REPORT

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HYDRATE FOR TRANSPORT AND STORAGE OF BIOGAS AND BIOMETHANE – A SCENARIO STUDY

Report from an f3 project

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THE SWEDISH KNOWLEDGE CENTRE
FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contributes to the development of sustainable fossil-free fuels for transportation. The centre is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see www.f3centre.se).

The report includes a comparison of three scenarios for converting farm-produced biogas to vehicle fuel quality gas including conventional upgrading and transport in pressurized vessels and two future-oriented scenarios based on formation, transport and dissociation of gas hydrates.

The project was conducted by JTI – Swedish Institute of Agricultural and Environmental Engineering and Swedish University of Agricultural Sciences (SLU). The company MetaHyd AB, which develops hydration processes, was also involved in the project discussions. The work was discussed and reviewed by Johanna Berlin at SP – Technical Research Institute of Sweden. The project was initiated by Ola Pettersson and Ida Norberg (JTI), Åke Nordberg (SLU) and Sven-Olov Holm (MetaHyd AB).

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EXECUTIVE SUMMARY

The biogas potential in manure from Swedish agriculture is estimated to 4-6 TWh year^{-1}. A general problem for biogas of vehicle fuel grade is cost- and energy efficient transportation and storage. One potential option could be to convert the biogas to gas hydrate, for further transport and upgrading to e.g. vehicle gas in a large scale. Gas hydrates (clathrates) are ice-like crystals formed under low temperature and high pressure with a potential to contain 164 m^3 gas m^{-3} of hydrate. Small gas molecules, such as hydrocarbons and carbon dioxide (CO_2) are captured in cages of hydrogen-bonded water molecules. The gas hydrates are stable and can be stored at atmospheric pressure at a regular freezing temperature of -17°C. To retain the methane gas (CH_4) from the hydrate, thermal dissociation is a common procedure.

The aim of the present work was to compare three scenarios for converting farm-produced biogas to vehicle fuel quality gas including conventional upgrading and transport in pressurized vessels and two novel scenarios based on formation, transport and dissociation of gas hydrates. The energy use and global warming potential (GWP) was evaluated using a life cycle perspective. Possible constraints when implementing the novel systems in practice were identified and the costs for the system were estimated.

The assessment was based on an assumed farm-scale biogas plant representing a typical biogas composition for manure-based digestion. In the reference scenario (*CBG; compressed biogas*), raw biogas was upgraded and compressed to reach vehicle fuel quality at the biogas plant, using conventional technology, before transportation in pressurized vessels to a centralized facility for storage and final use. In the second scenario (*biogas hydrate*), raw biogas was converted to hydrate at the biogas plant and transported in containers to a centralized facility for storage and further gas handling (dissociation of hydrate, upgrading and compressing). In the third scenario (*biomethane hydrate*), raw biogas was upgraded to biomethane and converted to hydrate at the biogas plant for transportation in containers to a centralized facility for storage and further gas handling (dissociation of hydrate and compressing). The CH_4 losses were set to 2% in the reference scenario and 4% in both the two hydrate scenarios. The different output of CH_4 from the systems was considered by compensation of natural gas in the two hydrate scenarios.

The functional unit referred to the processing and upgrading of the farm-produced biogas and was defined as 1 MWh biogas (60% CH_4, 40% CO_2 at 1 atm and 0°C) leaving the anaerobic digester. The study included energy use and greenhouse gas (GHG) emissions in all unit operations from the produced biogas through conversion, transport, storage to final delivery before fuelling. A Nordic electricity mix was assumed. The anaerobic digestion process and the use of compressed biogas were considered the same for all three scenarios and were outside the scope of the study. The construction phase was included in the cost calculations but not considered in the calculations of energy use and GHG emissions.

The overall energy use expressed as direct use at the facilities and for transport in the three scenarios was lowest in the reference scenario, where 81 kWh MWh^{-1} was used. In the biomethane hydrate scenario, 218 kWh MWh^{-1} was used while the highest energy use was obtained in the biogas hydrate scenario (315 kWh MWh^{-1}). The higher energy use in the hydrate scenarios was mainly due to the energy requirement for formation and dissociation of hydrate making up 62% and 56% of the total energy use for the biogas and biomethane hydrate scenario, respectively. The energy required for the natural gas compensation in the hydrate scenarios was 19.5 kWh MWh^{-1}. The electricity needed for formation, cooling for storage and dissociation of hydrates was calculated in more detail. The heating for dissociation and the cooling for the formation of hydrates are the most energy demanding operations making up ca 75% of the total power needed per kg of gas.

The contribution to GWP was considerably higher for the biogas and the biomethane hydrate scenarios compared to the reference scenario, 132% and 106% respectively. The main reasons were increased methane slip and higher energy demand. The methane slip contributed with 56% and 69% of the GWP increase in the biogas and biomethane hydrate scenarios, respectively. The higher energy consumption for the biogas and biomethane hydrate scenarios contributed with 44% and 31% to the respective GWP increase. The methane slip constituted 75% of the total GWP in the reference scenario. A reduction of the methane slip to zero during formation and dissociation would remarkably decrease the contribution to GWP for the hydrate scenarios also since no natural gas would be needed for compensation.

For the cost calculations, assumptions was made for the investment costs for hydrate formation and hydrate dissociation, because of there are no such facilities on the market today. The overall costs were lowest for the reference scenario (749 SEK MWh^{-1}) followed by the biomethane hydrate scenario (864 SEK MWh^{-1}) and 1142 SEK MWh^{-1} for the biogas hydrate scenario. The increase in cost in relation to the reference scenario was 15% and 52% respectively.

The future-oriented approach for the use of hydrates in systems for utilizing biogas as a vehicle fuel has several inherent uncertainties. Still, the biomethane scenario showed better performance than the biogas hydrate scenario regarding energy use, GWP and system costs implying that the biogas preferably should be upgraded before hydration. The measures needed for improving the performance of the biomethane hydrate scenario was identified in a sensitivity analysis. It is clearly important to reduce the electricity use and methane slip for hydration and dissociation as well as improve the hydration efficiency.

To the best of our knowledge, this is the first study regarding systems analysis on biogas and biomethane hydrates. However, this study clearly highlights hotspots in hydrate systems applied to biogas production, e.g. that the energy use is not favourable when considering using hydrate as a mean for transporting gas from a production site to be used at another site. For future studies, the integration of hydrate for storage at centralized biogas plants is an interesting aspect as well as integration with e.g. return water in a district heating system or surplus heat from a CHP-plant for dissociation heat. Furthermore, an expansion of the system also including the anaerobic digestion process, where low-grade heat from the cooling during hydrate formation could be utilized would likely improve the overall efficiency of the system. Moreover, the future development of hydrate technologies is, important to consider. For CH_4-CO_2 hydrate mixtures, the CO_2 is more easily released as compared to CH_4. This phenomenon has been proposed to be utilized as an upgrading process, which would make it possible to integrate dissociation and upgrading in one process. The use of detergents such as SDS (Sodium dodecyl sulfate) has been shown to enhance the hydrate formation rate at lower pressures with reduced energy demand. Thus, to reduce costs, energy use and greenhouse gas emissions for future use of hydrate, it is important to consider system integration as well as technological development.

SAMMANFATTNING

Biogaspotentialen i gödsel från svenska jordbruket uppskattas till 4-6 TWh år^{-1}. Ett generellt problem för biogas av fordonskvalitet är kostnads- och energieffektiva transporter och lagring. Ett möjligt alternativ för att minska detta problem skulle kunna vara att omvandla biogasen till gashydrat, för vidare transport och uppgradering till t.ex. fordonsgas i stor skala. Gashydrater (klatrater) är isliknande kristaller bildade under låg temperatur och högt tryck med en potential att innehålla 164 m^3 gas m^{-3} hydrat. Små gasmolekyler, såsom kolväten och koldioxid (CO_2) fångas i s.k. burar av vätebundna vattenmolekyler. Gashydraterna är stabila och kan vid atmosfärstryck lagras vid vanlig frystemperatur, -17°C. För att återfå metangasen (CH_4) från hydrat, används ofta termisk dissociation.

Syftet med detta projekt var att jämföra tre scenarier för att konvertera gårdsproducerad biogas till fordonsgaskvalité. Konventionell uppgradering och transport i trycksatta kärl jämfördes med två nya scenarier som var baserade på bildning, transport och dissociation av gashydrater. Energianvändning och global uppvärmning (GWP) utvärderades utifrån ett livscykelperspektiv. Begränsningar för praktisk implementering av de nya systemen identifierades och kostnaderna för systemet uppskattades.

Utvärdringen baserades på en gårdbiogasanläggning som representerar en typisk biogassammansättning för gödselbaserad rötning. I referensscenariot (*CBG; komprimerad biogas*), uppgraderades och komprimerades råbiogasen till fordonsbränslekvalitet med konventionell teknik vid biogasanläggningen för att sedan transporteras i trycksatta kärl till en central anläggning för lagring och slutlig användning. I det andra scenariot (*biogashydrat*), konverterades råbiogasen till hydrat vid biogasanläggningen och transporterades i containrar till en central anläggning för lagring och vidare gashantering (dissociation av hydrat, uppgradering och komprimering). I det tredje scenariot (*biometanhydrat*), uppgraderas råbiogasen till biometan och konverterades till hydrat vid biogasanläggningen. Sedan transporterades hydratet i containrar till en central anläggning för lagring och vidare gashantering (dissociation av hydrat och komprimering). CH_4 förlusterna var 2% i referensscenariot och 4% i båda de två hydratscenarierna. Skillnaden på CH_4 ut från systemen ersattes av naturgas i de två hydratscenarierna.

Den funktionella enheten som avser processning och uppgradering av gårdsbiogas definierades som 1 MWh biogas (60% CH_4, 40% CO_2 vid 1 atm och 0°C) som lämnar rötkammaren. I studien ingick energianvändning och växthusgaser (GHG) i alla enhetsoperationer från den producerade biogasen genom konvertering, transport och lagring till slutleverans före tankning. En nordisk elmix antogs. Rötningsprocessen och användning av komprimerad biogas ansågs densamma för alla tre scenarier och var utanför studien. Konstruktionssteget ingick i kostnadsberäkningarna men beaktas inte i beräkningarna av energianvändning och utsläpp av växthusgaser.

Den totala energianvändningen uttryckt som direkt användning vid anläggningar och för transport, var lägst i referensscenariot, där 81 kWh MWh^{-1} användes. I biometanhydratscenariot användes 218 kWh MWh^{-1} medan den högsta energianvändningen var i biogashydratscenariot (315 kWh MWh^{-1}). Den högre energianvändningen i hydratscenarierna beror främst på att energibehovet för bildning och dissociation av hydrat utgör 62% och 56% av den totala energianvändningen för biogas- och biometanhydratscenarierna. Den energi som krävs för att ersätta naturgas i hydratscenarierna var 19,5 kWh MWh^{-1}. Mer detaljerade beräkningar gjordes för bildande, kylning, lagring och

dissociation av hydrater. Värmen för dissociation och kylning för bildandet av hydrater var de mest energikrävande stegen och utgjorde ca 75% av den totala effekten per kg gas.

Bidraget till GWP var betydligt högre för både biogas- och biometanscenarierna jämfört med referensscenariot, 132% och 106%. De främsta orsakerna var högre metanslip och en högre energiförbrukning. Metanslipet bidrog med 56% och 69% av GWP-ökningen för biogas- och biometanhydratscenarierna. Den högre energiförbrukningen för biogas- och biometanhydratscenarierna bidrog med 44% och 31% till GWP-ökningen. I referensscenariot utgjorde metanslipet 75% av det totala GWP. En minskning av metanslipet till noll under hydratbildning och dissociation skulle markant minska bidraget till GWP för hydratscenarierna som dessutom inte skulle behöva någon komplettering med naturgas.

I kostnadsberäkningarna gjordes antaganden för investeringskostnader vid hydratbildning och dissociation eftersom det inte finns några sådana anläggningar på marknaden idag. De totala kostnaderna var lägst för referensscenariot (749 SEK MWh^{-1}) följt av biometanhydratscenariot (864 SEK MWh^{-1}) och 1142 SEK MWh^{-1} för biogashydratscenariot. Ökningen av kostnaderna i förhållande till referensscenariot var 15% respektive 52%.

Bedömningen av att använda hydrater i biogassystem till fordonsbränsle i framtiden har flera osäkerheter pga bristen på data och erfarenheter. Jämförelsen mellan hydratscenarierna visade dock att biometanhydratscenariot generellt uppvisade bättre prestanda än biogashydratscenariot avseende energianvändning, GWP och kostnader. Detta indikerar att biogas helst bör uppgraderas innan hydrering. De åtgärder som krävs för att förbättra prestandan i biometanhydratscenariot identifierades i en känslighetsanalys. Det är uppenbarligen viktigt att minska elanvändning och metanemissioner vid bildning och dissociation av hydrat samt att förbättra hydreringseffektiviteten.

Så vitt vi vet är detta den första studien som analyserat biogassystem där biogas- och biometanhydrat ingår. Studien belyser dock tydligt de delar i hydratsystemen som behöver förbättras för biogastillämpning, t.ex. att energianvändningen inte är gynnsam när man överväger användning av hydrat för att transportera gas från en produktionsplats till en annan användningsplats. För framtida studier skulle integrationen av hydratlagring vid centraliserade biogasanläggningar vara intressant att studera liksom integration med t.ex. returvatten i ett fjärrvärmesystem eller överskottsvärme från ett kraftvärmeverk för värme till dissociationen. Dessutom skulle en utvidgning av systemet med fördel kunna innefatta den anaeroba rötningsprocessen, där lågvärdig värme från kyla under hydratbildning kan utnyttjas bättre och troligtvis förbättra den totala effektiviteten i systemet. Vidare är det viktigt att beakta den framtida utvecklingen av hydratteknik. För CH_4-CO_2 hydratblandningar frigörs CO_2 lättare jämfört med CH_4. Möjligheter att använda dissociation för uppgradering av biogas har föreslagits, vilket skulle göra det möjligt att integrera dissociation och uppgradering i en och samma process. Användningen av detergenter såsom SDS (Natriumdodecylsulfat) har visat sig öka hydratbildningshastigheten vid lägre tryck med ett troligt minskat energibehov som följd. Således, för att minska kostnaderna, energianvändningen och utsläpp av växthusgaser för framtida användning av hydrat är det viktigt att beakta både systemintegration och teknisk utveckling.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

The biogas potential in manure from Swedish agriculture is estimated to 4-6 TWh year^{-1} (Dahlgren et al., 2013; Linné et al., 2008). At present, it is mainly cogeneration of heat and electricity that appears to be the most economically attractive option for utilizing this option. Upgrading to vehicle quality can provide an increased value of the gas, especially if it could be sold and used in urban areas. The distribution would be facilitated by injecting upgraded biogas to the fossil gas grid. However, the gas grid in Sweden is only restricted to the south and west coast, limiting this distribution option. Development of cost- and energy efficient techniques for transport and storage would generally improve the competitiveness of biogas and specifically make it possible to utilize the biogas potential in substrates which are geographically distributed. Formation of gas hydrates might be a technique to facilitate storage and transport of biogas produced in rural areas for use as vehicle fuel in more densely populated areas. The idea of biogas hydrate and the driving force for MetaHyd AB is described in Appendix 1.

Gas hydrates (clathrates) are ice-like crystals formed under low temperature and high pressure with a potential to contain 164 m^3 gas m^{-3} of hydrate (Pellenbarg & Max, 2000). Small gas molecules, such as hydrocarbons and carbon dioxide (CO_2) are captured in cages of hydrogen-bonded water molecules. The research and development regarding gas hydrate storage and transport is mainly associated with gas in offshore oil production and for bulk transport of natural gas from remotely located small and medium sized gas fields (Gudmundsson et al. 1999). The research related to anaerobic digestion (biogas) systems is limited to a few studies. Naing et al (2007) has proposed a system based on storage of biogas hydrate in order to match the production vs. demand of electricity and heat over the year at a sewage treatment plant. Furthermore, the energy use for formation of biogas hydrate at a 100 kW$_{el}$ biogas plant was assessed by Arca et al. (2011).These studies indicate that 15 to 20% of the energy in the biogas is needed for hydrate formation.

When proposing novel systems for handling of biogas, there is a need to analyse the energetic and environmental performance in a system perspective including a comparison with the conventional techniques implemented for converting biogas to vehicle fuel quality. Life cycle assessment (LCA) methodology is used for compilation and evaluation of potential environmental impacts of a product system throughout its life cycle (ISO, 2006) and is extensively used for comparisons of different bioenergy systems (*e.g.* Cherubini et al., 2009). Through a life cycle perspective, environmental hotspots can be highlighted for identification of potential improvements. This is important when evaluating future-oriented scenarios including technology not yet implemented in a specific setting. To the best of our knowledge, this is the first study regarding systems analysis on biogas and biomethane hydrates.

1.2 AIM

The aim of the present work was to compare three scenarios for converting farm-produced biogas to vehicle fuel quality gas including conventional upgrading and transport in pressurized vessels and two future-oriented scenarios based on formation, transport and dissociation of gas hydrates. The energy use and global warming potential (GWP) was evaluated using a life cycle perspective.

Possible constraints when implementing the novel systems in practice were identified and the costs for the system were estimated.

1.3 FORMATION OF HYDRATE

Gas hydrates are crystalline solids formed under proper conditions of temperature and pressure. Gas molecules like methane (CH_4) or CO_2, is captured in cages of polyhedra consisting of hydrogen bonded water molcules. Methane hydrate forms the structure called structure I (sI). For a given gas composition, it is possible to calculate the ideal hydration number, which for CH_4 is 5.75 (Mork, 2002). Depending of molecular properties, the formation of hydrate occurs at different conditions. In Figure 1, the hydrate equilibrium for CH_4 and CO_2 is shown. CO_2 forms hydrate easier as compared to CH_4.

Practically, the formation of hydrate can be performed in two different ways; either gas is bubbled into the continuous water phase or water is sprayed into the continuous gas phase. The former method has been most common studied. The most influencing parameters of the rate of hydrate formation are the gas injection rate and the pressure (Mork, 2002).

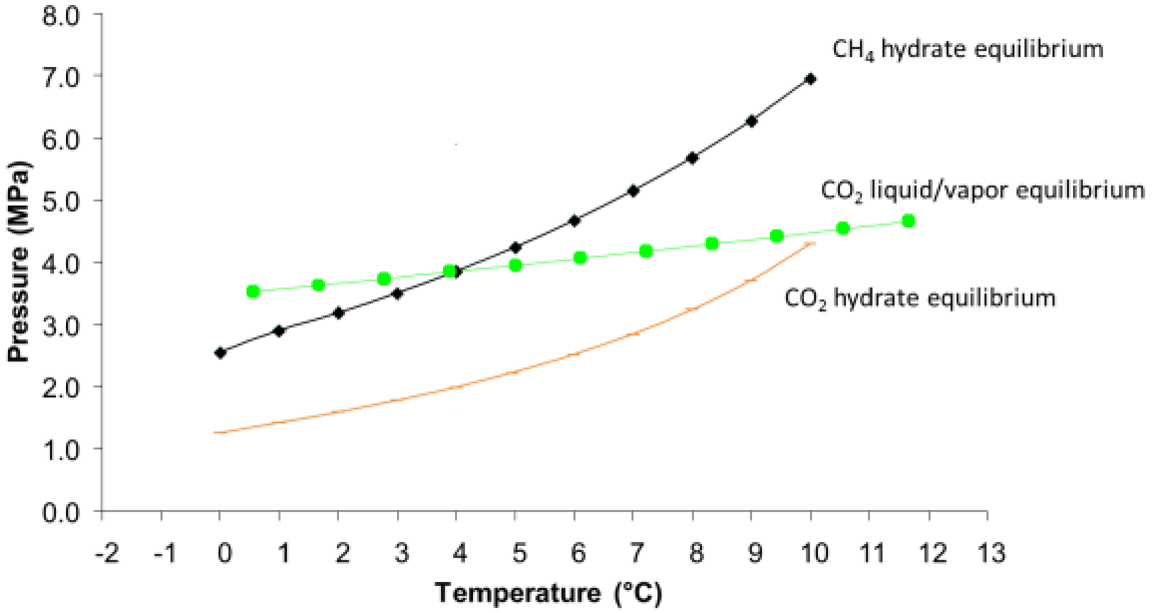

Figure 1. Hydrate equilibrium for methane (CH_4) and carbon dioxide (CO_2) [adapted from Arca et al., 2011].

1.4 STORAGE OF HYDRATE

A temperature of -15°C and a pressure of 4.5 bar is according to theory needed to maintain a stable hydrate according to Gudmundsson (1993), thus implicating that gas hydrates are unstable at atmospheric pressure. However, Gudmundsson (1994) showed that CH_4 hydrate is stable at atmospheric pressure at temperatures from -15°C and colder. In another study (Gudmundsson, 1993), a stable CH_4 hydrate was obtained even at -1.5°C at atmospheric pressure. This was explained as an isolation effect of the hydtare bulk mass itself. Shirota et al. (2011) showed that the CH_4 slip never is totally zero, and the lowest degree of hydrate dissociation was observed at -20°C with an average release of hydrate of 0.6-0.7% per day. Therefore, a gas tight chamber is important for storage without CH_4 slip.

1.5 DISSOCIATION

The reaction formula during dissociation can be written as $\mathrm{M} \cdot n\mathrm{H_2O}(s) = \mathrm{M}(g) + n\mathrm{H_2O}(l)$, where M is the hydrate forming gas or gas mixture and n is the hydration number (Kwon et al., 2011). Dissociation of the hydrate can be performed in three different ways; by increasing the temperature, by decreasing the pressure or by adding an inhibitor to the hydrate.

There are several studies regarding thermal dissociation of methane hydrate (Shirota et al., 2011, Kwon et al., 2011, Pang et al., 2009, Circone et al., 2004). In test tube scale experiments, Gudmundsson (1993) showed that increasing the temperature from -5°C to +5°C caused a 100% dissociation of the hydrate within two hours. An increase in temperature from -5°C to +1.5°C caused a slower release of gas (90% after 7 hours). Pang et al. (2009) studied thermal dissociation of methane hydrate in a 10 liter reactor. The reactor was heated with water (16-40°C) during dissociation. The dissociation behavior was similar for all water temperatures, but slightly faster at higher water temperatures. 100% of the hydrate was dissociated after 20 h and 90 % after 5-10 h. When heating the hydrate with air at 15°C, the hydrate dissociation was very slow. 50 % was dissociated after 10 h, and 60% after 24 h. The melting of ice was observed to cause a decrease in the dissociation process, a so called “buffering behavior” during dissociation. The buffering behaviour was remarkably decreased, but not eliminated, with higher water temperature.

The behavior during dissociation of pure gases and mixtures of gases is different. Kwon et al (2011) studied thermal dissociation of methane and carbon dioxide hydrate mixtures, aiming to better understand the dissociation behavior of geologic CO_2 storage and CH_4 gas recovery from natural gas hydrate deposits. During thermal dissociation, CO_2 is more easily released as compared to CH_4.

2 METHODOLOGY AND SYSTEM DESCRIPTION

2.1 GENERAL SYSTEM DESCRIPTION AND MODELLING

The assessment was based on an assumed farm-scale biogas plant producing 40 m^3_n biogas h^{-1} (60% CH_4, 40% CO_2 at 1 atm and 0°C) representing a typical biogas composition for manure-based digestion. The annual gross energy production was 2096 MWh, based on 9.97 kWh m^{-3}_n CH_4. Three different scenarios for conversion of biogas to vehicle fuel quality were compared in a systems analysis (Figure 2). In the reference scenario (*CBG; compressed biogas*), raw biogas was upgraded and compressed to reach vehicle fuel quality at the biogas plant, using conventional technology, before transportation in pressurized vessels to a centralized facility for storage and final use. In the second scenario (*biogas hydrate*), raw biogas was converted to hydrate at the biogas plant and transported in containers to a centralized facility for storage and further gas handling (dissociation of hydrate, upgrading and compressing). In the third scenario (*biomethane hydrate*), raw biogas was upgraded to biomethane and converted to hydrate at the biogas plant for transportation in containers to a centralized facility for storage and further gas handling (dissociation of hydrate and compressing). In all scenarios, the time for storage at the biogas plant was determined by the storage capacity of one transport of containers resulting in 6.9 d, 8.0 d and 4.4 d for the reference, biomethane hydrate and biogas hydrate scenario, respectively. At the centralized facility the storage time was 14 d and the dissociation started day 8. Furthermore, the transport distance from the biogas plant to the centralized facility was set to 100 km.

The model implementation and scenario calculations were performed using the calculation and modeling platform Matlab$^{©}$.

2.2 FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The functional unit referred to the processing and upgrading of the farm-produced biogas and was defined as 1 MWh biogas (60% CH_4, 40% CO_2 at 1 atm and 0°C) leaving the anaerobic digester and entering the system.

The study included energy use and greenhouse gas (GHG) emissions in all unit operations from the produced biogas through conversion, transport, storage to final delivery before fuelling, see Figure 2. Thus, the anaerobic digestion process and the use of compressed biogas (CBG) were not included in the system, since these were considered the same for all three scenarios. The electricity and fuel needed for the different operations within the system was included and presented as the direct energy used on the facilities and for transport. In addition, the energy was also expressed as primary energy. The electricity required for the processes was assumed to be Nordic electricity mix from 2008 according to Gode et al. (2011), consisting of electricity produced from nuclear (20%), fossil (13%) and renewable energy (67%) power plants. The generated surplus low-grade heat left the system and was not accounted for nor valorized in the calculations. Manufacturing of capital goods was not included in the calculations of energy use and GHG emissions. Environmental impacts from construction and demolition of biogas digesters are considered to be minor compared to the running phase (Michel et al., 2010) and it was assumed that the same was valid also for the hydrate systems. Emissions of greenhouse gases were expressed as CO_2-equivalents according to IPCC (2007) with the time horizon of 100 years, i.e. characterization factors used for GWP were 1, 25 and 298 for CO_2, CH_4 and N_2O, respectively. The CO_2-equivalents including production &

distribution and usage for natural gas, diesel and electricity was 251, 279 and 97 g CO_2 kWh^{-1}, respectively (Gode et al., 2011).

The CH_4 loss in the reference scenario was set to totally 2% of the produced biogas (Lantz et al., 2009), where 1% was associated with upgrading and 1% associated with compression. The CH_4 loss for the hydrate formation and dissociation was assumed to be in the same range as for the upgrading and compression, i.e. 2%. Thus, the CH_4 losses for the two hydrate scenarios were totally 4%, due to additional losses during hydrate formation and dissociation. This means that the output of CH_4 from the systems differed, which was compensated by expanding the two hydrate scenarios for differences in the amount of CBG (97% CH_4, 200 bars) produced per MWh raw biogas. Hereby, the production and use of natural gas corresponding to the differences in losses was included within the systems boundaries.

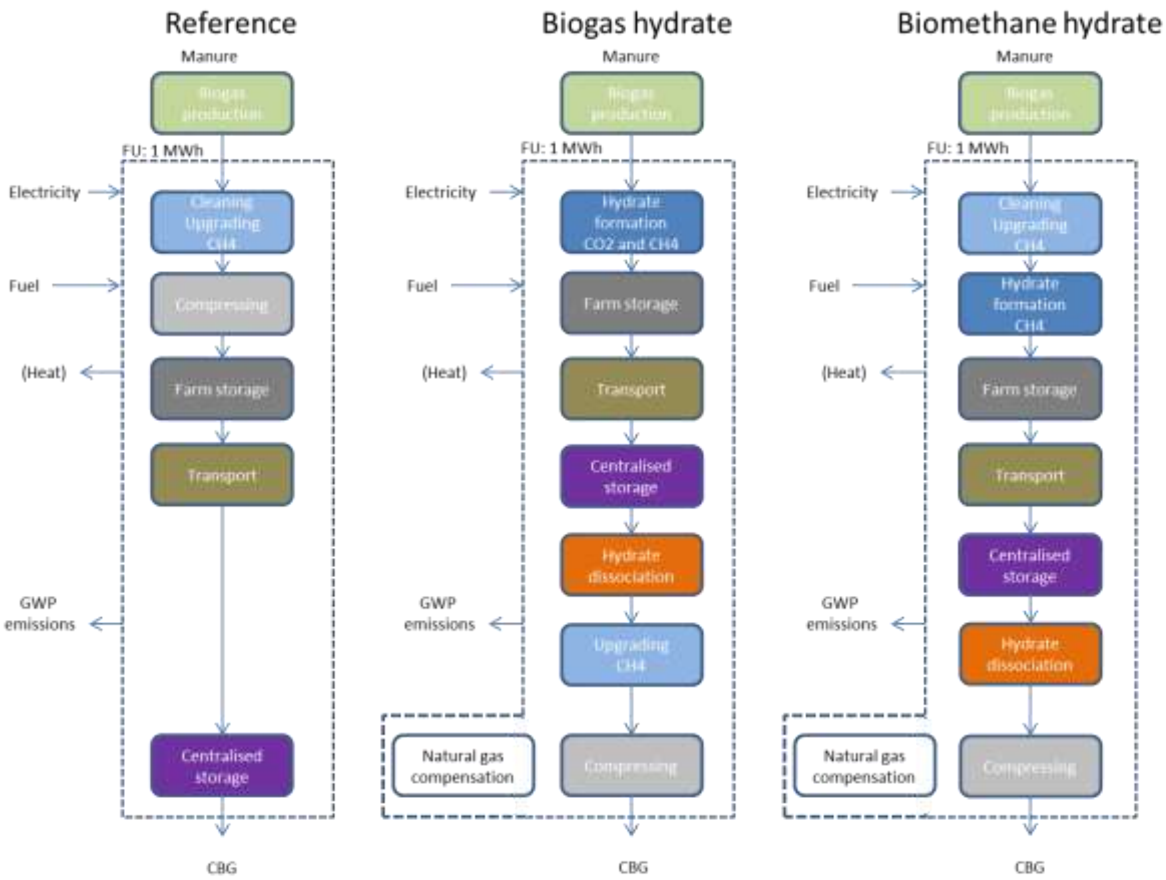

Figure 2. Flow scheme of the processes included within the systems boundaries in the three scenarios compared. FU = Functional unit and CBG = compressed biogas.

2.3 REFERENCE SCENARIO (CBG)

The small-scale upgrading was based on a water scrubbing technique using less pressure than a conventional water scrubber. The required electricity was 0.20 kWh m^{-3}_n and compression of biomethane to 200 bars based on four compression stages required 0.23 kWh m^{-3}_n according to Bauer et al. (2013). The compressed biomethane was transported in pressurized vessels of steel on a hook lift container and a capacity of 4 000 m^3_n per truck (Thelin, 2013) with a diesel consumption of 0.48 L km^{-1} (Benjaminsson och Nilsson, 2009).

2.4 BIOGAS HYDRATE SCENARIO

The equilibrium pressure and temperature profile for biogas hydrate was obtained from Arca et al. (2011). The working pressure and temperature was set to 3 MPa and 2°C, respectively. The hydrate formation process was divided into compression work, gas cooling, water cooling, hydrate formation, and pumping and mixing. Furthermore, the power for cooling the hydrate to -30°C was included. The input data used for the power demand calculations is presented in Appendix 2. The power demand was approximated as the weighted averages for the specific heat capacity and dissociation enthalpies of CH_4 and CO_2, thus 60% and 40%, respectively.

Two compression stages with equivalent compression ratio and a compressor efficiency of 0.8 were assumed (isoentropic work). The gas cooling power demand was calculated from 20°C to 2°C for a heat exchanger (Ex 1) with a thermal exchange efficiency of 0.75 (Figure 3). The water cooling was correspondingly calculated from an inlet temperature of 15°C to 2°C and a heat exchanger efficiency of 0.75 (Ex 2). The coefficient of performance (COP) for a compression chiller was set to 3.0. A gas-to-water stoichiometric ratio of 1: 5.75 for the hydrate formation was assumed with a water conversion efficiency of 0.8 (Arca et al 2011), thus resulting in a ratio of 1: 7.1875 for the calculations. The cooling power required for the hydrate formation was calculated based on the hydrate dissociation enthalpy for CH_4 and CO_2 (54.5 and 61 kJ mol^{-1}; Kwon et al., 2011) with a cooling efficiency of 0.75 (Ex 3). The electricity power for cooling the hydrate to -30°C was calculated for a heat exchanger (Ex 4) with a thermal efficiency of 0.75. The electricity power demand for pumping and mixing was approximated to 5% of the entire process demand.

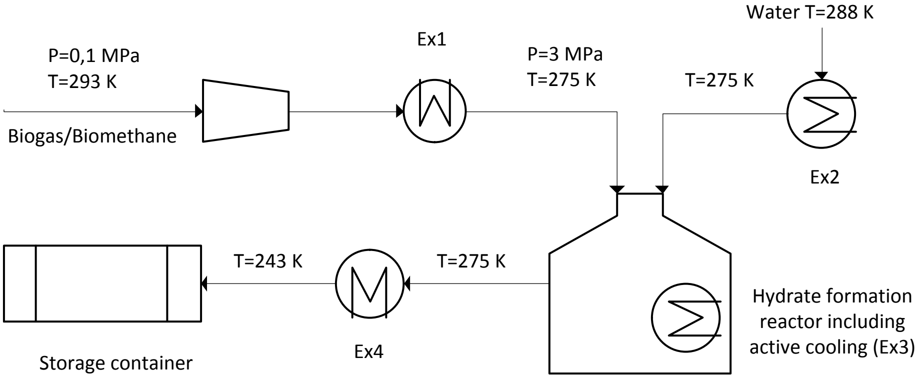

Figure 3. Flow scheme of the hydrate formation processes including four heat exchangers.

The hydrate was after formation transferred to gas tight freezing containers (15 m^3). The containers were assumed to consist of three jacketed vessels with a total inner volume of 11.1 m^3. The density of hydrate was assumed to 0.9 tonnes m^{-3} (Wang et al 2009), which means that the weight capacity was 10 tons of hydrate. Ethanol was selected to be the refrigerant surrounding the vessels. To prevent heat transfer from the surrounding environment each jacketed vessel was covered by 10 cm of styrofoam. The freezing containers were transported by a truck equipped with a hook lift with a total capacity of three containers.

The maxium temperature of the hydrate before dissociation was set to -10°C. By cooling the hydrate to -30°C at the plant, no cooling power during the transport or storage at the centralized facility was required. The heat needed for hydrate dissociation was based on melting the hydrate from -10°C to 0°C and the dissociation enthalpy. A compression heat pump with the COP set to 3 was used including recovery of heat from the subsequent compression of biomethane to 200 bars (Figure 4).

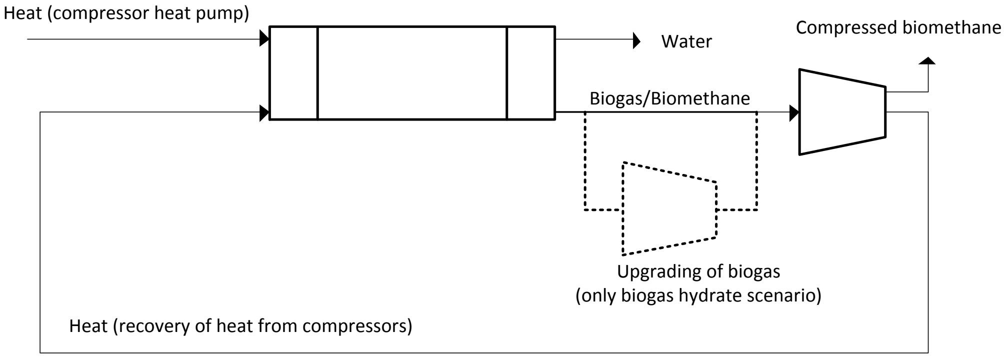

Figure 4. Flow scheme of the dissociation process including a compressor heat pump and recovery of heat from the compression of biomethane.

The upgrading at the central facility in the biogas hydrate scenario was a conventional water scrubber with a capacity of 320 m^3_n raw biogas h^{-1}. The required electricity for upgrading was 0.30 kWh m^{-3}_n and subsequent compression of biomethane to 200 bars required 0.16 kWh m^{-3}_n according to Bauer et al., 2013.

2.5 BIOMETHANE HYDRATE SCENARIO

The upgrading of biogas at the biogas production site was assumed to be the same technique as in the reference scenario. The equilibrium pressure and temperature profile for methane hydrate was obtained from Arca et al (2011). The working pressure and temperature was set to 4 MPa and 2°C, respectively. The calculation of power demand for methane hydrate formation including cooling of the hydrate to -30°C was calculated with the same gas and water temperatures and efficiencies as for biogas hydrate. However, for biomethane hydrate the weighted averages for the specific heat capacity and dissociation enthalpies were based on 97% CH_4 and 3% CO_2.

The hydrate was after formation transferred to freezing containers with the same capacity and handling as in the biogas hydrate scenario. The heat needed for hydrate dissociation at the centralized facility was based on melting the hydrate from -10°C and the dissociation enthalpy. The compression heat pump used was the same as in the biogas scenario including recovery of heat from the subsequent compression of biomethane to 200 bars.

2.6 SENSITIVITY ANALYSIS

Assessment of future-oriented scenarios such as the hydrate scenarios is associated with high uncertainties since no data are available from implementation in a real-setting. Without a well-defined process design, a number of assumptions and choices have to be made. Since assumptions made in a scenario study might be critical for the outcome and the results, a sensitivity analysis was performed.

Sensitivity analysis were made on all three scenarios by quantifying the impact of all essential parameters on the system output, i.e. total used energy (kWh), total greenhouse gas emissions (g CO_2 equivalents) and total cost (SEK). The sensitivity analysis was performed by changing each parameter by +/-0.5% and calculating the system output variations using the implemented model. The result was expressed as the relative sensitivity for each individual parameter, i.e. the relative system output variation in relation to the variation of each parameter.

3 RESULTS

The result is divided in three sections; 3.1 energy use, 3.2 global warming potential and 3.3 cost calculations. Moreover, a sensitive analysis is presented in section 3.4.

3.1 ENERGY USE

The overall energy use (expressed as kWh of the direct energy used on the facilities and for transport per MWh of produced biogas) in the three scenarios was lowest in the reference (CBG) scenario, where 81 kWh MWh^{-1} was used (Figure 5). In the biomethane hydrate scenario, 218 kWh MWh^{-1} was used while the highest energy use was obtained in the biogas hydrate scenario (315 kWh MWh^{-1}). The higher energy use in the hydrate scenarios was mainly due to the electricity reqirement for formation and dissociation of hydrate making up 62 % and 56 % of the total energy use for the biogas and biomethane hydrate scenario, respectively. The electricity use for formation and dissociation of hydrates is presented in detail in section 3.1.2. No energy was required during the storage in neither of the scenarios. The higher energy use for transport in the biogas hydrate scenario as compared to the biomethane hydrate scenario was because 75 % more hydrate mass needs to be transported when CO_2 is included. When comparing on farm upgrading with centralized upgrading, more energy was needed in the centralized upgrading system. The main reason for this was that the small scale technique had a lower electricity energy demand for increasing the pressure in the water scrubber, than the conventional water scrubber at the centralized upgrading unit.

The differences in energy use for the compression of biomethane to 200 bars in the biogas and biomethane hydrate scenarios was due to that the compression starts at a higher pressure in the biogas hydrate case because of the pressure build up in the upgrading process. There is no centralized upgrading in the biomethane hydrate scenario.

The energy required for the natural gas compensation in the hydrate scenarios was 19.5 kWh MWh^{-1}.

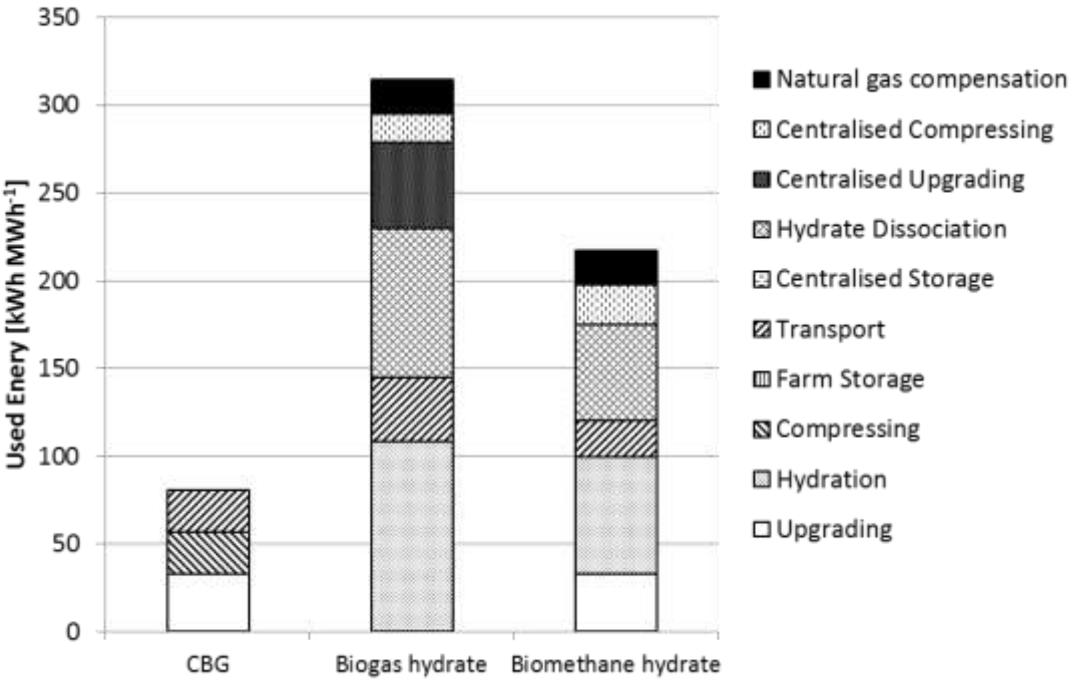

Figure 5. Direct energy use (kWh MWh^{-1} produced biogas) for the reference (CBG) scenario and the biogas and biomethane hydrate scenarios.

3.1.1 *Primary energy*

The distribution of the different energy carriers and the primary energy factors are shown in Table 1.

Table 1. Primary energy factors for the energy sources (Gode et al., 2011) and total use of primary energy in the three scenarios.

	Used energy (kWh/MWh)			Primary energy factor (kWh/kWh)	Primary energy (kWh/MWh)		
	CBG	Biogas hydrate	Bio-methane hydrate		CBG	Biogas hydrate	Bio-methane hydrate
Nordic electricity mix	57	259	177	1.74	99	451	308
Diesel (5 % RME)	24	36	21	1.09	26	39	23
Natural gas	0	20	20	1.09	0	22	22
TOT (Nordic mix)	81	315	218		125	512	353

3.1.2 *Electricity requirement for the formation and dissociation of biogas and biomethane hydrate*

The electricity needed for formation, cooling for storage and dissociation of hydrates is presented in Table 2. It should be noted that e.g. the compression work for biogas and biomethane is the same per m^3_n. However, the differences in density between biogas and biomethane will give a higher value for biomethane on a mass basis. The specific electricity consumption for the hydrate handling is 20% and 12% of the energy content (lower heating value, LHV) in biogas and biomethane (4.90 kWh kg^{-1} biogas and 12.81 kWh kg^{-1} biomethane), respectively. The heating for dissociation and the cooling for the formation of hydrates are the most energy demanding operations making up ca 75% of the total power needed per kg of gas.

Table 2. Electric power needed for the formation, storage and dissociation of hydrates.

	Biogas hydrate (60% CH_4, 40% CO_2)	**Biomethane hydrate (97 % CH_4, 3 % CO_2)**
	kWh$_{el}$ kg^{-1} biogas	kWh$_{el}$ kg^{-1} biomethane
Compression of gas	0.130	0.232
Cooling of gas, water and hydrate formation	0.295	0.457
Pumping and mixing	0.062	0.100
Cooling of hydrate to storage temperature	0.046	0.069
Heating for dissociation	0.467	0.710
Total electricity demand	**1.000**	**1.568**

3.2 GLOBAL WARMING POTENTIAL

The contribution to GWP was considerably higher for the biogas and the biomethane hydrate scenarios compared to the reference scenario, 132% and 106% respectively (Figure 6). The main reasons were increased CH_4 slip and higher energy demand. The CH_4 slip contributed with 56% and 69% of the GWP increase in the biogas and biomethane hydrate scenarios, respectively. The higher energy consumption for the biogas and biomethane hydrate scenarios contributed with 44% and 31% to the respective GWP increase. The CH_4 slip contributed 75% of the total GWP in the CBG reference scenario. The GHG emissions associated with the transport was highest for the biogas hydrate scenario due to the higher diesel consumption (see Figure 5).

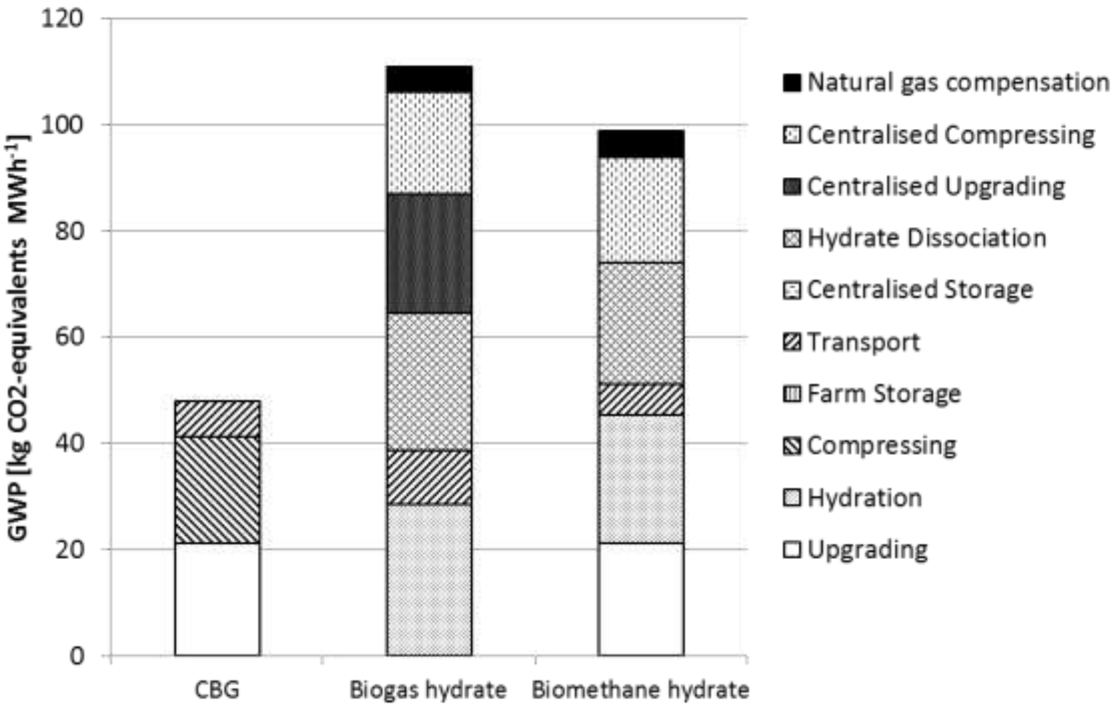

Figure 6. Global warming potential (CO_2-eq. MWh^{-1}) for the reference (CBG) scenario and the biogas and biomethane hydrate scenarios.

3.3 COST CALCULATIONS

Rough assumptions were made for the investment costs for hydrate formation and hydrate dissociation, since no such facilities are currently available on the market. For input data, see Appendix 3.

The overall costs were lowest for the reference scenario (749 SEK MWh^{-1}) followed by the biomethane hydrate scenario (864 SEK MWh^{-1}) and 1142 SEK MWh^{-1} for the biogas hydrate scenario (Figure 7). The increase in cost in relation to the reference scenario was 15% and 52% respectively.

The largest costs in the reference scenario were associated with upgrading in a small scale unit and storage of CBG at the gas station. For the second best scenario; the biomethane hydrate scenario, the upgrading using a small scale unit together with the hydrate formation step consituted more than half of the total cost, 224 and 266 SEK MWh^{-1}, respectively. The biogas hydrate scenario showed the highest costs. This is mainly because of upgrading at a later stage of the process chain, which means that the CO_2 in the biogas is first hydrated, then transported, stored and finally dissociated. The larger costs for these process steps are not compensated by the cheaper upgrading cost when using a larger scale centralized unit.

The investment costs for the containers used for hydrate storage and transport as well as the hook lift containers used for CBG has been included in farm storage and centralised storage. Thus, one of the advantages of using biogas or biomethane hydrate as compared to the reference scenario is the lower storage cost, which mainly is due to a higher investment cost for the hook lift containers with compressed biomethane in gas cylinders.

Some processes are more cost effective in a larger scale in the hydrate scenarios. Such effects can be seen in the upgrading stage in the biogas hydrate scenario and the compressing stage in both hydrate scenarios.

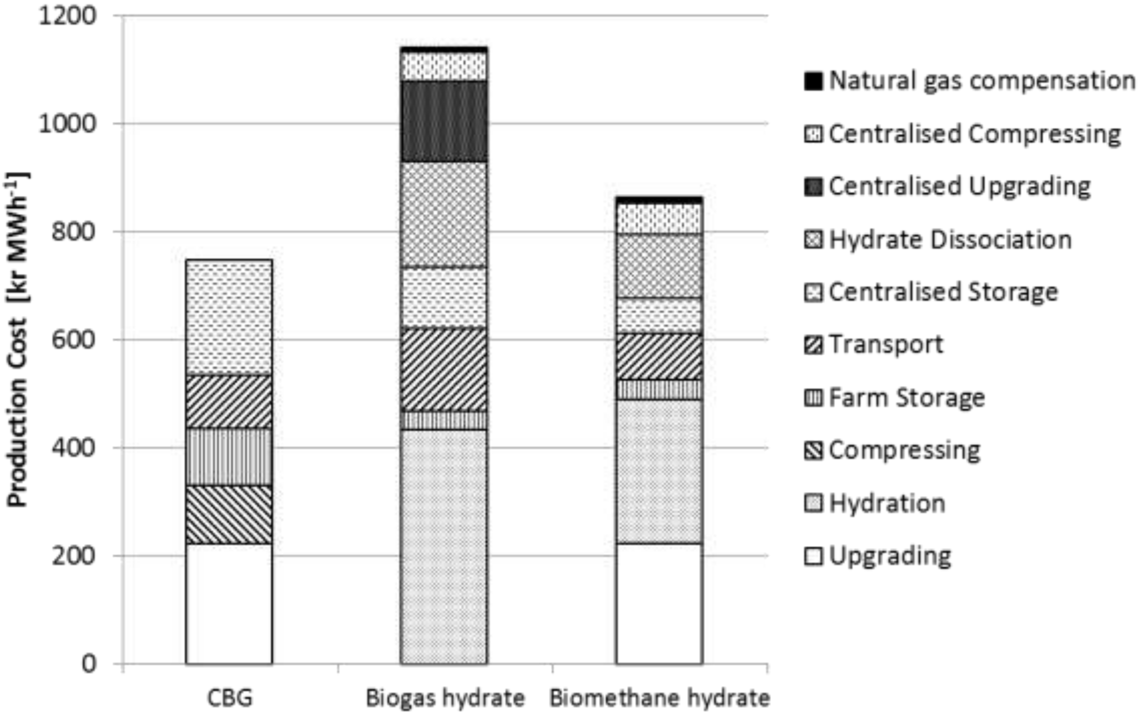

Figure 7. Production cost (SEK MWh^{-1}) for the reference (CGB) scenario and the biogas and biomethane hydrate scenarios.

3.4 SENSITIVITY ANALYSIS

The relative parameter sensitivity is the model variation in relation to the parameter variation. The analysis was performed by changing each parameter +/- 0.5 % while recording the model response. The parameters with equal or higher relative sensitivity than 0.10 on the total system results, are presented in the following tables.

3.4.1 Energy use

Table 3 presents the sensitivity analysis result on total energy consumption. The total energy consumption is sensitive to parameters related to electricity and diesel consumtion. The direct electricity consumption for the biogas upgrading and biomethane compression has a high relative sensitivity in the reference scenario as well as transport distance, loading capacity and the truck's diesel consumption, which has a direct influence on total diesel consumption.

The hydration scenarios also shows high relative sensitivity for the electricity use, which in these scenarios are associated with formation and dissociation of hydrate. However, the hydration number and the efficiency of hydration are clearly important parameters to consider for the energy efficiency of the system.

Table 3. Relative sensitivity on total energy use. Parameters with sensitivity 0.10 or higher.

Parameters	Relative sensitivity
Reference Scenario	
On farm upgrade electricity consumption	0.414
Compressed biomethane loading capacity	0.294
Transport distance	0.294
Diesel consumption (L km^{-1})	0.294
On farm compression electricity consumption	0.292
Biogas hydrate scenario	
Biogas hydration electricity consumption	0.345
Hydration efficiency	0.318
Hydration number	0.318
Biogas hydrate dissociation electricity consumption	0.270
Centralised upgrade electricity consumption	0.156
Hydrate transport capacity	0.116
Transport distance	0.116
Diesel consumption (L km^{-1})	0.116
Biomethane hydrate scenario	
Hydration efficiency	0.306
Hydration number	0.306
Biomethane hydration electricity consumption	0.305
Biomethane hydrate dissociation electricity consumption	0.251
On farm upgrade electricity consumption	0.154
Centralised compression electricity consumption	0.106

3.4.2 GWP

The GWP sensitivity analysis result is shown in Table 4. For all three scenarios, the CH_4 slip is the most important parameter for the GWP impact. Parameters related to diesel consumption have the second highest sensitivity on the GWP impact in the reference scenario. The second most important parameters for the GWP sensitivity in the hydration scenarios are hydration number and hydration efficiency.

Table 4. Relative sensitivity on GWP. Parameters with sensitivity 0.10 or higher.

Parameters	**Relative sensitivity**
Reference Scenario	
On farm upgrade CH_4 slip	0.381
On farm compression CH_4 slip	0.373
Compressed biomethane loading capacity	0.138
Transport distance	0.138
Diesel consumption (L km^{-1})	0.138
Biogas hydrate scenario	
Biogas hydration CH_4 slip	0.191
Hydrate dissociation CH_4 slip	0.186
Centralised upgrade CH_4 slip	0.182
Centralised compression CH_4 slip	0.179
Hydration efficiency	0.137
Hydration number	0.137
Biomethane hydrate scenario	
On farm upgrade CH_4 slip	0.214
Biomethane hydration CH_4 slip	0.210
Hydrate dissociation CH_4 slip	0.205
Centralised compression CH_4 slip	0.201
Hydration efficiency	0.099
Hydration number	0.099

Electricity mix sensitivity

The energy in the scenarios is mainly electricity which makes it interesting from a GWP point of view, to test a different electricity mix. Usage of the Swedish electricity mix produced from nuclear (42%), fossil (4.8%) and renewable energy (53.2%) power plants instead of the Nordic electricity mixture (Gode et al., 2011), the contribution to the total GWP will decrease (Table 5). The highest sensitivity was seen in the biogas hydrate scenario (14.2%) followed by the biomethane hydrate scenario (10.9%). The reference scenario showed the lowest sensitivity (7.2%). This indicates that the hydrate scenarios are more sensitive towards changes in the electricity mixture and hence, a 100% use of renewable energy will substantially reduce the GWP.

Table 5. The effect of using Swedish electricity mix instead of Nordic electricity mix on GWP.

	Scenario 1	**Scenario 2**	**Scenario 3**
		g CO2-eq MWh^{-1}	
Nordic electricity mix 2008*	48	111	99
Swedish electricity mix 2009*	44	95	88
Increase with Nordic mix	7.2 %	14.2 %	10.9 %

*: Gode et al. 2011

3.4.3 Costs

The parameters with the highest relative sensitivity for the costs in the reference scenario are related to investment costs, both direct investment costs and storage time that imply occupation of hook lift containers (Table 6). The parameters associated with loading capacity and transport of containers is also important.

The hydration number and the hydration efficienct have the highest sensitivity in the hydration scenarios. It is clearly important to have an efficient hydration process. In addition, the investment cost for hydration and the electricity cost are important parameters to consider.

Table 6. Relative sensitivity on total cost. Parameters with a sensitivity of 0.10 or higher.

Parameters	Relative sensitivity
Reference Scenario	
CBG hook lift container investment cost	0.424
Centralised storage days	0.284
On farm upgrade investment cost	0.245
On farm storage days	0.140
Compressed biomethane loading capacity	0.132
Compressed biomethane transport cost	0.132
On farm compression investment cost	0.102
Transport speed	0.101
Transport distance	0.101
Biogas hydrate scenario	
Hydration efficiency	0.360
Hydration number	0.360
Biogas hydration investment cost	0.278
Electricity cost	0.200
Hydrate loading capacity	0.132
Hydrate transport cost	0.132
Hydrate container investment cost	0.131
Transport speed	0.102
Transport distance	0.102
Centralised storage days	0.100
Biomethane hydrate scenario	
Hydration efficiency	0.313
Hydration number	0.313
Biomethane hydration investment cost	0.225
On farm upgrade investment cost	0.213
Electricity cost	0.182
Hydrate container investment cost	0.118
Hydrate loading capacity	0.100
Hydrate transport cost	0.100

4 DISCUSSION

The results show that the reference (CBG) scenario are the most energy efficient, has the lowest contribution to the global warming and also the best economic potential in comparison to the two hydrate scenarios. The biomethane scenario showed better performance than the biogas hydrate scenario regarding energy use, GWP and system costs implying that the biogas preferably should be upgraded before hydration. However, the futuristic approach of the hydrate scenarios means that considerable uncertainties are embedded in the results since assumptions had to be made due to lack of experiences and data. The discussion below is therefore addressing the most important parameters identified by the sensitivity analysis in order to show measures needed for improving the overall performance of the biomethane hydrate systems.

The hydrate scenarios in this study are based on formation of hydrate at one location and the dissociation at another location, in order to assess the use of hydrate for transport and storage compared to conventional handling. From the energy efficiency point of view there are obvious advantages if the formation and dissociation of hydrate could be arranged at the same physical site. A preliminary calculation on the heat energy available from the cooling of compressors and heat exchanger during formation of hydrate indicates that it represents 80-90% of the need for heating during dissociation. However, in such a scenario hydrate would merely be used for storage. Assuming that the electricity use for the hydration and dissociation in the biomethane scenario was reduced by 40%, the total energy use would decrease from 218 kWh MWh^{-1} to 169 kWh MWh^{-1}, thus a reduction with 22%. Furthermore, the total cost would decrease from 864 SEK MWh^{-1} to 821 SEK MWh^{-1} (5% decrease).

The results from the sensitivity analysis indicate that the hydration number and the hydration efficiency are important parameters for all the aspects assessed. In a model study by Anderson (2004), the hydration number was shown to vary with temperature and pressure. Between the temperatures 274 K and 318 K, the hydration number was calculated to be highest at 286 K (6.12) and lowest at 294 K (5.71). Another reported hydration number for methane hydrate is 5.99 (Circone et al., 2005). With an ideal hydration number for a structure I-hydrate (1:5.75) and an efficiency of 80% used in this study, the hydrate would contain 137 m^3 CH_4 m^{-3} hydrate (own calculations). Assuming that the ideal hydration number could be obtained with 100% efficiency, i.e. containing 164 m^3 CH_4 m^{-3} hydrate (Pellenbarg & Max, 2000), the overall energy use in the biomehane scenario would be 204 kWh MWh^{-1} compared to 218 kWh MWh^{-1} in the base case. The GWP would decrease from 99 to 97 g CO_2-eq. MWh^{-1} and the total cost would decrease to 809 SEK MWh^{-1} (6% decrease).

The CH_4 slip was clearly the most important parameter affecting the GWP according to the sensitivity analysis. In this study we have assumed that the CH_4 slip for hydrate formation and dissociation is in the same range as for upgrading, i.e. 2%. Assuming that the hydration and dissociation could be operated without any CH_4 slip and no compensation of natural gas would be necessary, the GWP would be 40% less for the biomethane scenario. This indicates the importance to take measures to avoid CH_4 losses in the biomethane hydrate system.

The investment costs for hydrate formation and dissociation is presumably the most uncertain parameters. The cost was assumed to be in the same range as today´s small upgrading units. However, the development of both a hydrate formation and a hydrate dissociation unit will require a cost that the market is willing to pay for. Another uncertain investment cost is the special containers used for transport, storage and dissociation. The number of containers needed for the whole system is also dependent on the storage time. Assuming that the total investment cost in the biomethane hydrate scenario would be the same as for the CBG-scenario, this would correspond to a reduction in the investment for hydration and dissociation of ca 30%.

Considering the total effect of all the suggested changes above in comparison with the base case for biomethane hydrate, i.e. 40% less electricity use for hydration and dissociation, 100% hydration efficiency, no methane slip from the hydrate formation and dissociation and 30% lower investment cost for hydration and dissociation, the outcome from the model shows the following results: The total energy used would be 158 kWh MWh^{-1}, which would be almost twice the energy used in the reference (CBG) scenario. The GWP would be 54 g CO_2-eq. MWh^{-1}, which is ca 12% higher than in the CBG scenario. The total cost would be 621 SEK MWh^{-1}, which is 17% lower compared to the CBG scenario (749 SEK MWh^{-1}).

The future-oriented approach for the use of hydrates in systems for utilizing biogas as a vehicle fuel has several inherent uncertainties as mentioned before. The results in this study indicate that the energy use is not favourable when considering using hydrate as a mean for transporting gas from a production site to be used at another site. For future studies, the integration of hydrate for storage at centralized biogas plants would be interesting to study as well as integration with e.g. return water in a district heating system or surplus heat from a CHP-plant for dissociation heat. Furthermore, an expansion of the system also including the anaerobic digestion process, where low-grade heat from the cooling during hydrate formation could be utilized would likely improve the overall efficiency of the system. The future development of hydrate technologies is, in addition to the system integration assessment, important to consider. For CH_4-CO_2 hydrate mixtures, the CO_2 is more easily released as compared to CH_4 (Kwon et al., 2011). This phenomenon has been proposed to be utilized as an upgrading process (Arca et al., 20011), which would make it possible to integrate dissociation and upgrading in one process. Furthermore, the use of detergents such as SDS (Sodium dodecyl sulfate) has been shown to enhance the hydrate formation rate at lower pressures with reduced stirring (Zhong & Rogers, 2000). Thus, the perspectives of technical development are promising and could reduce the limitations of future hydrate use in industrial scale.

5 CONCLUSIONS

- Overall, the reference (CBG) scenario showed the best results for all parameters assessed in the base case scenario.
- The biomethane hydrate scenario showed higher potential as compared to biogas hydrate scenario regarding all parameters assessed.
- A reduction of the investment costs with 30% in the biomethane hydrate scenario would be required to make it competitive to the reference scenario.
- The higher energy use in the hydrate scenarios was mainly due to the electricity reqirement for formation and dissociation of hydrate. The integration of hydrate formation and dissociation would improve the overall energy balance.
- The CH_4 slip contributed with 56% and 69% of the GWP increase in the biogas and biomethane hydrate scenarios, respectively. A reduction of the CH_4 slip to zero during formation and dissociation (compared to the assumption of 2%) would remarkably decrease the contribution to the GWP for the hydrate scenarios also since no natural gas would be needed for compensation.
- The uncertainties embedded in the data due to lack of experiences of commercialized hydration and dissociation processes have to be taken into account.
- To reduce the limitations for future use of hydrate it is important to consider aspects on system integration as well as technological development.

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APPENDIX 1

MetaHyd AB, Sven-Olov Holm

Metod och utrustning med potential att effektivisera lagring, uppgradering och transport av biogas

Bakgrund:

Våren 2010 började Sven-Olov Holm att arbeta som projektledare i ett offentligt finansierat projekt. Hans roll var att under två år försöka utveckla energi och miljöteknikbranschen i Gästrikland.

Sven-Olov som redan 30 år tidigare, för första gången, intresserat sig för biogasproduktion undersökte från sin nya position vad som skett inom området fram till dags dato. Tyvärr konstaterade han att de gamla stötestenarna fanns kvar, bland annat svårigheten att få till kostnadseffektiv uppgradering, transport och lagring av den producerade biogasen.

Så var alltså läget när olyckan med ”Deep Water Horizon” inträffade i mexikanska golfen 2010.

Oljebolagets problem med att stoppa gasläckan låg till grund för den idé som Sven-Olov då fick.

Att med hjälp av metanhydratbildning utveckla en helt ny metod för uppgradering, lagring och transport av biogas.

Drivkraften bakom viljan att genomföra detta är primärt att minska vår negativa miljöpåverkan och att öka lönsamhet och sysselsättning på landsbygden. Som en person med rötterna i jordbruket lider han av att se landsbygden utarmas och att urbaniseringen ökar.

Sekundärt finns förstås också önskan att utveckla ett företag vars utrustning och metoder kan saluföras både nationell och internationellt.

För att en innovatör och småföretagare skall kunna göra detta på ett bra sätt krävs att det finns goda relationer till den inom området existerande forskningen, både nationellt och internationell. Att hela tiden ha möjligheten att få en ”second opinion” är väldigt viktigt i utvecklingsarbetet.

APPENDIX 2

Input data for energy calculations.

Parameter	**Value**	**Unit**	**Reference**
Density CH_4 (0 °C, 1 atm)	0.717	kg m^{-3}	http://www.engineeringtoolbox.com/gas-density-d_158.html
Density CO_2 (0 °C, 1 atm)	1.977	kg m^{-3}	http://www.engineeringtoolbox.com/gas-density-d_158.html
cp CH_4 (0 °C, 1 atm)	2.22	kJ kg^{-1} K^{-1}	http://catalog.conveyorspneumatic.com/Asset/FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf
cp CO_2 (0 °C, 1 atm)	0.844	kJ kg^{-1} K^{-1}	http://catalog.conveyorspneumatic.com/Asset/FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf
cp H_2O	4.19	kJ kg^{-1} K^{-1}	Nordling and Österman, 2006
cp ice 0 °C	2.05	kJ kg^{-1} K^{-1}	http://www.engineeringtoolbox.com/ice-thermal-properties-d_576.html
cp ice -5 °C	2.027	kJ kg^{-1} K^{-1}	http://www.engineeringtoolbox.com/ice-thermal-properties-d_576.html
cp ice -10 °C	2.000	kJ kg^{-1} K^{-1}	http://www.engineeringtoolbox.com/ice-thermal-properties-d_576.html
cp ice -15 °C	1.972	kJ kg^{-1} K^{-1}	http://www.engineeringtoolbox.com/ice-thermal-properties-d_576.html
cv CH_4 (0 °C, 1 atm)	1.7	kJ kg^{-1} K^{-1}	http://catalog.conveyorspneumatic.com/Asset/FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf
cv CO_2 (0 °C, 1 atm)	0.655	kJ kg^{-1} K^{-1}	http://catalog.conveyorspneumatic.com/Asset/FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf
κ CH_4 (0 °C, 1 atm)	1.304		http://catalog.conveyorspneumatic.com/Asset/FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf
κ CO_2 (0 °C, 1 atm)	1.289		http://catalog.conveyorspneumatic.com/Asset/FLS%20Specific%20Heat%20Capacities%20of%20Gases.pdf
Hydrate dissociation enthalpy CH_4	54.5	kJ mol^{-1}	Kwon et al., 2011
Hydrate dissociation enthalpy CO_2	61	kJ mol^{-1}	Kwon et al., 2011
Energy content CH_4 (0 °C, 1 atm)	9.97	kWh m^{-3}	
Energy content diesel	9.778	kWh dm^{-3}	Gode et al., 2011
Thermal conductivity ethanol	0.185	W m^{-1} K^{-1}	Alvarez, 2006. p. 362
Thermal conductivity styrofoam	0.037	W m^{-1} K^{-1}	http://energihandbok.se/x/a/i/10673/Tabell---Varmeledningsformaga-och-U-varden-for-olika-material.html
Electricity demand small water scrubber	0.20	kWh $m^{-3}{}_n$	Bauer et al., 2013
Electricity demand large water scrubber	0.30	kWh $m^{-3}{}_n$	Bauer et al., 2013
Electricity demand compression 200bar (Biogas hydrate scenario)	0.16	kWh $m^{-3}{}_n$	Bauer et al., 2013
Electricity demand compression 200bar (Biomethane hydrate scenario)	0.23	kWh $m^{-3}{}_n$	Bauer et al., 2013

APPENDIX 3

Input data for cost calculations of hydrates.

Parameter	**Value**	**Unit**	**Reference**
Personal cost	245	SEK h^{-1}	Maskinkostnader 2012
Interest rate	7	%	assumed
Electricity (excl. vat)	0.89	SEK kWh^{-1}	E.ON, 2012
Natural gas compensation (excl. vat)	0.45	SEK kWh^{-1}	http://www.eon.se/privatkund/Produkter-och-priser/Naturgas/Naturgasprislista/
Hydrate formation			
Investment cost of hydration facility	5 000 000	SEK	assumed
Depreciation time	15	years	assumed
Residual value of hydration facility	10 000	SEK	assumed
Maintaince	2.5	% of investment cost	assumed
Working time	0.5	h day^{-1}	assumed
Storage of hydrate			
Investment cost of three containers	600 000	SEK	assumed
Depreciation time	15	years	assumed
Residual value of hydration facility	10 000	SEK	assumed
Maintaince	2	% of investment cost	assumed
Storage of CBG			
Investment cost, two gas trailers	2 000 000	SEK	Personal communication, Christopher Thelin, E.ON Gas
Depreciation time	15	years	assumed
Maintaince	10000	SEK	assumed
	2	% of investment cost	assumed
Transport			
Cost, truck + trailer	900	SEK h^{-1}	personal communication, MLT http://www.mltab.com/
Dissociation			
Investment cost, dissociation facility	10 000 000	SEK	assumed
Depreciation time	15	years	assumed
Residual value of upgrading unit	10000	SEK	assumed
Maintaince	2.5	% of investment cost	assumed
Working time	0.5	h day^{-1}	assumed
Upgrading			

Investment cost, water scrubber large scale	15 000 000	SEK	Persson, 2003
Depreciation time	20	years	Persson, 2003
Residual value of upgrading unit	10000	SEK	Persson, 2003
Maintaince	2.5	% of investment cost	Persson, 2003
Working time	0.25	h day^{-1}	Persson, 2003. (50/50 split between upgrading and compression)
Investment cost, water scrubber small scale	4 000 000	SEK	Bauer et al., 2013
Depreciation time	20	years	assumed
Residual value of upgrading unit	10000	SEK	assumed
Maintaince	2	% of investment cost	Kovac, 2013
Electricity demand	0.2	kWh Nm$_n^{-3}$	Bauer et al., 2013
Working time	0.25	h day^{-1}	Persson, 2003. (50/50 split between upgrading and compression)
Compression			
Working time	0.25	h day^{-1}	Persson, 2003. (50/50 split between upgrading and compression)
Cost of compression (2 GWh year^{-1})	0.10	SEK kWh^{-1}	45 % of the upgrading cost based on Benjaminsson and Nilsson, 2009