and oxyfuel combustion. These are presented in Figure 3. Another method is separation of CO_2 from air, which today is a technology at the development stage and has been suggested by for example (Lackner 2009).

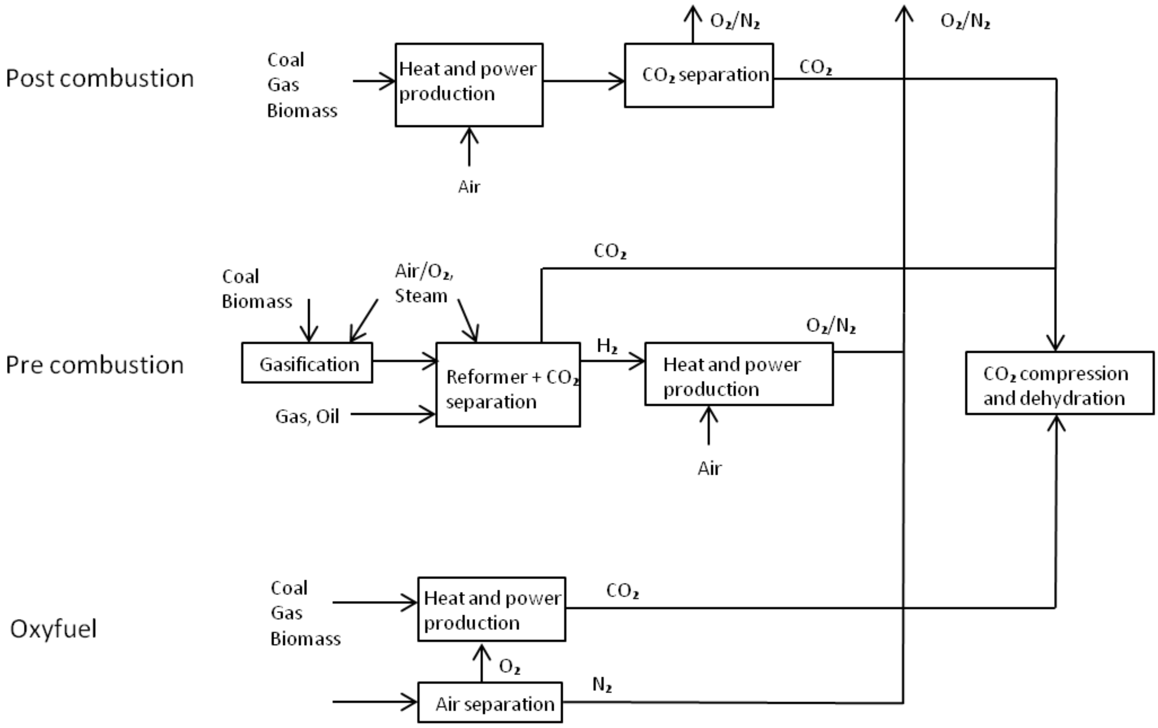

Figure 3 Principles of different CCS methods. Post-combustion, pre-combustion and oxyfuel combustion are different CCS technologies (IPCC 2005).

Post-combustion CO_2 separation is essentially a stand-alone process. As can be seen in the figure, it runs the flue gases through a separation unit and concentrates carbon dioxide before sending it to storage. Hence, such a principle opens up the possibility of retrofitting existing plants with CO_2 emissions. The pre-combustion method uses gasification to break the feedstock to different fractions of molecules and form syngas. Carbon dioxide can then be separated from this mix before the syngas (mainly H_2 left) is sent for combustion. Oxyfuel is basically the usage of pure oxygen in the combustion. This gives a high concentration of carbon dioxide in the flue gas, which can be sent for storage.

However, instead of storing the carbon dioxide as a final step, it could be “recycled” and used in e.g. a fuel synthesis. Such a process would reduce the need for “new” carbon since it is used twice before being emitted to the atmosphere. Reusing carbon dioxide in a fuel production has been suggested by George Olah (Olah, Goeppert, and Prakash 2006) and is referred to as CCR – Carbon Capture and Recycling or CCU – Carbon Capture and Use.

4.2 Hydrogen production from electricity

The most common method of extracting hydrogen today is steam reforming natural gas (Stein et al. 2009) but it is also a by-product in some industries, e.g. chlorine production. Most often it is used in the ammonia/urea industry to produce fertilizer. In terms of energy, hydrogen can be considered as an energy carrier. To retrieve the energy from hydrogen it could be combusted or used in fuel cells to produce either mechanical work or be converted to electricity.

The conventional methods of storing hydrogen are in pressurized form or as a liquid. Additionally it can be bound to metal hydrides. In this thesis, however, it is proposed to go one step further and "bind" the hydrogen on carbon to form methane (i.e. carbon dioxide will indirectly act as energy carrier). To get hold of the large quantities of hydrogen, electricity will be essential, since it will be needed to drive an electrolysis in production of hydrogen. To ensure a CO_2 lean product (i.e. synthetic biogas) the electricity should preferably originate from renewable sources, e.g. hydro, wind or solar power (which are the most used renewable sources today).

Of the different electrolysis technologies that exist (among others alkaline, proton exchange membrane, solid oxide), alkaline electrolysis is the oldest and most developed technology. Consequently, it is the most commonly used. As its name indicates, alkaline electrolysis uses aqueous alkali electrolytes (since pure water is a poor electrolyte), e.g. sodium or potassium hydroxide. The electric current running through the electrodes dissociates the water into its molecular bases i.e. hydrogen and oxygen. The free hydrogen adsorbs on the cathode until bubbles are formed and then released. To reduce polarization effects and concentration and heat gradients, the electrolyte is continuously circulated in the system. Alkaline electrolysers can be operated in temperatures up to 150 °C depending on system configuration (Grimes, Varghese, and Ranjan 2008).

4.3 Fuel synthesis

As mentioned in the introduction, basically any fuel can be synthesized. However, some of the propellants used today are very complex. Gasoline and diesel are such examples and contain C4-C12 and C10-C17 hydrocarbon chains respectively. The diversity of molecules and the relatively long hydrocarbon chains make the fuels difficult to synthesize. Long and more complex chains often require many steps which in turn lead to energy losses. Therefore, small molecules are preferable from a synthesis point of view. Two molecules that could be considered as relatively easy to synthesize are methane (CH_4) and methanol (CH_3OH), the simplest alkane and simplest alcohol. The reactions are shown below in Equation 1 (also known as the Sabatier reaction) and Equation 2.

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ ΔH= - 165 kJ/mol

Equation 1 The Sabatier reaction

$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$ ΔH= - 49 kJ/mol

Equation 2 Methanol synthesis of carbon dioxide

Both methane and methanol are fuels that can be used in commercial vehicle engines. As a liquid fuel at NTP conditions, methanol has the advantage in terms of handling and distribution. The reaction also shows a lower heat loss than the methanation reaction.

4.3.1 Synthetic biogas production

Using the Sabatier reaction to synthesize methane from carbon dioxide and hydrogen is a well-known method and was discovered in the early 1900s by the French chemist Paul Sabatier (Sabatier 1912). Today, the commercial use of the reaction is mainly coupled to ammonia production, where carbon dioxide, which is considered an impurity, is present in small amounts and must be removed. However, in this case, the carbon dioxide is supposed to constitute a major part of the reactants. In Figure 4 a general flow scheme of the suggested SBG production is presented. The source of carbon dioxide can vary, but to avoid the need for expensive cleaning equipment it is highly preferable to locate processes that emit pure CO_2 streams. Such streams could come for example from water treatment plants (or other digestion plants with CO_2 separation), ethanol production and gasification processes.

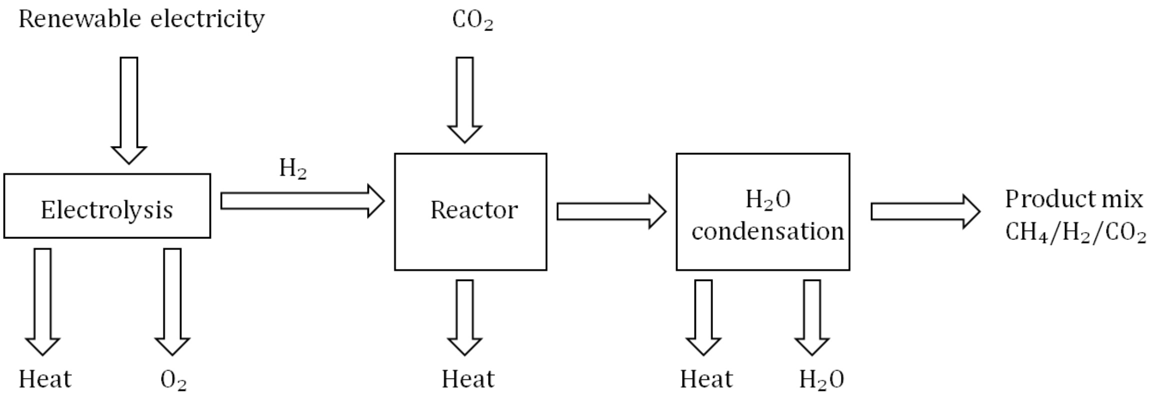

Figure 4 Flow scheme over the SBG production

An almost complete conversion of carbon dioxide to methane is theoretically possible due to the excellent equilibrium of the reaction. It is shown in Figure 5 that if it is possible to run the reaction close to equilibrium conditions at temperatures in the interval between 250 and 300 °C, more than 95 % of the carbon dioxide could be converted. Different research groups have conducted experiments, which verify the potential of the reaction and have obtained more than 90 % conversion (Van der Wiel et al. 2000; Lunde 1974).

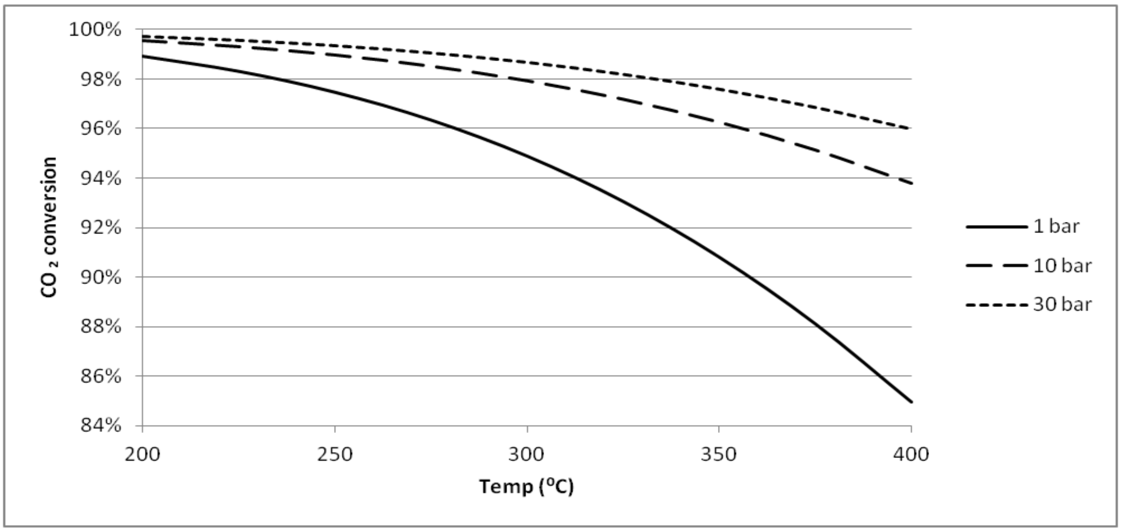

Figure 5 Thermodynamic equilibrium of the CO_2 fraction in the Sabatier reaction with CO_2:H_2 ratio of 1:4. Calculations done with (CEAgui).

However, to keep the reaction close to equilibrium, reaction conditions must be carefully balanced. Among other things reaction temperature, pressure, reactant flow, space velocity and catalyst must be taken into consideration. The catalyst is particularly important since it facilitates for the reaction to take place. In general various metals coated on supporting material (explained below) are used in the Sabatier reaction. Since it is an established reaction there are even commercial catalysts for purchase. Examples are rhodium, nickel and PK-7R (Haldor Topsoe). Some of the catalyst metals are noble and very expensive; it would therefore not be economically feasible to utilise these in pure form. Consequently, in such situations a catalyst support is normally used; a less costly material than the catalyst, which has a high contact area relative to its size. The active metal is then coated onto the surface of the support (impregnation) which results in a high exposure of the active metal, even though it only constitutes down to about 0.5 % of the total weight.

4.3.2 Synthetic methanol

The methanol synthesis uses the same reactants as the Sabatier reaction. The difference is, as seen in Eq. [2] in section 4.3, that it needs one H_2 less compared to the Sabatier reaction. This leads to only one water molecule as by-product, and in turn, less energy is converted to heat. Additionally, methanol as a fuel is liquid at NTP conditions which makes it easier to handle and distribute compared to biogas. So the question arises, why choose methane when methanol can be produced? One good reason is the equilibrium. As can be seen in Figure 6 the equilibrium is by far not as favorable as in the case of methane. The reaction requires very high pressures to obtain a fair conversion potential. Additionally, the reaction will probably need at least 200 – 300 ˚C to commence, hence the equilibrium is lowered even more. For example at 70 bar and 240 ˚C the maximum conversion of the CO_2 is only 30 %; the remainder stays as reactant. Due to unfavorable equilibrium, the risk for production of other compounds is also high.

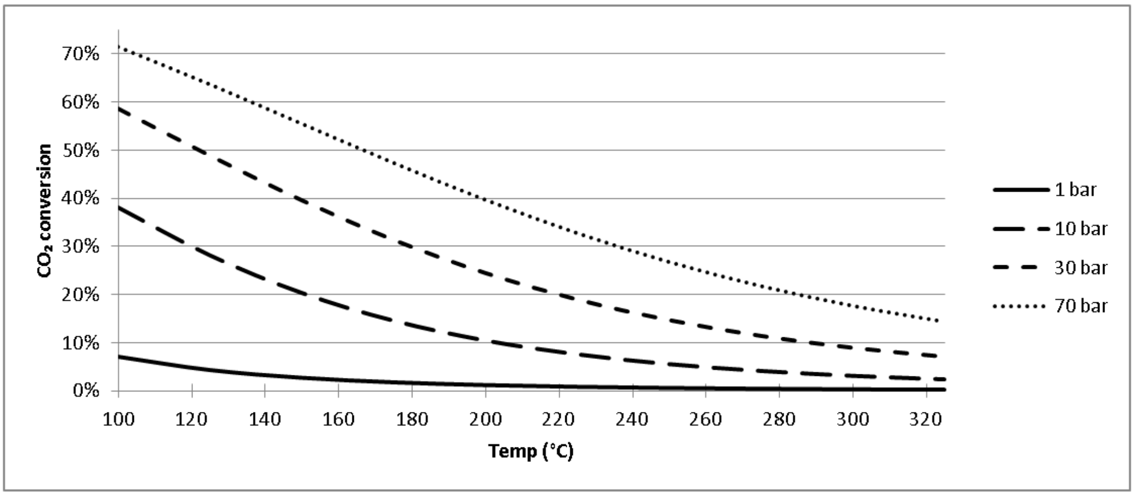

Figure 6 Thermodynamic equilibrium of the CO_2 fraction in the methanol reaction with CO_2:H_2 ratio of 1:3. Calculations done with (CEAgui).

A chemical reaction with such an equilibrium curve will need to be run at high pressures, and a recirculation stream which is "looped" several times will also be necessary before a high yield of CO_2 conversion can be obtained. This makes the process complicated and more difficult to design, handle and run compared to the suggested methanation process.

The difference between the equilibrium of methane and methanol is clearly shown in Figure 7.

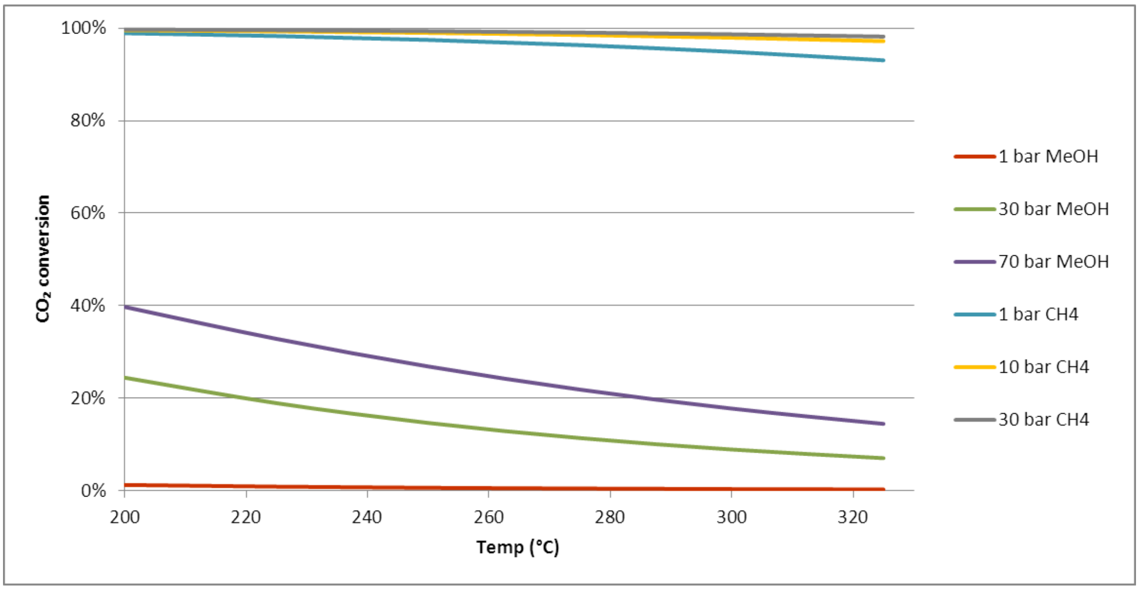

Figure 7 Comparison of the equilibrium between methane and methanol. Calculations done with (CEAgui).

5 Applications of synthetic biogas production

There are many applications where Power to Gas could be implemented. Principally, the most suitable integration possibilities are those which produce carbon dioxide as by-product, preferably with high concentration, due to energy losses in handling large amounts of inert gases. This chapter presents the potential of Power to Gas, if integrated in suitable processes. Digestion and gasification are two excellent alternatives and are exemplified in the following sections.

5.1 Synthetic biogas production combined with digestion

Digestion of organic material occurs when it is degraded without the presence of air. Basically any organic compound could be a subject for digestion and the most commonly used substrates on a commercial scale today are sewage sludge, agricultural waste, slaughterhouse waste and food and industrial waste. Before the waste can be sent for digestion it must be in homogenous form and is generally diluted with water before entering the digestion (ISAT and GTZ).

After digestion the resulting product becomes a mixture of mainly methane and carbon dioxide. Depending on substrate, varying amounts of other compounds are found as well, most often hydrogen sulphide and siloxanes (silicon compounds). In its original form, before any cleaning or other treatment, the product gas is called crude gas with a general composition, as shown in Table 2 (Nordberg 2006). The crude gas is cleaned of carbon dioxide and other impurities to increase the calorific value and make it suitable for combustion.

Table 2 Typical composition of crude gas from digestion (Nordberg 2006)

Component	Fraction range
Methane (CH_4)	45 – 85 %
Carbon dioxide (CO_2)	15 – 45 %
Hydrogen sulphide (H_2S)	0 – 2000 ppm
Siloxanes	Trace amounts
Ammonia (NH_3)	Trace amounts

Another aspect that must be emphasized is the yield of methane in relation to the amount of dry solids in the digestate. A survey including the most common substrates used in digestion (except sewage sludge), i.e. agricultural waste, slaughterhouse waste and food and industrial waste, show that between 0.16 and 0.63 m^3 methane/kg dry solid could be obtained with a mean value of about 0.36

m^3 methane/kg dry solid (Nordberg 2006). This figure can be increased substantially (by about 20 – 40 %) by using different methods prior to and during digestion. To mention a few, there are thermal pre-treatment, co-digestion and improved process control. These and additional examples are more thoroughly presented and discussed in paper II.

In vehicle applications the methane fraction is upgraded to about 98 ±1 %, while carbon dioxide covers the remaining part. In this way the biogas resembles natural gas (the main gaseous fuel in Sweden) in energy content and combustion. In other applications, e.g. town gas, the CO_2 fraction can be much higher, hence the CO_2 removal does not need to be as thorough as in vehicle application upgrading.

As can be seen in Table 2 quite a large fraction of the crude gas is carbon dioxide. Normally it is vented to the air after separation. If it is possible to use the carbon dioxide in synthetic biogas instead, the total methane production potential could be increased drastically. As has been mentioned in previously, high CO_2 conversion yields are possible to obtain due to, among other things, excellent equilibrium conditions.

Based on a general 5 MW biogas production facility, Table 3 exemplifies the potential increase in biogas output if applying process improvements and retrofitting with an SBG production which uses the CO_2 by-product.

Table 3 Increase in biogas production potential with process improvements and SBG production

Digestion	Output [MW]
Conventional process	5
Process improvements	1.5
SBG production	2.2
Total	**8.7**

In a typical digestion process, as exemplified above, the methane production capacity could be increased by about 44 % (or even more depending on carbon dioxide in the crude gas) if implementing the Sabatier process. Another 30 % could be obtained by using various process improvements. Considering the limitations in biogas potential, mainly due to limited amounts of raw material, it is highly valuable to be able to implement measures in order to increase the potential.

5.2 *Synthetic biogas combined with gasification*

The essence of the Sabatier process in terms of energy is that it uses hydrogen as an intermediate energy carrier, which binds to carbon dioxide to create methane.

This makes the Sabatier reaction an efficient way of storing hydrogen in a more energy-dense form. However, in some cases possibilities occur that hydrogen could be used in another manner with the same resulting product, i.e. methane. Such a possibility exists in gasification. If using hydrogen combined with gasification, the question is where in the process to use it for optimal effect. The following sections compare the introduction of hydrogen at the beginning of the gasification, i.e. hydrogasification, or at the end i.e. Sabatier reaction. A conventional gasification is first exemplified which will represent a reference case.

5.2.1 Oxygen blown gasification – "conventional" gasification

Gasification opens up the possibility of producing several different fuels from biomass e.g. methane, hydrogen, methanol and dimethyl ether (DME). However, no large scale gasification plant has yet been built; therefore a general process description is shown in Figure 8.

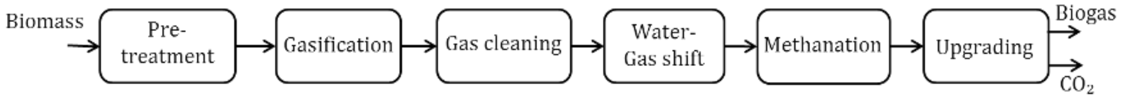

Figure 8 Principle scheme of an oxygen-based gasification

The pretreatment of biomass includes chipping and drying. In order to increase the energy density e.g. for long distance transport, the biomass could be pelletized or pyrolized. During gasification the biomass is thermally degraded, i.e. it is heated with air or pure oxygen which results in syngas formation and contains mainly carbon monoxide, hydrogen, carbon dioxide (and nitrogen if air is used). Gasification is suitable for operation in atmospheric conditions as well as pressurized up to 20-30 bar. In the following step impurities such as sulphur, tars and alkali metals are removed, mainly to reduce the risk of damage to the downstream equipment. Thereafter follows the water-gas shift reaction (WGS) which is shown in Equation 3. Here steam is added, which partially converts carbon monoxide to carbon dioxide in addition to forming hydrogen. This step increases the ratio of hydrogen in relation to carbon monoxide, which is important further on in the process.

$$CO + H_2O \rightarrow CO_2 + 3H_2 \qquad \Delta H = -41 \text{ kJ/mol}$$

Equation 3 The water gas shift reaction

In the following step the methanation reaction occurs and can be seen in Equation 4. In this step available carbon monoxide has been converted to methane and is followed by the upgrading, where mainly the methane is separated from the carbon dioxide.

$$3H_2 + CO \rightarrow CH_4 + H_2O \qquad \Delta H = -217 \text{ kJ/mol}$$

Equation 4 Methanation of carbon monoxide

5.2.2 Adding hydrogen to gasification

To increase the yield of methane from the same amount of biomass (or other organic material), it would be possible to add hydrogen at different stages of the gasification process. As mentioned, the hydrogen could be added either before (i.e. hydrogasification) or after (i.e. Sabatier) the gasification. These processes are presented in Figure 9 and Figure 10 respectively.

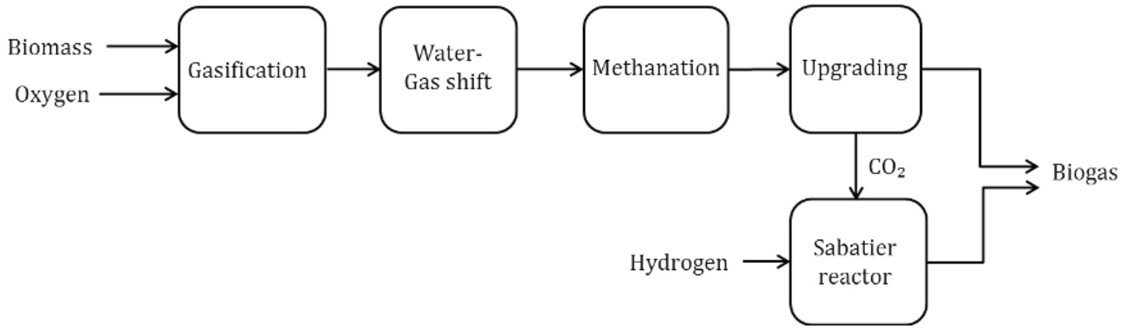

Figure 9 Flow scheme of oxygen gasification retrofitted with Sabatier reaction

The Sabatier reaction can be integrated in the upgrading, where the carbon dioxide could be converted to additional methane after adding stoichiometric amounts of hydrogen. Since large quantities of carbon dioxide are produced upstream in the process, using the Sabatier would increase the final amount of biogas significantly. Table 4 presents the potential increase in biogas production (input data for gasification from (Mozaffarian et al. 2004)).

Table 4 Increase in biogas production potential by using the Sabatier reaction (gasification input data from (Mozaffarian et al. 2004)).

Gasification	Biomass	H_2	CO_2	CH_4
In (mol)	100 (mol C)	-		
Out (mol)		0.7	54	36
Sabatier				
In (mol)		217	54	
Out (mol)		22	5.4	49
Total CH_4 out				**85**

The table presents a production capacity increase of about 136 % if integrating Sabatier to an oxygen blown gasifier. Additionally, it must be emphasized that there will be some unreacted hydrogen left in the product stream.

Hydrogen as gasification medium is an interesting alternative path of gasification and has been studied by among others (Mozaffarian and Zwart 2000). A principle scheme of such a process is shown in Figure 10.

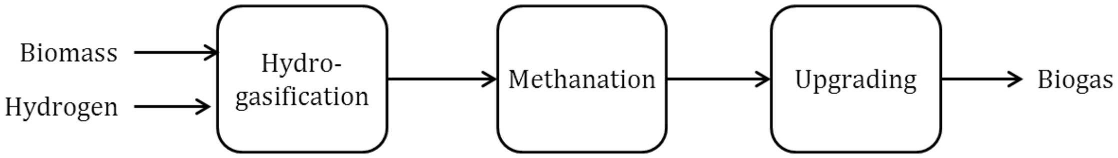

Figure 10 General scheme of a hydrogasification process

Besides hydrogen, carbon dioxide is fed in to the process as a measure of avoiding nitrogen in the system. Table 5 presents different feeds and the corresponding potential increase. Compared to producing 36 mol CH_4/100 mol input biomass as in conventional gasification (top section of Table 4), hydrogasification produces about 83 mol CH_4/100 mol biomass, an increase of about 130 %.

Table 5 Increase in of biogas production potential by using hydrogasification (Mozaffarian et al. 2004)

Hydrogasification	Biomass	H_2	CO_2	CH_4
In (mol)	100 (mol C)	178	12	
Out (mol)		8	8	83
Total CH_4 out				**83**

In Table 6 the energy balance for the different processes can be seen. However, it must be emphasized that the product gas contains hydrogen in addition to methane, which is combustible and increases the total energy in the product. Moreover, the hydrogasification has a higher feed of carbon (due to the supplementary inflow of carbon dioxide) compared to the others, which takes part in the methane formation. There is a flow of carbon dioxide in the oxygen gasification also, although in that system the carbon dioxide is re-circulated and does not add to the amount of carbon. The higher energy output from the Oxygen/Sabatier process is due to the higher amount of hydrogen in the product (about 20 mol-% in Sabatier and 8 mol-% in hydrogasification).

Table 6 Energy efficiencies for various synthetic methane processes. Oxygen gasification can be considered as reference. All values in LHV and biomass moisture content about 15 %. Gasification data from (Mozaffarian et al. 2004)

Synthetic methane production		Hydro-gasification	Gasification + Sabatier	Oxygen gasification
Input (MW)	Biomass	100	100	100
	Hydrogen	94.8	117.7	
Output (MW)	Methane (+ unreacted hydrogen)	154	165.9	66.3
Product efficiency		79 %	76.2 %	66.3 %
Hydrogen efficiency[1]		92.5 %	84.6 %	

[1]Hydrogen efficiency refers to the increase in fuel production compared with the amount of added hydrogen. In the hydrogasification case, 94.8 MW hydrogen is added, which increases the output by 87.7 MW compared to the oxygen blown gasifier. The efficiency is obtained by dividing the increase (87.7MW) by the added hydrogen (94.8 MW), 87.7/94.8 = 0.925.

The table shows that hydrogen would contribute slightly more in the hydrogasification compared to the Oxygen gasification/Sabatier process, which makes it beneficial when building new plants or industries. Sabatier on the other hand has the advantage of being flexible and can be used to retrofit various processes that have a CO_2 stream.

5.3 Other process integration possibilities of synthetic biogas production

Basically it would be possible to integrate the SBG production in any industry or facility where carbon dioxide is emitted. One key factor is to examine the added value of an SBG production before considering it as an option. Since the main product is methane it is desirable to integrate the SBG production in an existing methane production which has carbon dioxide as a by-product. Those alternatives are however relatively few, which makes it necessary to investigate other industries as well. Ethanol production using fermentation could be a suitable process since it is emits a concentrated and relatively clean CO_2 production besides ethanol.

Various combustion processes, e.g. biomass combustion, are also interesting sources of carbon dioxide. However, in flue gas from combustion, the carbon dioxide is often diluted with nitrogen since air has been used in the combustion. The flue gas also suffers from other compounds, e.g. particulates, SOx, and NOx. Such contaminants must be removed before they enter the SBG production since these would damage downstream equipment.

5.4 General process efficiency of synthetic biogas production

Depending on where Power to Gas is integrated, the complete processes will look different with different efficiencies. A general energy balance is illustrated with a Sankey diagram in Figure 11. The magnitudes of the flows are based on 1 MW of input electricity with a hypothetical CO_2 conversion of 100 % to simplify the diagram (a more realistic conversion would be 90 – 95 % but has little influence on the flow magnitudes). About 50 % of the input energy comes out of the process in the form of a fuel. The remaining energy is mainly emitted from the process in the form of heat.

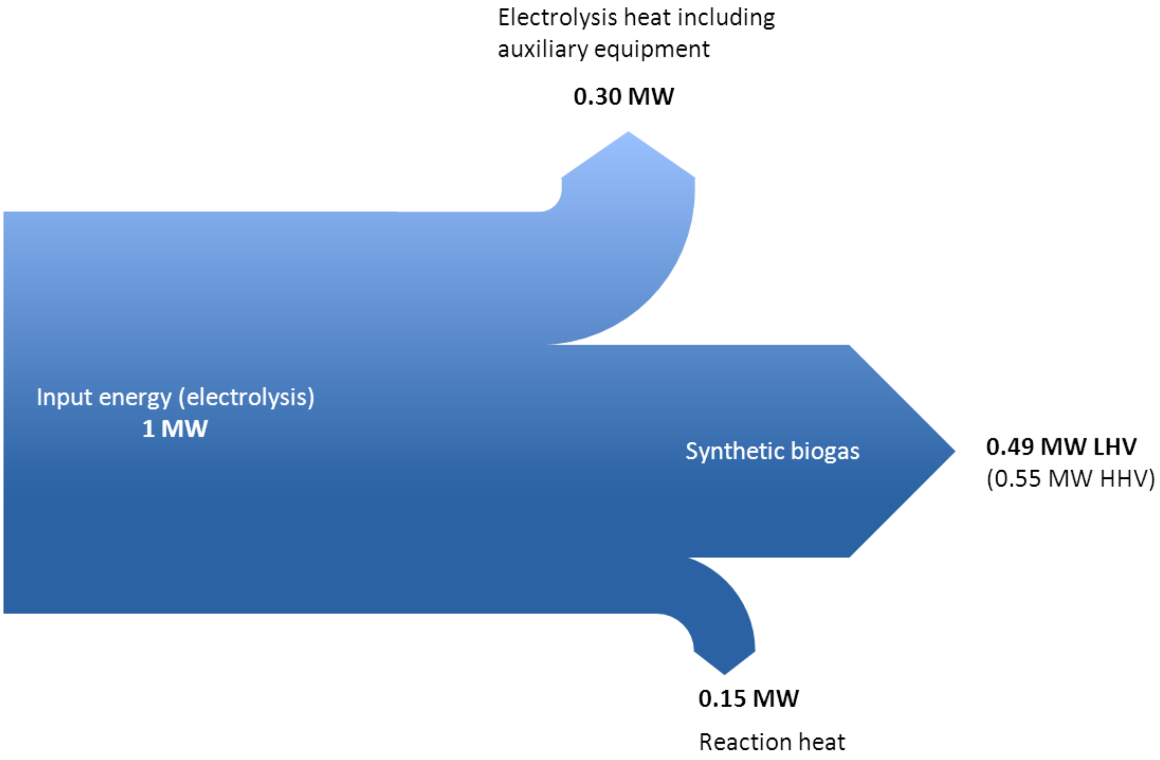

Figure 11 Sankey diagram of the Power to Gas concept

An electricity to fuel energy balance is not attractive if focusing entirely on the fuel production. However, to get the most out of the process, the heat, both from the electrolysis and from the reaction, should be utilized as well. It could most likely be possible to sell or be used in the facility's own process. In that case, the overall efficiency could be regarded as quite advantageous.

6 Economical perspectives of synthetic biogas

This chapter presents the economic possibilities and limitations of the Power to Gas-concept with Swedish conditions and addresses paper III. The economic viability is essential to analyze, and shows if synthetic biogas production is a realistic alternative to implement on a large scale or not. As a first step feasibility studies are often made to give an indication of the economics.

The process basically buys and sells energy, but at different prices and in different form; from electricity to biogas. Hence the biogas selling price must be much higher than the electricity purchase price per kWh; hence, a minimum "spread" must be obtained. This is mainly due to different losses during conversion of energy from electricity to biogas. The losses such as chemical conversion losses, heat losses and capital costs are added to the electricity purchase price and must be reimbursed. Thereafter there must be a marginal for earnings as well. The spread will very much depend on commodity prices, but could also be highly influenced by different taxation rules, subsidies or other political tools. If aiming towards a society with a greater focus on sustainability and renewable energy it is not unreasonable that these tools could be used in favour of such technology, as has been done with preceding green technologies. The calculations in the following sections are based on current laws and regulations but it must be emphasized that these could change with time.

This chapter makes a case study of a pilot scale plant of about 1.2 MW SBG production capacity. Firstly, relevant market conditions are analyzed and discussed, followed by the setting of the base scenario. Thereafter annual costs (cost of capital and running costs) and income are presented and it ends with a presentation of the final results. Since many assumptions are used and market conditions are highly uncertain in a long-term perspective, the results from the case study should be regarded as indicative.

6.1 Market conditions assessment

Knowing the market conditions is key and must be determined before being able to make an evaluation of the feasibility. As was mentioned in earlier sections the system boundary is set to Sweden. When the area is located, it is important to identify the different aspects that must be taken into consideration. In this case energy taxation, trends in fuel utilization, price trends of transportation fuels and GHG emission legislations are among the most important.

One tool commonly used by the government is taxation. Taxation is powerful and very effective when trying to set a path for any kind of implementation. For the SBG production it will have a significant effect and as the taxation is established today it works in favour of the process. In Sweden, energy is subject to additional taxation in addition to VAT; these are energy tax and CO_2 tax. They are set differently on different energy carriers. In terms of road transport fuels, petrol and diesel are subject to relatively high tax rates while those of renewable origin, e.g. biogas and ethanol, are relieved of both energy and CO_2 tax (in the case of ethanol the gasoline fraction is still taxed) (Swedish law on Energy Taxation 1994a). A more complete list of energy carriers and taxation levels is shown in paper III.

Regarding electricity, only the energy tax is comprised. However, almost all utilization forms are due to pay it except for some exceptions, of which some examples are listed below (Swedish law on Energy Taxation 1994a):

- Track-bound transport
- Metallurgical processes
- Electrolytical processes

The location of the process will have a substantial impact on the process' economic feasibility. Firstly, a market for the synthetic biogas must exist along with an available district-heating grid. As has been shown in earlier sections, the process has an excess production of heat. The main heat production takes place within the electrolyser, but production also occurs during the reaction. The electrolysis heat is about 80 °C and the reaction heat can be assumed to be about 300 ˚C. Heat from the reaction can be used to boost the electrolysis heat to about 100-120 ˚C. Such temperatures are ideal in for example district heating systems, which normally have a supply temperature in the same range. District heating is a common heating system in Sweden and consists of many "clusters" of grids, i.e. there is no national grid. The systems today have their limitations though, since grid owners and heat producers are normally the same company, which gives a kind of "natural monopoly". External companies who want to deliver heat have had problems getting access to the existing grid, also known as third party access (Swedish Government Official Report 2005). In this work, however, it is assumed that a current net owner will agree on the integration of the SBG production to the current grid. The main reason is that the offered heat has an advantageous temperature and that the net owner actually receives the energy as heat and not as fuel (while the calculations are based on selling the heat at the same price as fuel). This is assumed to be a sufficient incentive for the grid owners to grant access since they would increase their heat delivery capacity with high quality heat without needing to expand their source.

Oxygen is another by-product of the electrolysis and is produced when the water is split. Half the amount of oxygen gas is produced compared to hydrogen. The purity of oxygen is normally very high (> 99 %)(Hangzhou Fei Meng Import And Export Co.). It can be used in for example combustion applications or in hospitals.

Hence, a strategic location of the SBG plant is crucial for the economic feasibility since heat accounts for a large amount of the energy output of the process and will have a significant part of the total revenue.

6.2 Base scenario settings

A base scenario is set to give an indication of what prerequisites are needed to obtain an economically feasible process. For the suggested SBG production the main factors are electricity prices and biogas prices. However, the calculations show that the potential income from by-products will also have a significant effect on the total revenue.

The calculations are based on several variables that are set with reference values, as listed below:

- Expected plant lifetime: 15 years
- Required rate of return: 10%
- SBG price: 0.133 €/kWh
- Electricity price: 0.047 €/kWh
- Operation time: 8000 h/year

The variables are assumed to be set in reasonable and realistic ranges. More thorough discussions and arguments for the chosen values are further presented in paper III.

The case plant is designed to produce 1.2MW of synthetic biogas and according to the reference values total production reaches about 9.6 GWh/year.

Regarding the CO_2 feed to the plant, it is assumed to be of high purity and possible to use directly in the reaction. Different sources for such carbon dioxide could be from for example oxyfuel combustion processes, ethanol production processes or to some extent gasification processes.

6.3 Costs and sales revenue

The investment costs of the case study are based on information from manufacturers, literature data and cost estimation tools for chemical plants (Turton et al. 2003). The total investment cost for the plant, which includes electrolyser, reactor, planning, district heating connection and storage for the different gases amounts to 1.257 M€ (see Paper III for details).

The annuity method is used in order to calculate the annual cost of capital, i.e. to determine the time value of money and the depreciation of the equipment. In principle, a project could be considered profitable when the annual income (sales revenue – production cost) is higher than the annual cost of capital (which includes the required rate of return on investment). Table 7 (taken from paper III) presents the annuity for various interest rates and economic life expectancy of the process.

$$Annual\ cost\ of\ capital = C_{tot} \times \frac{i(1+i)^n}{(1+i)^n - 1}$$

n = expected economic lifetime

i = interest rate (required rate of return on investment)

Table 7 Annual cost of capital as a function of expected lifetime (n) and interest rate (i), values in k€

i / n	0.06	0.08	0.10	0.12	0.14
5	432	456	480	505	530
10	247	271	296	322	349
15	187	213	**239**	267	296
20	159	185	214	244	275

As can be seen in the table the annual cost varies substantially; the higher the risk the project poses the more expensive the annual cost of capital will be. In this work, it has been estimated that a required return on investment (ROI) of 10 % over 15 years is reasonable.

The annual running costs include all expenses that are needed to run the project. These comprise purchase of electricity, product distribution, water, catalyst and operational costs. Together they add up to 1.35 million € where the electricity alone accounts for over 1 million € if using base values. Hence, small changes in electricity price substantially affect the total running cost.

6.4 *Results*

The following section presents the final results of the economical evaluation in brief by showing some key values. A more holistic picture of the economical durability is described in paper III where among other things a sensitivity analysis is made which includes variations of electricity and gas prices.

The total annual income (which includes income from sold synthetic biogas, heat and oxygen) is estimated to be about 1675 k€ with a surplus of 84 k€ after production costs and capital costs are paid. The total amount represents the full length of the bar in Figure 12. It is divided into different items to give an overview of how much each comprises.

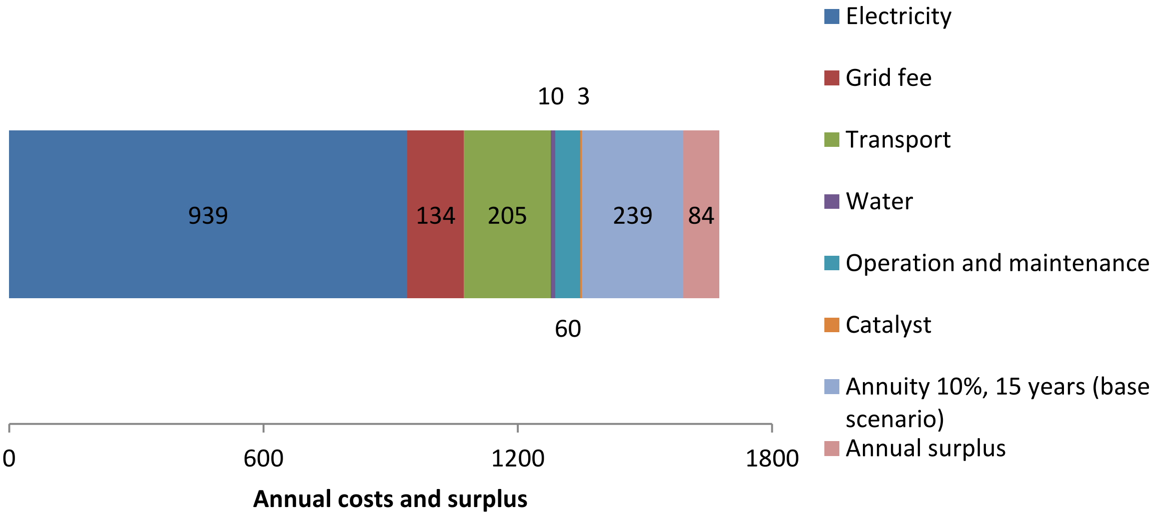

Figure 12 Annual costs and surplus before income tax (k€)

As mentioned, heat and oxygen are crucial for the economic survival of the process and they account for 154 and 293 k€ respectively. Together they constitute about 25 % of the total income.

The figure uses base scenario settings, hence the annual surplus would change significantly if fluctuation occurs in the different variables, e.g. electricity price or gas selling price.

The electricity is the single most important item. Hence, it will have the greatest influence on feasibility among the alternatives on the cost side. In the base scenario 8000h per year is assumed, but it would also be possible to run the process fewer hours if cheap electricity could be obtained. Figure 13 presents the break-even electricity price as a function of the annual operating hours.

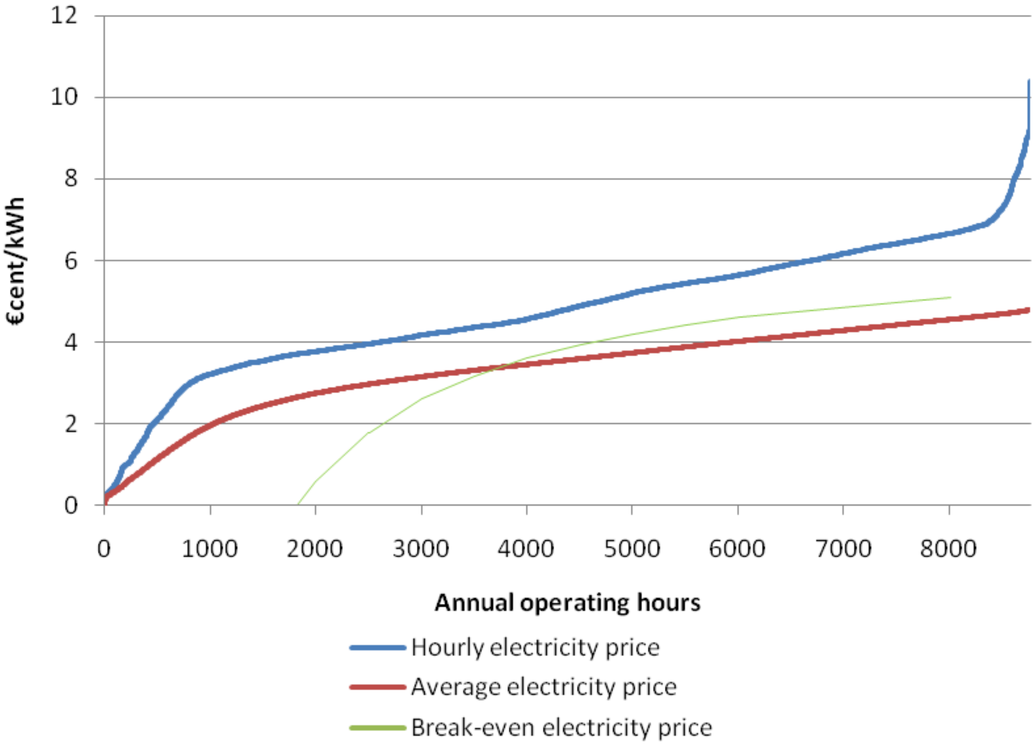

Figure 13 Duration diagram of electricity prices 2011 and break-even electricity price as a function of annual operation time (15 years, 10%)

At around 4000 hours it is theoretically possible to reach a break even, if it is possible to run the electrolysis during the cheapest 4000 hours of the year. Since it is probably not possible to match the cheap hours with the electrolysis it is reasonable that somewhere between 5000 – 6000 hours is the minimum operating time needed to reach at least break–even.

Using the base scenario values calculations be made to obtain an indicative figure of the minimum spread between bought kWh in form of electricity and sold kWh in form of biogas. According to the calculations the synthetic biogas must be sold at a price about 2.6 times higher bought. If doing so, breakeven will be reached where the synthetic biogas (and by-products) income covers all expenses including the cost of capital.

7 Reflections and discussions

The energy supply to the global transport sector is obviously a key issue that must be solved in terms of CO_2 mitigation. However, it is very difficult to determine how this can be done. One problem may be that we will have to replace fossil fuels(!). Fuel derivates from crude oil such as petrol, diesel and LPG are excellent products for energy storage, distribution and usage. Fossil fuels are dense in energy and cheap to obtain, which is the main reason for their success. It is interesting to reflect over how cheap energy actually is and to put it into perspective. For instance, 1 kWh of energy (corresponding to about 0.1 litres of gasoline) costs only about 10-15 €cent. The corresponding work that could be done with 1 kWh is to lift a small car from ground level to the top of the Eiffel Tower. Thanks to such qualities of accessibility and cheap cost, living conditions have improved vastly for people since fossil fuels' fullest potential were revealed. To a large extent society´s growth and progress is dependent on such products and have leant on these for many decades. Today fossil products are extremely well-founded. Hence, trying to switch from a fossil- based society to a renewable-based society will take time.

At the other end, current usage of renewable energy is expanding fast (compared to half a century ago) in several countries. Increased shares of renewable energy in all sectors are goals that have been set by many countries and in international collaborations between them. Among the alternatives in power production, wind power is growing most aggressively. Solar power is also growing fast, especially since prices for PV's have fallen drastically over the last couple of years. Other alternatives such as wave energy and solar thermal energy are also attracting increasing interest. Many of the renewable alternatives are quite often intermittent. And with a high penetration of intermittent power it is necessary to have well-founded regulatory power for times when intermittent power production is low. As a complement, energy storage capacity is also necessary, but during times with high power production.

In road transport, alternative fuels as well as various electric solutions are emerging and will probably have a large impact on the sector. An electric motor has many advantages compared to an otto motor; for example it has a high tank to wheel (TTW) efficiency, it has no local emissions and it is quiet. However, using electricity as energy carrier has proven to be complicated in most road applications. The battery is one of the main issues, and still needs much research and development. Today´s batteries are heavy in relation to their storage capacity, making vehicles very heavy if energy capacity is desired for a longer range. Lithium-ion batteries are expected to dominate the market for vehicle applications in the future (Becker et al. 2009). Roughly, a high-power lithium-ion battery that contains 50 kWh of energy (corresponds to about 5 litres of gasoline) weighs about 500kg (Campanari et al. 2009). Since it has a higher TTW efficiency it only needs about one third of the energy that is needed in a corresponding petrol driven car (Hjalmarsson et al. 2011), but it would still be too heavy to be practical in a passenger car, especially if it should be possible to drive long distances.

Another possible route to integrate electricity in the transport sector is to create a "physical" propellant via electricity by synthesizing fuels. In this work hydrogen, synthetic biogas or synthetic methanol are suggested and compared. These have different qualities and advantages. Their physical characteristics are presented in Table 8 where they are put against each other and conventional fossil fuels. In the table it can easily be distinguished what purpose would be suitable for each fuel.

Table 8 Lower heating value of various fuels and phases

Energy carrier	Phase	LHV per weight (kWh/kg)	LHV per kmol (kWh/kmol)	LHV per vol (kWh/m^3)
Hydrogen (NTP)[2]	Gas	33.6	67.2	3
Hydrogen (200 bar)[2]	Gas	33.6	67.2	600
Hydrogen (- 273 °C)[3]	Liquid	33.6	67.2	2360
Hydrogen (MgH_2)[4]	Solid	2.5 (kWh/kg Mg)		3650
Methane (NTP)[2]	Gas	13.9	222.9	10
Methane (200 bar)[2]	Gas	13.9	222.9	2000
Methane (- 162 °C)[3]	Liquid	13.9	---	5800[a]
Methanol (STP)[3]	Liquid	5.6	179.2	4420
Ethanol (pure)[5]	Liquid	7.5	343.5	5900
Gasoline (pure)[6]	Liquid	12.1	---	9100
Diesel (pure)[6]	Liquid	12.0	---	9800

[a]LNG instead of pure methane

Firstly, hydrogen as a propellant is interesting since its production only requires one conversion step (electrolysis), which keeps energy losses relatively low. Many countries in Europe are collaborating and several infrastructure projects based on hydrogen are being developed on national level and on EU level. Hydrogen can be used in otto engines and in fuel cell vehicles driven by an electric motor. However, hydrogen has low energy content per volume compared to for example methane (in the corresponding aggregation phase). Even hydrogen stored in metal hydrides,

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[2] Ref: Wester, L. 2003

[3] Ref: Amrouche et al. 2011

[4] Ref: Sakintuna, Lamari-Darkrim and Hirscher 2007

[5] Ref: SPBI (Swedish Petroleum and Biofuel Institute)

which contain about 55 % more hydrogen per volume compared to liquid hydrogen (Sakintuna, Lamari-Darkrim, and Hirscher 2007), cannot match liquid methane.

Another issue with hydrogen is the compression effort before storage. Depending on what type of compression is used, i.e. adiabatic, multistage or isothermal, the energy needed will vary significantly. However, to simplify the matter, the compression effort in this case is described using an adiabatic compressor. Figure 14 compares the difference in specific energy need between hydrogen and methane for an adiabatic compressor and is calculated with the adiabatic compression equation for gases greatly exceeding their boiling temperatures (Bossel 2006). For instance, looking at the gases compressed to 200 bar, for hydrogen the compression effort accounts for almost 12 % of the energy content of the gas. The corresponding figure for methane is about 3 %.

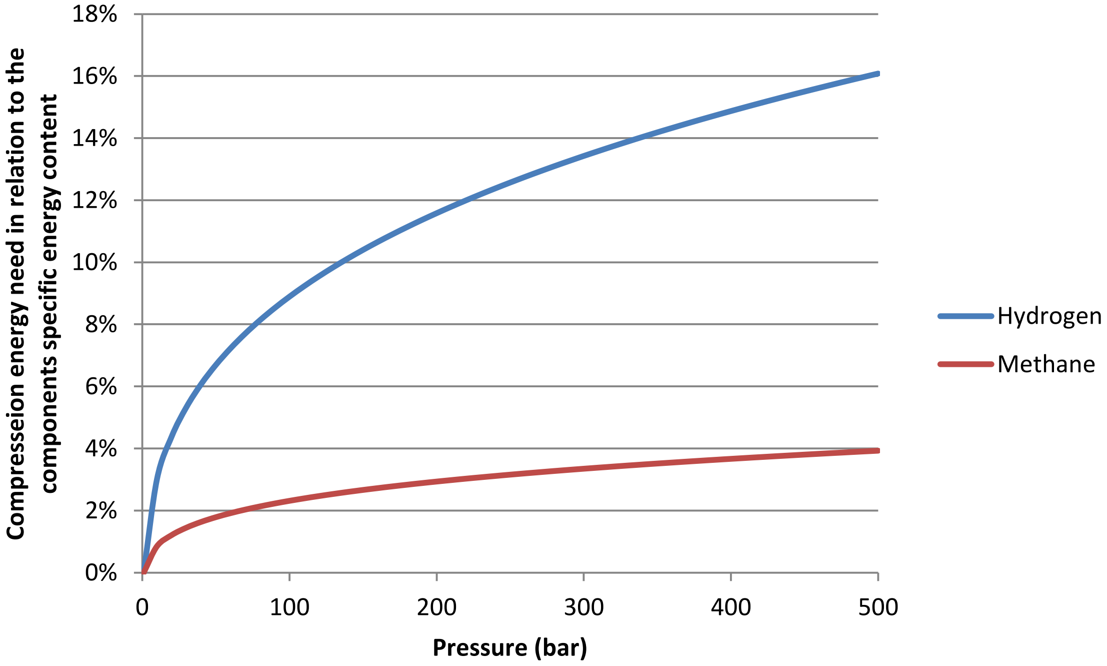

Figure 14 The compression energy need in relation to the components' specific energy content for hydrogen and methane. Calculations based on adiabatic compression.

However, in energy per weight ratio, hydrogen is superior to the other alternatives. Hence, hydrogen would be an excellent fuel in stationary applications where storage volume and weight is not a limitation.

As an energy carrier in mobile applications, methane should be considered more advantageous than hydrogen in general terms. Methane is relatively energy-dense when compressed (shown in Table 8). As a propellant methane is commonly applied in form of vehicle gas[6]. It is used commercially and has an existing distribution grid, mainly in the southern parts of Sweden and in Stockholm. It is normally used in otto engines, but it could also be used in methane/diesel blends. Moreover, it is relatively easy to synthesize due to the simplicity of the molecule structure and the reaction has a beneficial equilibrium towards the product, which yields high conversion rates.

Methanol has the advantage of being liquid at NTP compared to the two preceding fuels, hence containing much more energy per volume. It has similar combustion properties to ethanol and it could basically be used in the same engines as today's ethanol engines. SAAB's ethanol engines were first developed for methanol but were later relabelled "ethanol engines" with only minor modifications on the original engine (Bergström 2007).

Regarding its synthesis, the reaction is similar to the Sabatier. However, since it has an unfavourable equilibrium, it is more complex to produce. In a single pass, only a small fraction of the carbon dioxide will convert to methanol, hence the process needs to recirculate the reactants a couple of times before reaching higher levels of conversion.

One core issue when synthesizing fuels is the supply of energy. What kind of energy should be used to make it worth the synthesis? It is difficult to determine exactly what energy source will be used when running the electrolysis. In a purely fossil-based energy system, the synthetic fuels would obviously not contribute anything to CO_2 mitigation since fossil carbon is emitted at the source. It is mainly of interest in systems with high shares of renewable energy or where high penetration of intermittent power exists. During periods of excess power production, electricity is sold at lower prices. Even negative prices have occurred in for example Denmark and Germany. These and many other countries are planning for increased shares of wind power and solar power (mainly PV) in their system, which opens up for even more situations of a similar kind. Using electrolysis should be considered useful in grids with limited transmission and/or as a regulator since plant flexibility is often limited.

If synthesizing fuels beyond hydrogen, such as methane and methanol, another matter that arises is the carbon used in the process. There are many possibilities of where carbon could be obtained, e.g. from combustion processes in heat and/or power production, as a by-product in chemical or biotechnical processes or from air to mention a few. Which source of carbon is then considered "CO_2-lean", could it be carbon dioxide from a coal fired plant or must it originate from a biomass-based

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[6] Vehicle gas is a common term that normally contains a blend of natural gas and biogas. The pricing/Nm^3 is normally set depending on the amount of energy in the gas.

process? Wherever it comes from it must be remembered that the carbon will be emitted eventually, when the synthetic fuel is burned.

A biomass-based process, e.g. combustion of biomass or carbon dioxide as by-product from anaerobic digestion, is obviously no problem to use from a CO_2 mitigation point of view. However, if the source is fossil, some factors must be taken into consideration and discussed.

Basically, the usage of fossil carbon dioxide can be viewed from two more central perspectives. Firstly, it could be reasoned that since the carbon dioxide is basically emitted to the atmosphere it should be comparable to carbon dioxide “taken from the air” and therefore be seen as climate neutral. It was being emitted anyhow, and using it for another purpose before “final” emissions does not account for any net contribution.

Another viewpoint is that the fossil carbon dioxide takes a longer path, a “detour” via synthetic biogas but still released to the atmosphere, hence it is still fossil. However, it is reasonable to argue that it has at least reduced its level of “fossility” since the carbon has been used twice before being emitted, and has thus reduced the need for “new” carbon. In cases where the carbon is to be taxed, a more “fair” tax model should be applied.

Having obtained the synthetic fuels, they can be used in a more energy-efficient manner than in otto engines, namely fuel cells. Fuel cells utilize physical propellants to create electricity, which could drive an electric motor. There are different kinds of fuel cells, for example proton exchange membrane (PEM), alkaline (AFC), molten carbonate (MCFC) and solid oxide (SOFC). Fuels that are common in such fuel cells are as mentioned earlier hydrogen, but also methane, methanol and other hydrocarbons. Today these reach efficiencies up to 60 % (U.S. Department of Energy 2011a, U.S. Department of Energy 2011b). The discussion regarding fuel cells and hydrogen economy was lively in the middle of the last decade. However, it lost attention with time. It is not unlikely that fuel cells will again be up for discussion, but this time together with other fuels with higher energy density. If using fuel cells in vehicles that run on e.g. methane, it would be possible to get the best of two worlds; an energy dense fuel combined with the efficiency of an electric motor. Such technology exists today but is not used in a commercial scale. Together with locally produced biogas, the technology has the potential to be a key component in a future self-sufficient transport.

Other storage technologies like Compressed Air Energy Storage (CAES) and Pumped Hydro Energy Storage (PHES) will most certainly have a role to play in the future. However, these alternatives are dependent on certain prerequisites, mainly geological, and are not universally applicable. Hence, if lacking right conditions, a more flexible energy storage system must be used. Synthesizing methane through

Power to Gas is an alternative that is, not only flexible, but also applicable in large scale. The electrolyser could be placed near the site where hydrogen is needed to avoid long transport distances.

From an energy systems point of view, Power to Gas is an interesting solution due to its flexibility. The energy stored as synthetic biogas could be used either in the transport or in the stationary sector. It could be argued that the gas is more beneficial in the stationary sector, since efficiencies are higher in e.g. CHP plants than in otto engines. However, one matter that is going to play an important role is the transportation and/or distribution of the synthetic biogas. If the synthetic biogas production (which most probably is placed near the CO_2 source) is located far from a gas-fired power plant, the effort and cost of bringing the gas to the plant could be relatively high compared to selling the biogas locally as a vehicle fuel.

8 Conclusions

The transport sector faces many necessary changes in the future, whether we like it or not. In the short term, because leaders of nations around the world have agreed that we need to do something to minimize anthropogenic impact on the environment. In a longer perspective, because fossil resources are limited and will one day be too expensive for the majority of the population. Essentially, one day we will have a deficit of fossil energy. The main issue is how one relates to coming changes. Are they of a negative or a positive nature? Are we going to live exactly as we have done in the past or are we going to adapt our way of living (in this case transportation)? Today, a full tank of petrol in Sweden costs over 1000 SEK (about 110 €) and is starting to be a considerable amount of a household's economy if they fill up at least twice a month. In recent years, oil and gas prices have risen considerably, and the trend is still in an upward direction. In addition, the government is increasing taxes on fossil fuels. Development in recent years has therefore become a reminder that perhaps it is time to rethink and reevaluate things that we have taken for granted for a long time. It actually costs quite a lot to use a car today compared to a couple of years ago.

The increasing prices of fossil fuels could in a near future create an opportunity to introduce new technologies to the market with a chance to compete with existing products. One example is synthetic fuels, in this case synthetic biogas, which is interesting from many perspectives. Primarily, synthetic biogas can be produced within country borders. The capability to produce its own fuel would be highly advantageous for most countries or regions in terms of security of supply. The presented process could be a potential contributor to reach such a goal.

Synthetic methane production through Power to Gas is possible to introduce commercially in a relatively short period of time. This can be achieved since all parts in the SBG production are known technologies and are accessible on the market. Additionally, methane is a well-established energy source and distribution systems already exist. The process is highly dependent on electricity and fuel prices. In Sweden, it is predicted that there will be a surplus of electricity in the future (Swedish Energy Agency 2011d) which opens up for relatively stable prices. In addition, there are increasing trends in fuel prices. Hence, it should be possible to produce synthetic biogas in Sweden with good economic viability in the future.

Biomass is today used as the main source in production of renewable fuels but it is by far not sufficient to alone supply the energy needed in road transport. Hence, synthetic biogas is a possible replacement or complement. As opposed to biofuels, synthetic fuels are not dependent on land area. In principle, they could be produced anywhere as long as electricity and carbon dioxide are available.

Finally, Power to Gas presents a unique possibility to produce renewable fuels in large scale and will probably have a key role in future transport.

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