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Biogas as an option for industrial applications

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Abstract: Biogas is typically burned to produce electricity, or used as vehicle fuel. This case study analyses possibilities to utilise biogas directly in industrial applications to replace current fossil raw materials. True industrial cases are analysed by considering economic impacts of using either landfill gas or gas produced from biomass. Utilisation of biogas is economically viable and technically possible. However, for biogas to be an economical alternative as a raw material, investment supports for biogas production and farming subsidies are required in the same manner as currently for food production. Landfill gas is a real option for large landfills or small industrial needs.

Keywords: renewable energy; biogas; landfill gas; synthesis gas; farming; chemical industry; sustainability.

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1 Introduction

The global discussion on climate change and the effects of carbon dioxide emissions derived from fossil energy has lead to a new environmental thinking and legislation (e.g. White & Sulkowski 2010; Gallucci et al., 2010). The use of renewable energy instead of fossil energy is currently seen as an essential way to reduce the green house gas emissions (United Nations, 1997; Hoffert et al. 2002; IPCC, 2008). The nature produces some 200 billion tons of biomass through photosynthesis per year, out of which only 3-4 percent is utilised by humans (Jenck et al., 2004). Biomass is a sustainable source of energy for producing steam, fuel and chemicals when the bio-energy chain is such that there is climate neutrality and efficient recycling of nutrients (Reijnders, 2006). The traditional use of wood as fuel is not considered sustainable as only the heat component is utilised. Co-generation of electricity and heat is preferred as the full potential of raw material is better exploited this way. Agricultural and forest residues and solid waste can also be used for producing transportation fuels. (Goldemberg & Teixeira Coelho, 2004). Biomass has potential significance in the future global energy supply, regardless of whether it is considered from the viewpoint of climate change. However, expanding bio-energy sector can potentially interact with other land uses, such as food production, biodiversity, soil and nature conservation. (Berndes et al., 2003).

There are many ways to convert biomass into energy, while the form of utilisation depends on the applications (e.g. McKendry, 2002; Demirbas, 2005). Biogas is one of the fastest growing means to produce bioenergy. Biomass containing large quantities of water can be converted to usable energy, biogas, mainly methane (CH_4) and carbon dioxide (CO_2) by using microbes through anaerobic fermentation (Pimentel, 2002). Fermentation does not require the raw material to be dry. Anaerobic fermentation can also be seen as a waste management system and an energy recovery process for sewage, industrial sludge and waste water (Green & Byrne, 2004). The European energy production from biogas was 8.3 Mtoe in 2009 and the production of electricity was 25.2 TWh. The fast growth of biogas production is based on European Union policies: Renewable energy directive that is aiming for a 20 % renewable energy share in gross final energy consumption by 2020 and Directive on landfill of waste that requires member states to reduce the amount of biodegradable waste disposed of in landfills and to implement laws for waste recycling and recovery. (EurObserv'er, 2010). In the world, Germany is the leading biogas producer with enormous development of agricultural biogas plants on farms (Weiland, 2010).

Biogas can originate from landfills, from wastewater and industrial effluents or it can be produced in purpose-designed methanation plants. Methanation units locate in farms, industrial food processing plants. Germany produces over 80 % of its biogas, 4200 ktoe, using purpose-built methanation plants whereas Finland has practically no purpose-built production but 30 ktoe landfill and 11 ktoe sewage sludge gas production (EurObserv'er, 2010). The legislation in Germany encourages biogas production by providing feed-in tariffs, additional payments for the use of energy crops, and investment supports (Hahn et al, 2010). Currently, in Finland, biogas has not been under focus as discussion has concentrated on wood biomass. The national target is to increase the use of purpose-built biogas by 0.7 TWh/a before 2020. Noteworthy is that biogas is not a major energy source for electricity or fuel production in Finland. (Finnish government, 2008).

One tangible option is to look for applications where fossil based energy consumption is replaced and where wood biomass is not a practical alternative. Chemical, process, and mining Industries currently using carbon monoxide or hydrogen as raw materials, are potential significant consumers of biogas. The literature has a number of general articles on the use of biogas as a fuel for producing energy (e.g. Weiland, 2003;

Murphy et al., 2004; Abraham et al., 2007) . However, tangible industrial examples are scarce.

This study analyses industrial cases where fossil based raw materials can be locally replaced by biogas alternatives. The analyses concentrate on considering economic impacts of such replacements. The above discussed can be condensed into the following research questions:

RQ 1 Does biogas have potential of being an alternative as raw material for industry?

RQ 2 Is biogas an economical alternative to be used as raw material?

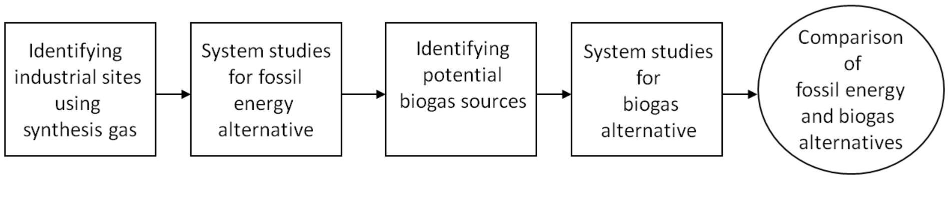
These questions are answered by analysing tangible industrial examples in Northern Finland.

2 Methodology

The purpose of this study was to examine the idea of the use of biogas as a raw material in industry in northern Finland. The study was geographycally restricted to the area of Northern Ostrobothnia and Kainuu.

The methodology of the research is illustrated in Figure 1.

Figure 1. Research process



The first action was to identify industrial sites using fossil synthesis gas or hydrogen as raw material by analysing the environmental permits granted by authorities. The production processes are well described in the permits. To make the analysis it was necessary to study how the systems found at the present moment work. Then it was studied whether there are suitable biogas sources or any potential for the start up biogas production near the identified industrial plants. The existing biogas production sites were also sought from the environmental administration register and by using Biogas plant register of Finland (Kuittinen et al., 2010) and Bioenergy plan for Kainuu (Karjalainen, 2010). The fourth action was to estimate the viability of the biogas alternatives. The fifth action was to compare the fossil and biogas alternatives. It was calculated whether biogas is economically viable both for biogas producers and for the industry.

3 Current state analysis

There are a total of 262 environmental permits for industrial and municipal sites in the studied area. Five industrial sites were identified as potential cases for replacing the raw material of synthesis gas or hydrogen by biogas. These sites include Ruukki steel mill, Eka Chemicals' hydrochloric acid plant, Kemira's formic acid plant, Kemira's hydrogen peroxide producing plant, and Talvivaara mining's hydrogen plant. Appendices 1 and 2 provide more detailed information on the studied cases.

Ruukki steel mill produces gases containing methane, carbon monoxide and hydrogen as by-products and utilises them for energy production. Eka Chemicals produces hydrogen as a by-product in sodium hydroxide production process and utilises it for energy and hydrochloric acid production. As these two producers produce the gases as natural by-products, there is no real motivation to replace the existing gas production. On the other hand, Talvivaara's hydrogen plant and Kemira's formic acid and hydrogen peroxide plants produce their gases from fossil raw materials (Environmental permission office of northern Finland, 2007; Environmental centre of northern Ostrobothnia, 2007), making these processes interesting for this study.

3.1 System study, case hydrogen from propane

According the environmental permit, Talvivaara mine produces annually 4000 tons hydrogen by using steam reforming process requiring 15 000 tons of propane as raw material. Hydrogen is further used for producing hydrogen sulphide.

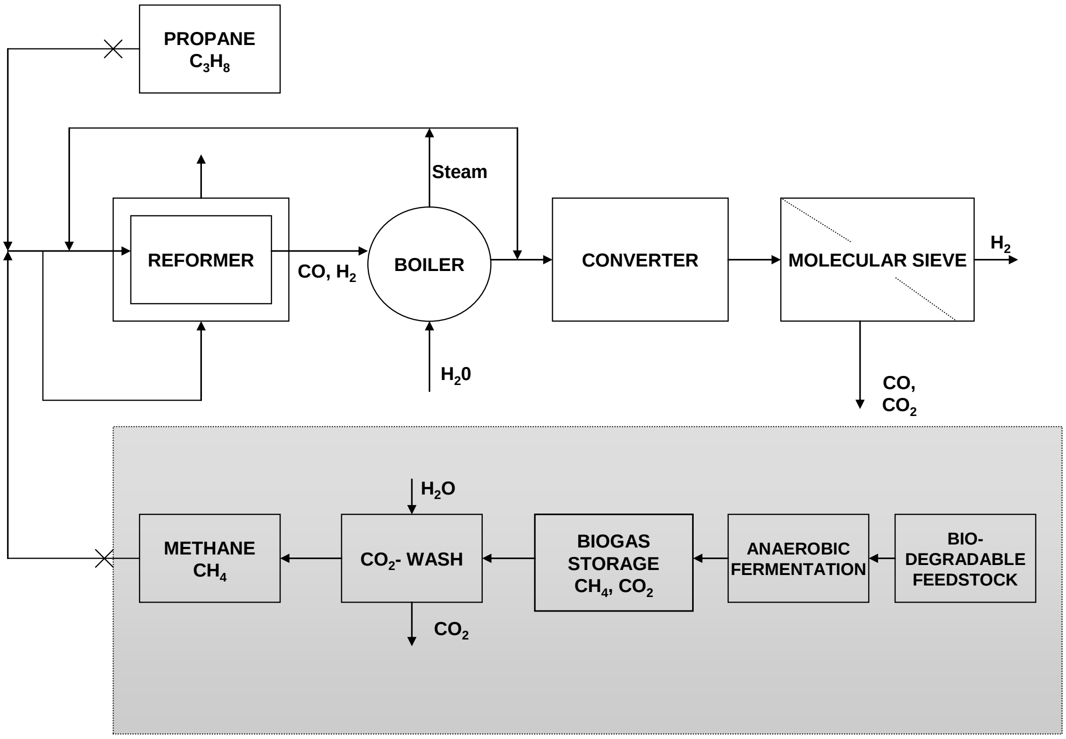
The main reactions in Talvivaara mine production process in reformer and in converter respectively:

$$C_3H_8 + 3H_2O \rightarrow 3CO + 7\ H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

Figure 2 illustrates the existing hydrogen production system, derived based on the environmental permit (without shading) and a biogas alternative (shaded in grey) constructed in this research.

Figure 2. Hydrogen from propane or from biogas



3.2 System study, case 1: substitution of propane with biogas

In steam reforming it is possible to use different hydrocarbon feed stocks in the reactor. Changing from heavier to lighter hydrocarbon, e.g. from propane to methane, does not require significant modifications in the reformer. However, some minor problems may occur, e.g. in the form of coking of the catalyst if process parameters are not tuned to a new feedstock. (Holladay, J. D. et al., 2009; Turpeinen E. et al., 2008; Shu-Ren, H., 1998).

Using biogas methane as a raw material in reforming would result in the main reaction being:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (3)$$

One mole of propane produces 10 moles hydrogen and one mole of methane produces 4 moles hydrogen. Consequently, 2.5 times more methane is needed compared to propane when calculated in moles. Also, considering the amount of energy needed for heating the system, it can be calculated that yearly roughly 19 million Nm^3 (2300 Nm^3/h) of methane needed to ensure 8500 running hours.

Currently there are no significant biogas production sites near Talvivaara mine. However there are plenty of farms in proximity that could potentially provide the required biogas. The biogas could be produced from grass, silage, willow, or reed canary grass (RCG). RCG is considered as one of the most interesting alternatives for a feed stock for bio fuel production in Finland (Paappanen et al., 2008). There are some 30 000 hectares of unused fields near Talvivaara site that could potentially be used for producing the required crop (Karjalainen, 2010).

According to Seppälä et al. (2009) one hectare of land can produce about 2500 Nm3 CH4 in Finland but also figures above 3000 Nm^3 CH_4 have been presented (e.g. Lehtomäki, 2006; Paavola 2007). However, several studies indicate that heat energy needed in the production, purification and pressurisation of biogas results in the loss of 15 – 25 per cent out of theoretical maximum (e.g. Persson, 2006; Murphy & Power, 2009). Using 20 % reduction results in net gas production of 2000 Nm^3/ ha that is used in this study. Talvivaara’s annual need of 19 million Nm3 CH4 can thus be served by a cultivation area of 9500 hectares, when RCG is used as the crop.

Economic impact of replacing propane by renewable biogas can be calculated as follows. The overall cost of biogas production results from the costs of biomass delivered to site, capital costs of the biogas plant and operational costs. The possible annual advantage of replacing propane by methane:

Advantage = cost of propane – cost of biomass – capital costs – operational costs (4)

Cost of propane = consumption of propane x price of propane (5)

Cost of biomass = crop yield / hectare x cultivated area x price of crop / MWh (6)

Capital costs are scaled using three real German cases and their investments costs as a starting point (see equation 7 below). Investment costs are converted into annual costs with the annuity method by using 10 % rate and 20 years service life.

This study estimates the *operational costs* for a biogas plant to be 10 % of the unsupported investment costs following the principles of Smyth et al. (2010).

Price of propane for Talvivaara in 2010 is 700 €/t (Neste Oil, 2010) and the estimated consumption is 15 000 t/a (The Environmental permission office of Northern Finland, 2007).

The crop yield of RCG used in the calculation is 30 MWh/ha when used for heat production in boiler houses (Vapo, 2010).

The market price of RGC is near the price of peat in Finland, around 9 € / MWh (Pahkala et al., 2005). According to Paappanen et al. (2008) the price of RCG for farmer should be between 3 – 9 € / MWh when taking farming subsidies into account. Without these subsidies farming RCG is not feasible. As energy prices can be forecasted to increase, and in order for RCG farming to be viable, figures of 6 and 12 € / MWh have been used for RCG in this study.

The capital costs of biogas plant have to be taken into account in calculations. In Germany three biogas investments of the same magnitude and type have been made during the last years for methane production capacities of 15 million, 10 million and 5 million normal cubic meters per year and investments costs of 31.5 M€, 21 M€ and 10 M€ (Weltec Biopower, 2010; TheBioenergySite News desk, 2009a; TheBioenergySite

News desk, 2009b) respectively. Typically in industry, costs for new investments can roughly be scaled from a known case using formula (Green & Perry et al, 2007):

Investment cost = A x (B / C) exp D, (7)

where A is the investment cost for a known case

C is the capacity of the known investment

B is the capacity of the investment to be estimated

D is a case specific exponent.

When analysing the three example investments mentioned above, it was found that , the exponent D was near 1. In order to clarify the impact of varying D, this study includes calculations with D values of 0.5, 0.75 and 1. Government has a policy to support the use of renewable energy, e.g. supporting related investments. In this study, investments are assumed to receive a maximum state subsidy of 40 % (Ministry of employment and the economy, 2001; The council of state, 2002) thus the net capital cost for the investor would be 60 per cent of the total.

3.3 System study, case 2: synthesis gas production from heavy fuel oil

Kemira produces synthesis gas for formic acid (FA) and hydrogen peroxide (HP) in Oulu. Currently this is done by using two oil gasifiers. One of the gasifiers is in use while the other is idle. (Environmental centre of Nothern Ostrobothnia, 2007). The production capacities are according the environmental permission 100 000 t/a and 60 000 t/a for formic acid and hydrogen peroxide respectively. According to Uhde Technologies (2010) the existing gasification process is a non-catalytic process; a combination of exothermic and endothermic reactions, thermal cracking, steam reforming etc. The net reaction is exothermic and produces gas containing mainly CO and H_2:

$$2CH_n + O_2 \rightarrow 2CO + nH_2 \ (1 < n < 4) \qquad (8)$$

Hydrocarbon fuels, such as natural gas, refinery gas, bunker C-oil, vacuum residue, vacuum-flashed cracked residue, asphalt and liquid waste can all be used as feedstock for the gasification process. Gas is treated, according to the environmental permission, in a way that CO_2 and sulphur compounds are separated from the gas by amine wash and CO and H_2 are separated with a membrane system.

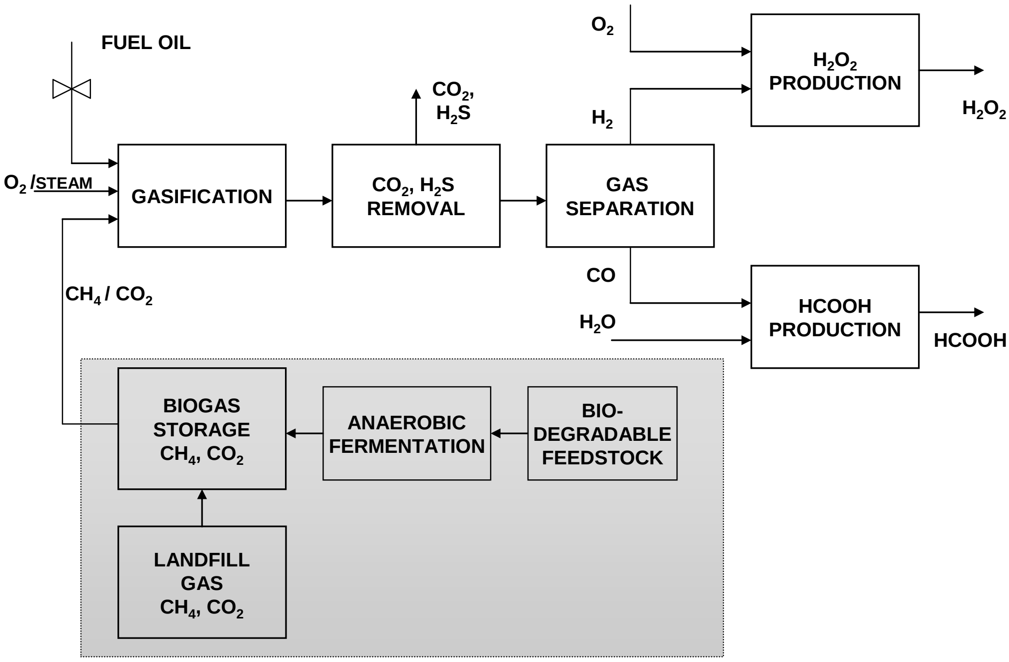
The net reaction equations for formic acid and hydrogen peroxide are as follows:

$$CO + H_2O \rightarrow HCOOH \qquad (9)$$

$$H_2 + O_2 \rightarrow H_2O_2 \qquad (10)$$

Assuming 10 % gas loss during the treatment, FA production consumes around 500 Nm^3/t CO and HP production 700 Nm^3/t H_2. Thus the need for CO is around 50 million Nm^3/a and for H_2 42 million Nm3/a when 100 000 tonnes FA and HP are produced. One tonne of heavy oil produces 2700 Nm^3 synthesis gas and the produced gas contains almost equal amounts of CO and H_2 (Uhde Technologies, 2010). Consequently, it can be calculated that the consumption of oil in gasification is 50 million Nm^3/ (0.5 x 2700) = 37 000 t/a. The additional H2 which is not used in HP production can be utilised for energy production. Figure 3 illustrates the existing process (in white) and a potential replacement avenue for heavy fuel oil (in grey). The replacement can be done by using two different alternatives landfill gas or biogas based on anaerobic fermentation. These two alternatives can also be used simultaneously. The volume of landfill gas is too low to alone cover the needs.

Figure 3. Synthesis gas production from fuel oil or biogas



3.3.1 System study, case 2a: Substitution of heavy fuel oil with landfill gas

Around 8 million Nm^3/a biogas is produced in a landfill 3 km from the Kemira production site (Environmental centre of Northern Ostrobothnia, 2003). The landfill gas is currently used for energy production through pipeline to a mineral wool factory and a hospital heating plant besides own use. Landfill gas is already utilised following the principles of the concept of Ecological District and the theory of Industrial Ecology (e.g. Côté and Cohen-Rosenthal, 1998; Roberts, 2004; Korhonen and Snäkin, 2005). This study analyses the alternative where the landfill gas would replace a more expensive industrial raw material. In 2009, 1710 MWh electricity and 6092 MWh heat were produced from the landfill gas according to Biogas plant register of Finland. Typical gas composition of landfill gas is 50 % CH_4, 45 % CO_2, 5 % N_2 and less than 1 % hydrogen sulphide (H_2S) (Themelis and Ulloa, 2007). In this case the methane content is 48 %.

According the Biogas register part of the landfill gas is not utilised but flared. The unutilised gas can be sold with the wood biomass energy price. If all the gas is sold, current small users have to replace their needs with e.g. biomass.

The existing gasifiers are assumed to be capable of utilising the landfill gas instead of heavy fuel oil. According to calculations made with HSC Chemistry® software programme synthesis gas can be produced when the landfill gas is compressed and fed to the existing idle gasifier. Synthesis gas can be produced without having to purify CO_2 before gasification:

$$CH_4 + ½\, O_2 + CO_2 \rightarrow 2CO + H_2 + H_2O \qquad (11)$$

CO_2 of the biogas increases the desired CO formation and creates an additional environmental advantage through capturing a part of the CO_2 to the end product instead of releasing it to the atmosphere. In practice, the reaction (11) does not reach equilibrium, but a good ratio of CO - H_2 can be reached according thermodynamic calculations (e.g. Turpeinen et al., 2008). More CO is obtained with higher CO_2 concentrations.

The economical advantage of utilising landfill gas in the gasifier can roughly be described:

Advantage = cost of oil – value of gas (12)

cost of oil = amount of substituted oil x price of oil (13)

value of gas = amount of methane x price of methane (14)

amount of substituted oil = 3 x amount of methane / 2700 (15)

It has been assumed that this arrangement does not require significant investments nor increase operational costs as the existing system is capable of using landfill gas.

One ton of oil produces in gasification 2700 Nm^3 synthesis gas as stated earlier. According the equation (11) synthesis gas is produced three times the quantity of methane. 8 million Nm^3 of landfill gas is produced annually 48 % of which is methane. The gas must be compressed to 30 bars before feeding into a gasifier. In this study, 10 % loss of energy is estimated, covering possible losses including compression energy. Consequently, the annual amount of oil to be substituted equals 3 x 0.90 x 0.48 x 8 million Nm^3 / 2700 Nm^3 / t = 3800 t.

This study utilises methane price of 20 €/MWh equal to the market price for wood biomass fuel (Poyry Management Consulting Oy, 2011) as wood biomass is a natural local fuel alternative.

3.3.2 System study, case 2b: Substitution of heavy fuel oil with gas from anaerobic fermentation

This sub-chapter describes calculations for a case when heavy fuel oil is replaced by RCG based biogas, in the same manner as in case 1. The main difference is case 1 (Talvivaara) requiring a reformer, this case (Kemira) utilising gasification. However, the technical differences do not influence the economic analyses.

The size of the required investment can be estimated by using equation (7):

31.5 x (33.3/15)exp0.5 = 47 M €

The investment is assumed to receive a maximum government subsidy of 40%, resulting in net investment cost of 28 M €. Should the used exp value be 0.75 or 1, the investment costs would be 57 M€ and 70 M€ respectively, and with subsidies the net investment costs would be 34 M€ and 42 M€.

Required gas in Kemira case is 33 300 000 Nm^3 annually. In the Talvivaara case, the required gas volume is 19 000 000 Nm^3, requiring 9500 hectares for farming RCG. By scaling this to Kemira case, the required farm land would be 33.3 /19 x 9500 = 16 700 ha.

Currently, Kemira is estimated to use 37 000 t/a heavy fuel oil. According to Statistics Finland (2010), the price of heavy fuel oil for producers has varied between 200 – 500 €/t in years 2005-2010.

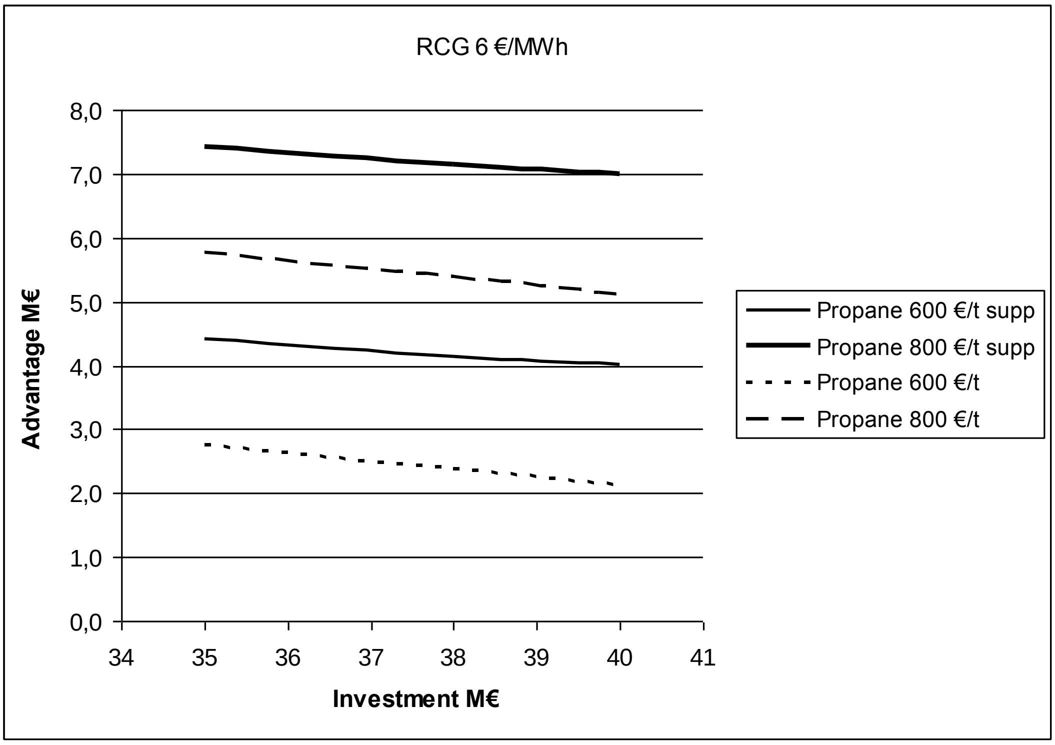
4 Results and discussion

4.1 Substitution of propane with biogas

Figure 4 illustrates the annual economic advantage obtainable, for Talvivaara case, should propane be replaced with biogas. Calculations assume the volumes to be constant equalling Talvivaara's true volumes. Calculations have been made with RCG price of 6 €/MWh and propane prices of 600 and 800 €/t. Figure 5 shows the same calculations for RCG price of 12 €/MWh.

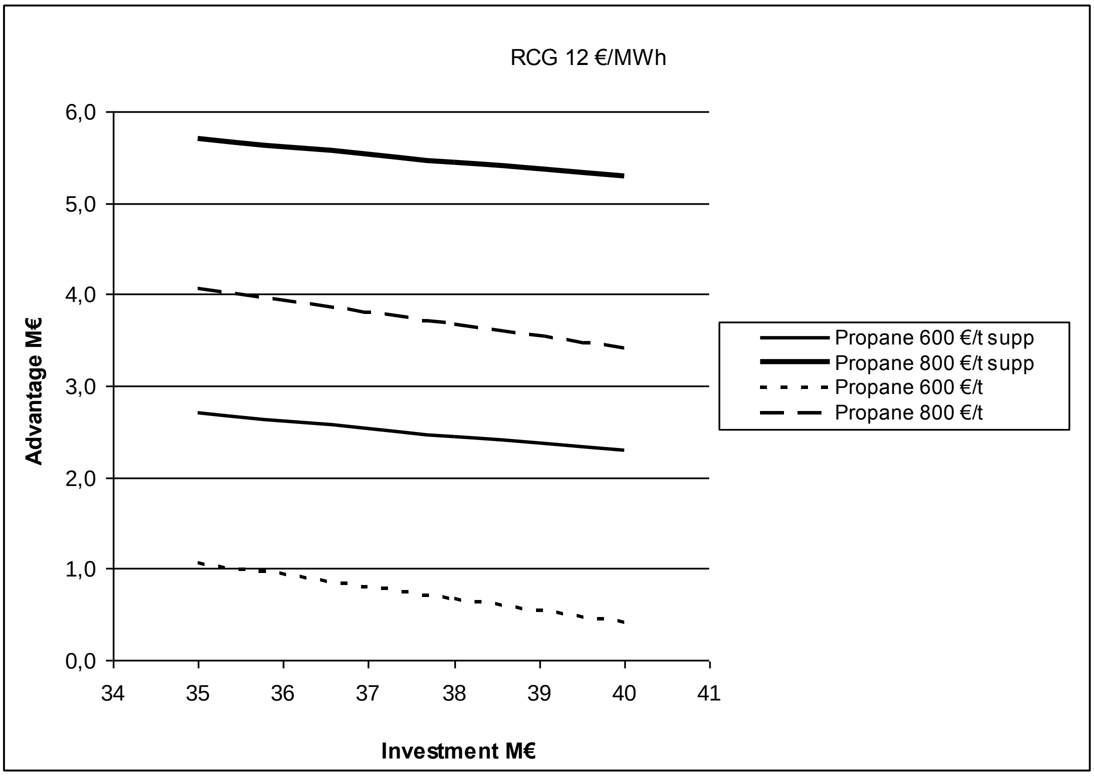
The calculations behind the figures are based on formulas in chapter 3.2. The magnitudes of investments have been obtained by using exponent values of 0.5, 0.75 and 1. The figures show calculations when maximum investment support of 40 % have been taken into account (indicated as Supp.).

Figure 4. Annual economic advantage of substituting propane with biogas, RCG price 6 €/MWh.



With all the parameter values the advantage indicates a positive value. The advantage is significantly dependent of propane price and investment support.

Figure 5. Annual economic advantage of substituting propane with biogas, RCG price 12€/MWh.



From Figures 4 and 5 it can seen that the economic advantage is positive in all considered cases, even without investment support, and even with a RCG price of 12 EUR/MWh. By comparing Figures 4 and 5 it can be noticed how an increase in RCG price from 6 €/MWh to 12€/MWh annual advantage decreases by approximately 3 million €.

It is also possible to calculate production costs for methane produced from RCG by acknowledging capital costs, raw materials and operational costs. With RCG price of 6 €/MWh and government supported investment costs of 35 – 40 M€, the production costs for methane would be 24 – 26 €/MWh. Should the RCG be priced at RCG 12 €/MWh, the production costs for methane would be 33 – 35 €/MWh. Without government support the production costs for methane would be 33 – 36 €/MWh and 42 – 45 €/MWh respectively. Northern Finland does not have a natural gas pipeline available, however, in

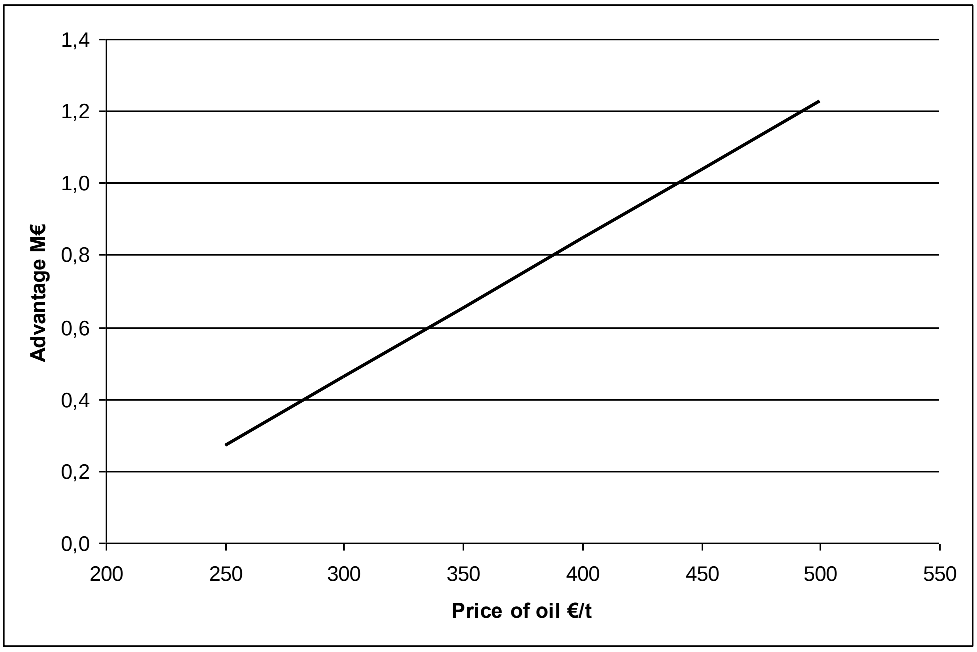
Southern Finland the untaxed price for natural gas has varied between 25 – 30 €/MWh between 2008-2010 (Statistics Finland, 2010). Consequently, it seems that the price for methane produced from RCG via anaerobic fermentation is in line with the price for natural gas, if the government investment support is available. It is noteworthy that the national parliament has accepted a new law for reducing CO_2 emissions that will increase tax on natural gas, making RCG based methane even more competitive.

4.2 Biogas for synthesis gas production instead of heavy fuel oil

4.2.1 Substitution of heavy fuel oil with landfill gas

Figure 6 illustrates the annual economic advantage of replacing heavy fuel oil with landfill gas, for Kemira case 1, when oil prices are between 250 – 500 €/t. As the availability of landfill gas is limited in this case, the replacement can only cover 3800 t/a or some 10 % of the oil usage. Calculations have been conducted by using the price of wood biomass, a realistic alternative for the area, for landfill gas. It has been assumed that no significant investments are required as the existing equipment is assumed to be compatible.

Figure 6. Annual economic advantage when substituting oil with landfill gas (Kemira Case 1).

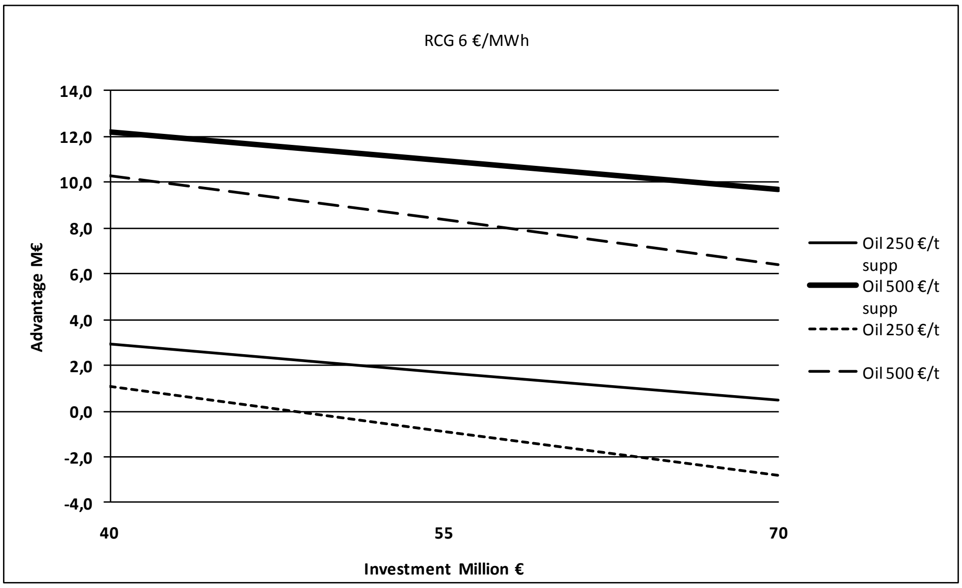


Annual economic advantage of replacing heavy fuel oil with landfill gas varies between 0.4 – 1.2 M€ depending on oil price. The advantage is relatively small as the available volume is limited. In principle, replacing heavy fuel oil with landfill gas can be lucrative, should there be adequate volume of landfill gas available.

4.2.2 Substitution of heavy fuel with gas from anaerobic fermentation

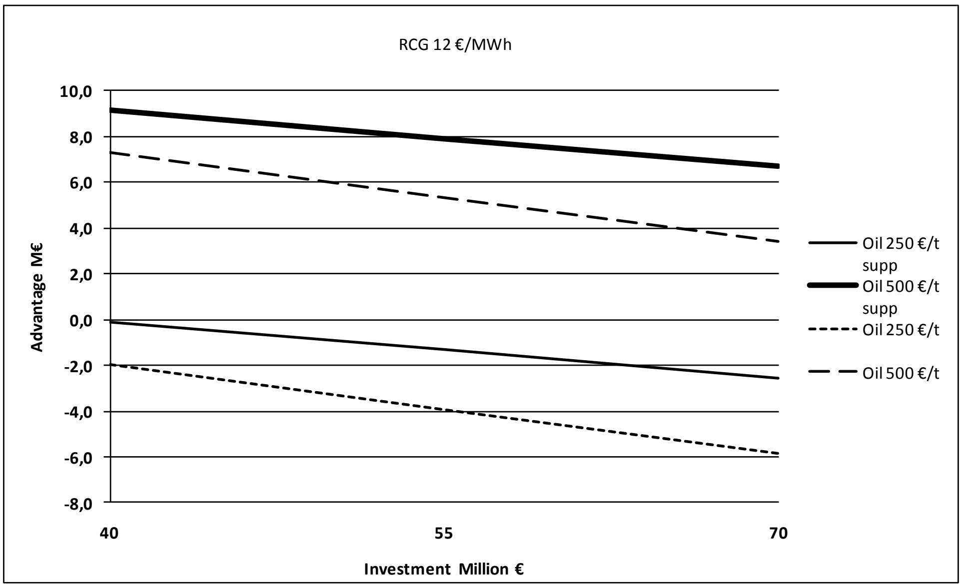
Figures 7 and 8 illustrate the annual economic advantage, for Case Kemira 2, for substituting heavy fuel oil with gas from anaerobic fermentation. The process in this case is the same as for case Talvivaara, but scaled for this case. Calculations have been made for fuel oil prices of 250 and 500 €/t, and for investments ranging between 40 – 70 M€. Figure 7 presents a case where RCG price is 6 €/MWh, and Figure 9 a case where RCG price is 12 €/MWh.

Figure 7. Annual economic advantage when substituting oil with gas from anaerobic fermentation, RCG price 6 €/MWh.



It can be seen that oil price has a significant impact on the annual economic advantage. With oil price of 250 €/t the investment does not seem feasible, but with prices of some 500 €/t the investments is clearly worth considering. The investment support has also some impact, even though the oil price dominates.

Figure 8. Annual economic advantage when substituting oil with gas from anaerobic fermentation, RCG price 12 €/MWh.



By comparing Figures 7 and 8, it can be seen that increase in RCG price from 6 to 12 €/ MWh results in reduction in annual economic advantage of some 3 million €. At a RCG price of 12 EUR/MWh and an oil price of 250 EUR/t the economic advantage is always negative, even with investment support.

It is also possible to calculate production costs for biogas produced from RCG by acknowledging capital costs, raw materials and operational costs. With RCG price of 6 €/MWh and government supported investment costs of 40 – 70 M€, the production costs for biogas would be 19 – 26 €/MWh. Should the RCG be priced at RCG 12 €/MWh, the production costs for methane would be 28 – 35 €/MWh. Without government support the production costs for biogas would be 25 – 36 €/MWh and 34 – 45 €/MWh respectively.

5 Conclusions

Biogas is globally one of the fastest growing means to produce bioenergy. Typically biogas is used by burning to produce energy, or to be used as vehicle fuel. This research analyses possibilities of utilising biogas directly in industrial applications by replacing current fossil based raw materials. This case study analyses true industrial cases concentrating on considering economic impacts of replacing current raw materials either by landfill gas or gas produced from reed canary grass.

In the studied case, the use of landfill gas is straightforward and profitable. However, the volumes of landfill gas are relatively low for the studied case. Consequently, landfill gas is a real option only should the landfill be large, or the industrial need small enough.

Utilisation of biogas, or methane, produced from reed canary grass is economically viable and technically possible. However, investments at industrial sites are required for producing the gas and farming of RCG needs to be organised.

For biogas to be an economical alternative as raw material, investment supports for biogas production and farming subsidies are required in the same manner as currently for food production. However, this type of expansion of the use of subsidies depends on political decisions. As the prices for fossil raw materials are rising, the studied alternative becomes more competitive reducing the need for government support.

The implications of this study include that municipalities with large landfill sites could potentially utilise the principle presented for Kemira case 1 by identifying industrial sites using oil based synthesis gas.

The use of biogas can be promoted by identifying existing industrial sites currently using fossil based gas as raw material and by analysing whether they can utilise biogas. Case specific calculations can be made by using the examples presented in this study. Biogas utilisation is often assessed as decentralised options by considering biogas production at farm sites. The results of this study show, however, that a centralised option at industrial sites may be an attractive alternative. The crop used for biogas production should obviously be arranged at farms.

In addition, by constructing biogas producing unit at industrial sites potentially enables development of other biogas applications. Building pipelines to other biogas users, or vehicle uses, are potential options.

Practitioners should note that this study must be considered only as an initial investigation for them and that they need analyse the technical feasibility in more detail, including process and raw material details. In addition, economic calculations need to be accurate, using exact parameter values for the case in question.

The limitation of this paper is the analysis of a limited number of case studies. Economic conclusions are dependent on true investment and operational costs. This study relied on figures from available sources, making the conclusions dependent on them. Potential further research could include studying a larger number of cases and analysing different biogas production technologies. In addition, simultaneous use of multiple raw materials such as municipal waste and sewage, industrial waste and other biomass is worth further research.

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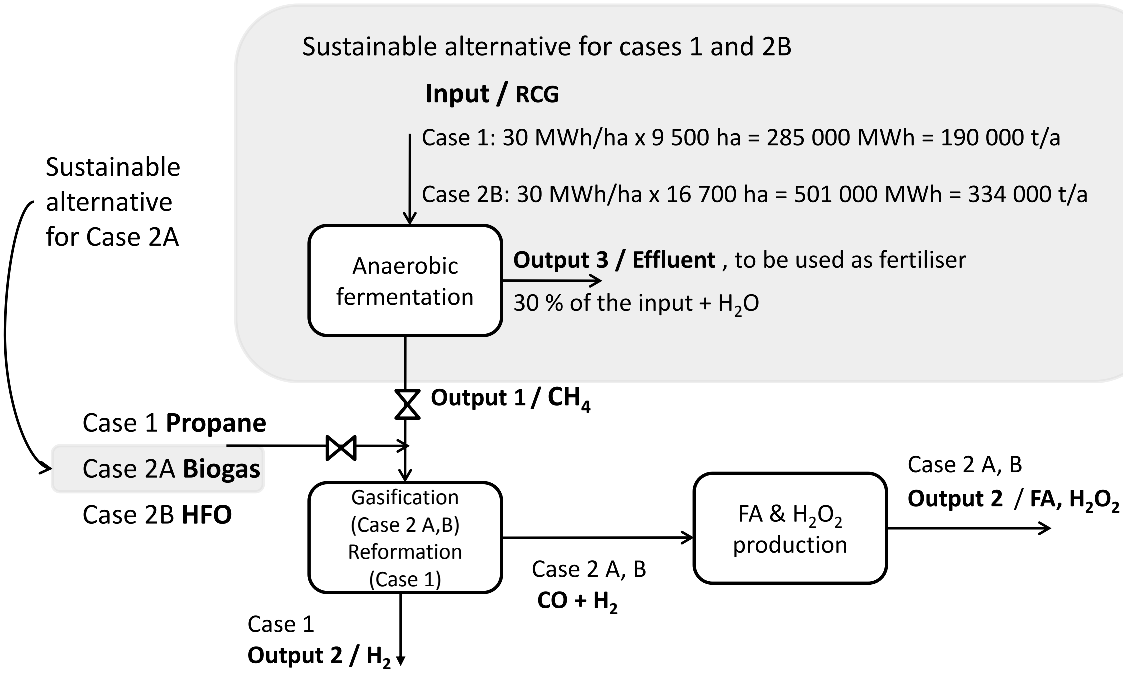
Appendix 1 - material flows of production chains

Case 1	Current solution	Biogas alternative
Input	propane: 15 000 t	RCG: 190 000 t/a (50 % H_2O)
Requires		9 500 hectares of farm land
Output 1	H_2: 4 000 t	methane: 19 000 000 Nm^3
Output 2		H_2: 4 000 t
Output 3		Effluent: 100 - 200 000 t/a

Case 2A	Current solution	Landfill gas alternative
Input	heavy fuel oil: 37 000 t	methane: 4 000 000 Nm^3
Requires		landfill gas
Output	formic acid & hydrogen peroxide: 160 000 t	formic acid & hydrogen peroxide: 9 700 t

Case 2B	Current solution	Biogas alternative
Input	heavy fuel oil: 37 000 t	RCG: 334 000 t/a (50 % H_2O)
Requires		16 700 hectares of farm land
Output 1	formic acid & hydrogen peroxide: 160 000 t	methane: 33 300 000 Nm^3
Output 2		formic acid & hydrogen peroxide: 160 000 t
Output 3		Effluent: 170 - 350 000 t/a

Appendix 2 – material flow chart



Sustainable alternatives are shaded as grey.