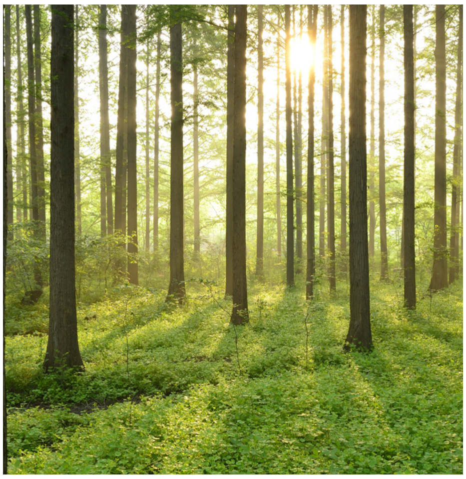
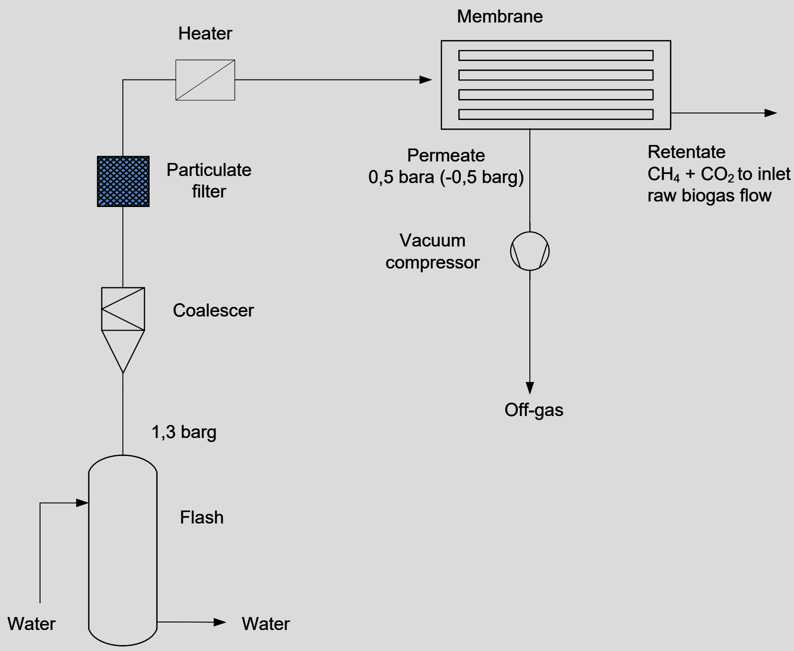
MEMBRANE INTEGRATION TO SIGNIFICANTLY IMPROVE WATER SCRUBBER PERFORMANCE

REPORT 2015:179



ENERGY GASES AND LIQUID FUELS



Energiforsk

Membrane integration to significantly improve water scrubber performance

Optimized water scrubber

JOHAN BENJAMINSSON
GUNNAR BENJAMINSSON
KERSTIN HOYER
TOBIAS PERSSON

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Energiforsk AB | Telefon: 08-677 25 30 | E-post: kontakt@energiforsk.se | www.energiforsk.se

Authors' foreword

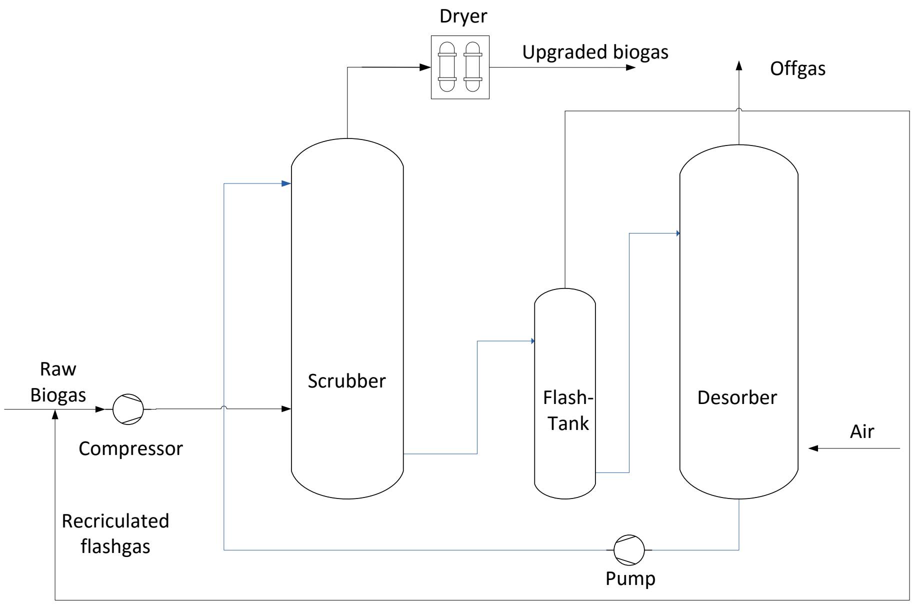
Gasefuels has a patent application regarding biogas upgrading with a hybrid solution using membranes and water scrubber technology. This study is a step in the commercialization of this hybrid technology. The report has been produced in collaboration with Air Products and Malmberg Water. Authors are Johan Benjaminsson, Gunnar Benjaminsson, Tobias Persson (Gasefuels) and Kerstin Hoyer (Malmberg Water).

The study was funded by the Swedish Energy Agency, Gasefuels and Malmberg Water. The study had a reference group with following members: Mattias Svensson (Energiforsk), Johan Benjaminsson (Gasefuels) and Kerstin Hoyer (Malmberg Water).

Sammanfattning

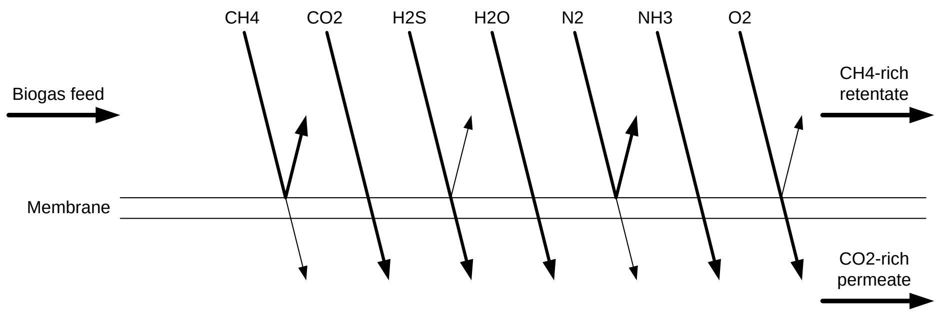
Biogas används idag både i Sverige och internationellt som drivmedel till fordon. Biogasen består normalt sett till huvudsak av metan (50-70 %) och koldioxid (30-50 %) samt även mindre mängder vatten och svavelväte. Grundläggande för användandet av biogas till fordon är att den producerade biogasen måste uppgraderas till fordonsgaskvalitet, vilket görs genom avlägsnande av koldioxid, men även vatten och svavelväte. Denna uppgraderingsprocess kan utföras med olika tekniker, så som vattenskrubber-, aminoskrubber-, Pressure-Swing-Adsorption- och membranteknik. Genom att kombinera vattenskrubberteknik och membranteknik kan fördelar vinnas och denna rapport har som syfte att utreda och klarlägga dessa fördelar.

Den vanligaste tekniken för uppgradering av biogas till fordonsgaskvalitet i Sverige är vattenskrubbertekniken. Vattenskrubbertekniken baseras på att koldioxid har en högre löslighet i vatten jämfört med metan, där ett högre tryck påverkar lösligheten positivt ytterligare. Detta utnyttjas genom att biogasen leds in i en kompressor där gasen komprimeras till 7 bar(g) för att därefter ledas in till en skrubberkolonn där biogasen möter ett motriktat vattenflöde (se bild nedan). När biogasen möter vattnet löser sig koldioxiden i vattnet samtidigt som biogasen renas från koldioxid och uppgraderad biogas kan tas ut i toppen av skrubberkolonnen. Vattnet innehåller inte bara koldioxid utan även en viss mängd metan som hunnit lösa sig i vattnet. Därför leds gasen till en flashkolonn där trycket sänks till 1,3 bar(g). Vid trycksänkningen frigörs den största delen av metanen från vattnet tillsammans med en viss andel av koldioxiden och leds tillbaka till kompressorn, vilket minskar metanförlusterna avsevärt. Totalt återcirkuleras cirka 25 % av inkommande biogas på detta sätt. Återstoden av vattnet leds sedan till en desorptionskolonn där trycket sänks till atmosfärstryck och koldioxiden avgår till atmosfären samtidigt som vattnet återcirkuleras till skrubberkolonnen.



Kapaciteten i absorptionskolonnen bestäms i huvudsak av flödet biogas in till skrubberkolonnen. Då cirka 25 % av biogasen återcirkuleras via flashgasen innebär det att en minskning av detta flöde både skulle leda till högre kapacitet i vattenskrubbern samt att den specifika energikonsumtionen skulle minska då mindre mängd gas måste tryckhöjas flera gånger.

En annan teknik för uppgradering av biogas är membrantekniken som använder sig av membran genom vilket vissa gaser passerar lättare än andra (exemplifierat i bilden nedan). Membranen sätts ihop i så kallade membranenheter och den enklaste typen av uppgradering är att bara använda en membranenhet genom vilken biogasen flödar och koldioxiden avskiljs, vilket dock medför stora metanförluster för att uppnå önskad reningsgrad. För att uppnå önskvärd kvalitet på biogasen används därför många membranenheter mellan vilka gaserna cirkuleras, där de första stegen i sådana konfigurationer är de som tar bort bulkmängden av koldioxiden.



Genom att integrera vattenskrubbertekniken och membrantekniken för uppgradering till en hybridlösning kan synergieffekter uppnås. Dessa nås genom att stora delar av koldioxiden i det återcirkulerade flashgasflödet från flashkolonnen avskiljs med hjälp av membranteknik. Genom detta kan det återcirkulerade flödet minskas, med högre kapacitet och lägre specifik energiförburkning i vattenskrubbern som följd.

Potentialen i en hybridlösning mellan vattenskrubberteknik och membranteknik undersöktes genom simuleringar av olika fall i samarbete med Malmberg Water AB, leverantör av vattenskrubbrar, och Air Products, leverantör av membran.

Totalt undersöktes fyra olika kofigurationer för vilka påverkan på den totala kapaciteten, den specifika energianvändningen samt den specifika investeringskostnaden togs fram och jämfördes med en GR14-anläggning från Malmberg Water. De fyra konfigurationerna som undersöktes var:

Hybridfall I – Högre flashtryck för ökat feedtryck till membranet

Hybridfall II – Blåsmaskin före membranet för ökat feedtryck till membranet

Hybridfall III – Vakuumpump för lägre permeattryck

Hybridfall IV – Kombinerad blåsmaskin och vakuumpump

Simulationerna utfördes med utgångspunkt från att de totala metanutsläppen inte skulle öka mer än 30 % jämfört med en vanlig vattenskrubberanläggning.

Baserat på simulationerna kan det ses att hybridfall III är det mest intressanta: Jämfört med en GR14-anläggning gav det 7,2 % lägre specifik energikonsumtion, 4,9 % lägre specifik investeringskostnad samt 2,1 % lägre uppgraderingskostnad. Minskningen i specifik energikostnad kan härledas till minskningen av det återcirkulerade flödets storlek, vilket frigör kapacitet i vattenskrubberanläggningen. Den lägre specifika investeringskostnaden är vidare ett resultat av den relativt sett låga kostnaden, i förhållande till den vunna kapaciteten, som membran uppbringar vid denna enkla typ av bulkseparering av koldioxid. Totalt bidrar den lägre energikonsumtionen och specifika investeringskostnaden till den lägre specifika uppgraderingskostnaden, även om denna motverkas något av ökade metanförluster.

Utöver att hybridlösningen mellan vattenskrubber- och membranteknik verkar intressant för nya anläggningar, innebär det även en intressant möjlighet för befintliga vattenskrubbrar att utöka sin kapacitet genom integrering av membranteknik.

Summary

Biogas is currently used both in Sweden and internationally as an automotive fuel. The biogas mainly consists of methane (50-70%) and carbon dioxide (30-50%). Fundamental to the automotive use of biogas is that the biogas must be upgraded to automotive fuel quality, which is done by the removal of mainly carbon dioxide.

The most common technique for upgrading biogas to vehicle fuel quality in Sweden is the water scrubber. The water scrubber technology is based on the fact that carbon dioxide has a higher solubility in water compared to methane. The capacity of a water scrubber is mainly determined by the flow into the scrubber column. Since about 25% of the biogas is recirculated via the flash gas, a reduction of this flow would lead to both higher capacity and lower specific energy consumption.

Another technique for upgrading biogas is membrane technology that uses membranes through which certain gases pass more easily than others. The membrane is particularly useful for bulk separation of carbon dioxide.

By combining water scrubber- and membrane technology into a hybrid solution for upgrading, synergies can be achieved. These are achieved by reducing the recirculated flash gas stream from the flash column by means of membrane technology. By this, the recirculated flow is reduced with higher capacity and lower specific energy consumption in the water scrubber as a result.

The potential of the hybrid solution between the water scrubber- and the membrane technology was investigated through simulations of different cases in cooperation with Malmberg Water AB, a supplier of water scrubbers, and Air Products, a supplier of membranes.

In total, four different configurations were examined for which the impact on the total capacity, specific energy consumption, specific investment cost and specific upgrading cost was outlined and compared with a GR14-plant from Malmberg Water AB.

Based on the simulations, it can be seen that the hybrid case with a vacuum pump lowering the pressure on the membrane permeate side is the most interesting implying 7.2% lower specific energy consumption, 4.9% lower specific investment cost and 2.1% lower specific upgrading cost compared to a GR14 plant.

Beside that the hybrid solution of water scrubber- and membrane technology seems interesting for new plants, it also reveals an interesting opportunity for existing water scrubbers to expand their capacity through the integration of membrane technology.

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1 Introduction

1.1 BACKGROUND

In Sweden electricity is produced by hydro, wind and nuclear power without contribution to the greenhouse effect to any great extent, while our vehicles are running on almost exclusively fossil fuels. Sweden has a vision of a fossil-free vehicle fleet by 2050 and an increased development of renewable alternatives is necessary to realize this vision. Biogas production in Sweden in 2005 was approximately 1.3 TWh and 9 years later (2014) it was approximately 1.8 TWh[1] (2% of the energy consumed in the transport sector[2]). The largest barrier to speed up the development of a greater utilization of the biogas potential in Sweden is the limited profitability of the production of upgraded biogas. Biogas production is mainly based on substrates, such as food waste and sewage sludge, that are cheap, free or even such substrates that the biogas producer is being paid to receive. The biogas production potential of the substrates mentioned is limited to 2-3 TWh in Sweden. However, if we can reduce costs throughout the chain in the production of upgraded biogas, more expensive substrate such as straw may be used, and then Sweden can reach a biogas production of 10 TWh.[3]

Biogas upgrading costs are frequently singled out as one of the challenges to achieve higher profitability in the production of biomethane used as automotive fuel from anaerobic digestion. Sweden's and the world's most common technology for upgrading biogas is the water scrubber (69% of the Swedish upgrading plants[1] and 41% of world's upgrading plants[4]). This project is a pilot study to dimension, design and theoretically evaluate a hybrid solution to reduce both the specific investment cost and energy consumption of the water scrubber. This innovative technology solution is intended for installation in both new and existing water scrubbers in the market. A patent application is submitted in order to protect the invention by Gasefuels AB.

The technology has been developed through a unique combination of knowledge of membrane technology and the design of a water scrubber. In a water scrubber there is a circulating gas flow between the flash column and the compressor. This consists mainly of carbon dioxide (80-90%) and a minor proportion of methane (10-20%). This circulating gas flow increases power consumption in both the compressor and water pump by about 20-25% while limiting the capacity of the absorption and desorption columns by 20-25%.

[1] Produktion och användning av biogas och rötrester år 2014, ES 2015:03
[2] Energy in Sweden 2014 – Facts and figures, Swedish Energy Agency
[3] Den svenska biogaspotentialen från inhemska restprodukter, BioMil (2008)
[4] Biomethane – Status and Factors Affecting Market Development and Trade, IEA (2014)

Although the pressure of this gas is quite low (about 2 bar(g)), the partial pressure of carbon dioxide is on a suitable level for membrane separation. By placing a membrane for bulk removal of CO_2, the flash gas flow will be reduced by around 50%. The beauty of this process is that the carbon dioxide concentration just needs to be reduced from 90% to 50% in order to have a significant reduction of energy consumption of the water scrubber.

The project has been carried out in cooperation between one of the world's leading biogas upgrading companies, Malmberg Water AB, and Gasefuels AB that is an experienced consultant in the field. A significant contribution has also been made by Air Products which is one of the leading companies in the field of gas separation by membrane. The cooperation is crucial for the project since there must be confidence in the product from the existing suppliers of water scrubbers. The executors of the project have great knowledge about the biogas upgrading industry and particularly in-depth knowledge of both the water scrubber and the membrane technology.

2 Theoretical and Technical Background

2.1 BIOGAS UPGRADING USING WATER SCRUBBER TECHNOLOGY

The solubility of carbon dioxide in water is about twenty times higher than the solubility of methane in water. The water scrubber technology uses this fact to separate carbon dioxide and methane, which are the main components in biogas. The solubility is increased with increased pressure and decreased temperature. Figure 1 shows a flow chart of a water scrubber.

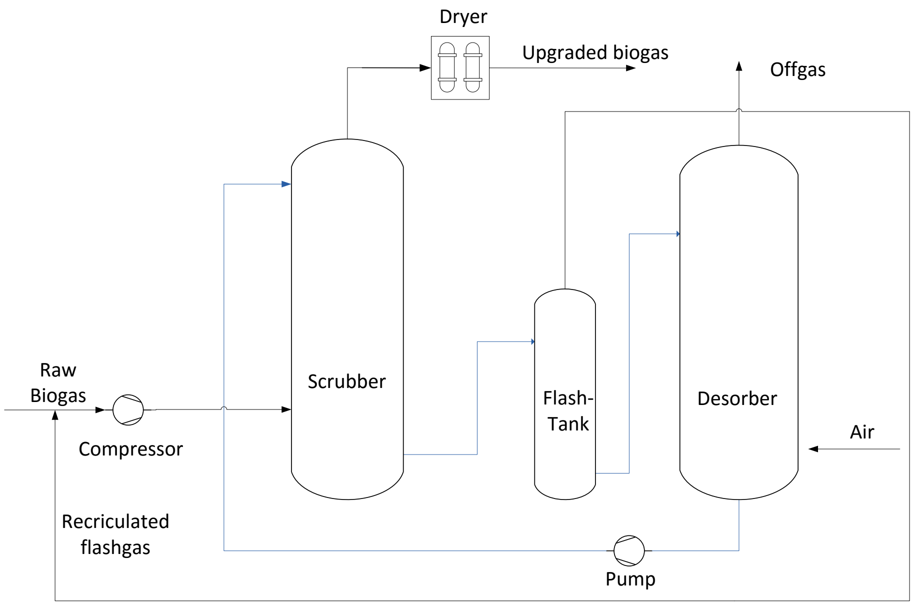

Figure 1 **A flow sheet of a water scrubber**

In the water scrubber, incoming raw biogas is compressed in a compressor up to 5-10 bar(g) and led to the scrubber column in which the water absorbs the carbon dioxide. In the upper part of the scrubber column, close to pure methane is obtained. The carbon dioxide is dissolved in the water together with a minor part of the methane gas. In order to minimize the methane loss, the water is led to the flash column in which the pressure of the water is reduced to around 1,3-2,5 bar(g). A flash gas flow with 10-20% methane and 80-90% carbon dioxide is released from the water and led back to the compressor. The pressure of the water is thereafter decreased to atmospheric pressure in the desorption column and air is bubbled through the water in order to reduce the partial pressure of the carbon dioxide and thereby release the remaining carbon dioxide from the water. The water is finally circulated back into the absorption column to absorb carbon dioxide once again.[5]

The capacity of the water scrubber is mainly determined by the compressor, the water pump and the diameter of the scrubber, flash and the desorption

[5] SGC Report 270, Bauer et al

column. The capacity of all these units is in turn determined by the incoming gas flow to the compressor and thereafter the scrubber column.

2.2 BIOGAS UPGRADING WITH MEMBRANES

A membrane is a dense filter that can separate the components in a gas or a liquid down to the molecular level. The permeability of the gases varies depending on which membrane material that is used and how the membranes are produced.

The initial commercial applications for gaseous membrane separations were for separating H_2 from N_2 in ammonia purge gas applications and CO_2 from CH_4 in natural gas and landfill applications. Air separation applications followed almost 10 years later, as the membrane economics improved.

All commercially available polymeric membranes are more permeable to carbon dioxide than to methane. This is the reason why the membranes can be used for biogas upgrading, as illustrated in Figure 2.

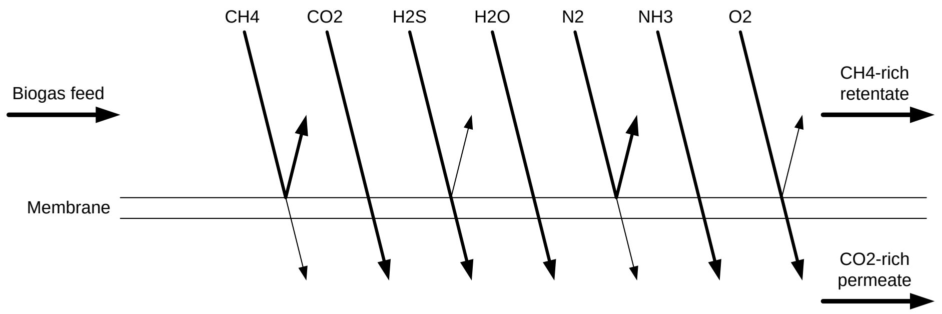

Figure 2 **Basic principle of a membrane**[6]

Polymeric hollow fiber membranes are the most common type of membranes used for separation of methane and carbon dioxide.[7] An example of a polymeric hollow fiber membrane used in commercial biogas upgrading plants is shown in Figure 3.

[6] http://bio.methan.at/sites/default/files/images/Gaspermeation_Prinzip_en_normal.png
[7] Membrane based biogas upgrading processes, Scholz (2013)

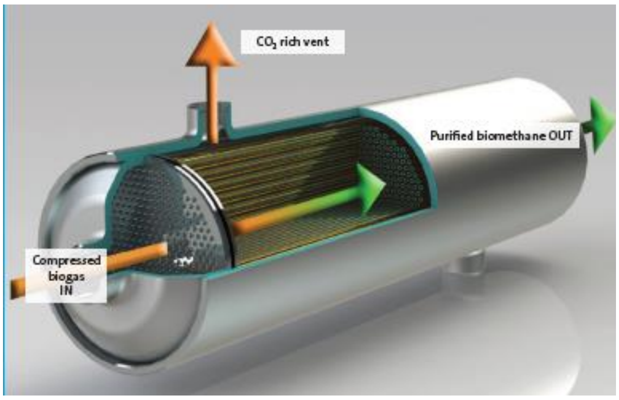

Figure 3 **Polymeric hollow fibers that are packed in a module[8]**

2.2.1 Permeability and selectivity

Membranes performances are characterized by their permeability and selectivity. The permeability of a membrane is a measure of how easy a certain gas permeates through the membrane. Permeation is a function of both diffusivity and solubility. Figure 4 shows how the methane molecule is bigger than the carbon dioxide molecule and therefore less permeable in the membranes used.

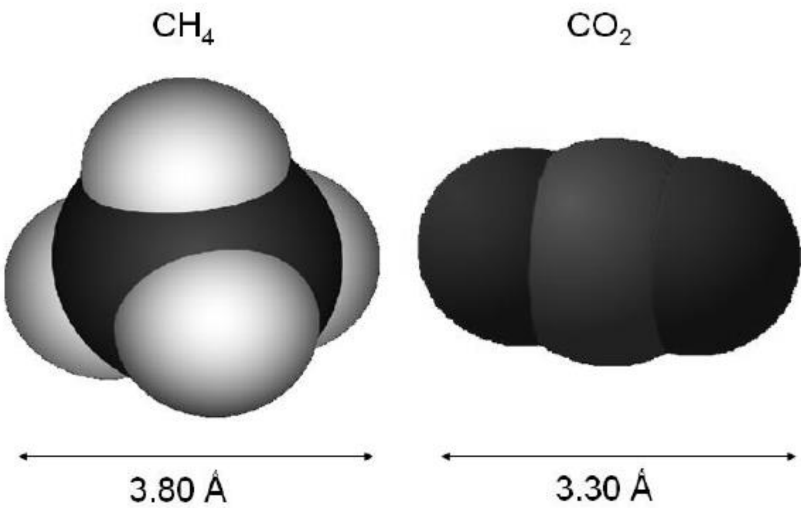

Figure 4 **Sizes of methane and carbon dioxide molecules[9]**

The difference in diffusion velocity through the membrane together with the solubility of the gas in the membrane strongly affects the selectivity (α) between two gas molecules to pass through the membrane. The selectivity is defined as $\alpha = (P\ CO_2)/(P\ CH_4)$ where P is the permeability coefficient. Typical

[8] Prism membrane separators for biogas upgrading, Air Products
[9] Membrane technologies for CO2 capture, Simons (2010)

selectivity between carbon dioxide and methane, when using polymeric membranes, are in a wide range from 1,4 – 42,8.[10]

In order to maintain a high permeability it is important to keep the incoming gas stream clean from particles as well as contaminants that can condensate on the membrane surface.

2.2.2 Driving forces

The driving force of a specific gas to pass across the membrane is the difference in partial pressure of the gas on the different sides of the membrane. Hence, it is of great importance to keep up a difference in partial pressure of the specific gas over the sides of the membrane. The difference can as an example be obtained by increasing the pressure on the retentate side or of the use of a vacuum pump on the permeate side.[11] An increased driving force corresponds to a reduced demand of membrane surface and thus also a reduced investment costs.

2.2.3 Membrane configurations

In order to obtain the driving force needed for successful separation, membranes can be configured in various ways. Examples of a membrane separation plant with a single membrane stage are illustrated in Figure 5.

The upper example shows how a compressor is used on the retentate side and ambient pressure on the permeate side in order to increase the pressure and hence the driving forces for permeation. This is a very easy set up for membrane separation.

The lower example shows how a vacuum compressor is connected to the first example. Thereby a sub ambient pressure on the permeate side is created by the vacuum compressor and hence the result is a higher driving force in comparison to if ambient pressure is used on the permeate side.

[10] Membrane gas separation technologies for biogas upgrading, Chen et. al (2015)
[11] SGC Report 270, Bauer et al

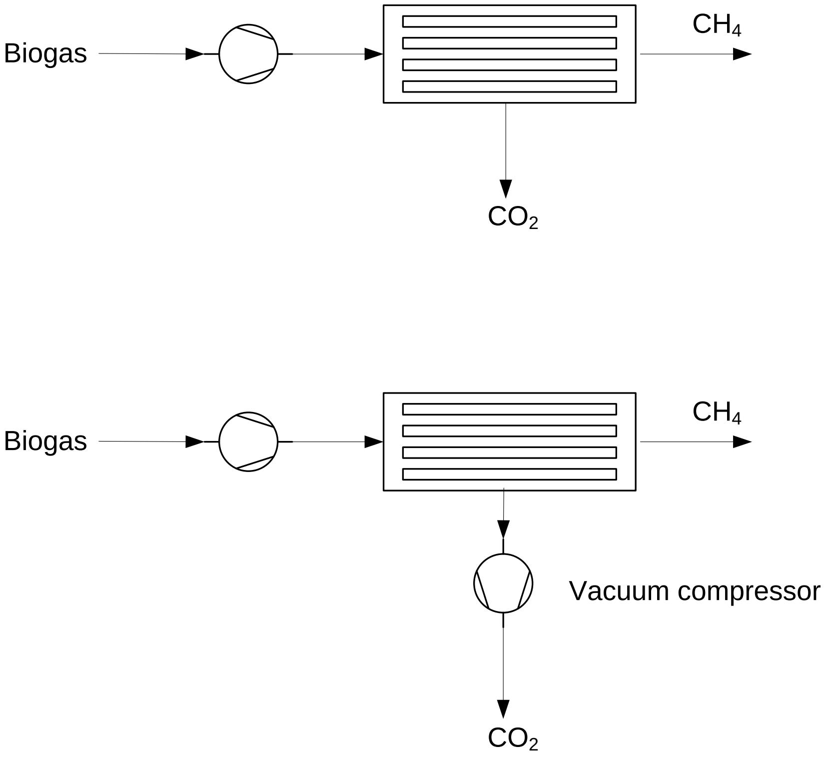

Figure 5 **Examples of a membrane separation plant with a single membrane stage**

2.3 WATER SCRUBBER AND MEMBRANE HYBRID PLANT

Gasefuels AB has applied for a patent of a water scrubber that is integrated with a membrane unit as shown in Figure 6.

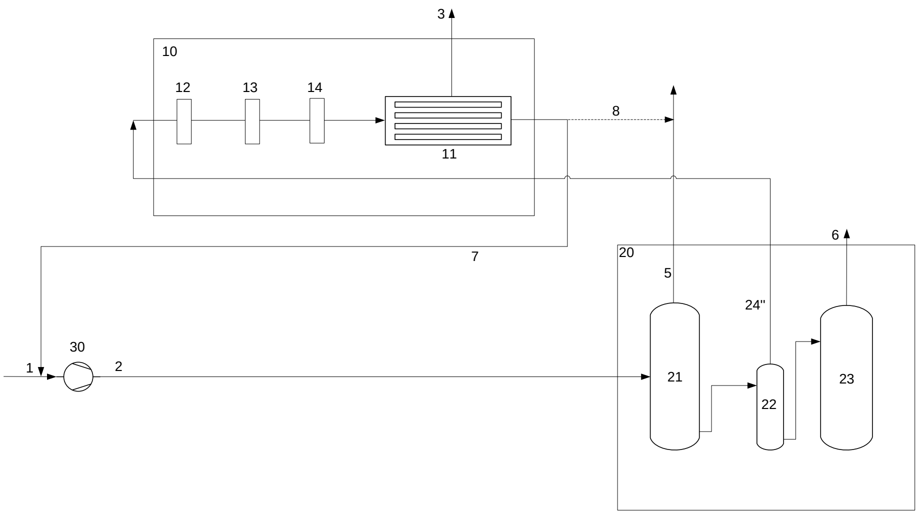

Figure 6 **Flow chart of how a membrane unit can be integrated with a water scrubber**

At normal operation of a water scrubber the incoming raw gas stream is merged with the flash gas stream and thereafter pressurized in the compressor and led to the absorption column. This results in a situation in which 20-25% of the incoming raw gas flow is recirculated through the system generating higher energy consumption. Also, the raw gas capacity is limited as both the raw gas and the recirculated gas stream need to be compressed. Therefore, the raw gas stream could be increased if the recirculated stream would have been smaller or used for something else.

By combining a water scrubber with a membrane unit, the methane in the gas released in the flash column is concentrated in the membrane unit before it is led back to the compressor. By decreasing the recirculated gas flow, through the addition of a membrane stage, the raw gas flow can be increased. A higher incoming raw gas flow results in decreased specific energy consumption (energy consumption per purified unit of biomethane).

3 Case Study of Membrane Integration with a Water Scrubber Plant

In order to quantify the advantages of a water scrubber/membrane hybrid solution for biogas upgrading, different cases of such hybrid solutions have been studied based on simulations. Totally, 4 different cases have been simulated.

The simulations have been carried out in cooperation with Malmberg Water and Air products. For the simulations, the parameters found in Table 1 have been set as basis/limiting factors for the simulations.

Table 1 Parameters used in the simulations to evaluate different cases of membrane integration with a water scrubber

Maximum methane loss in comparison to normal water scrubber	30	% increase
Yearly production time	8500	h/year
Depreciation time	10	Years
Interest	5	%
Cost methane	7,50	SEK/Nm3 methane
Cost electricity	0,75	SEK/kWh

3.1 BASE CASE - WATER SCRUBBER GR14

The simulations of a hybrid water scrubber/membrane upgrading solution are based on the GR14 water scrubber from Malmberg Water with a capacity of 1400 Nm3/h raw biogas. The principles of GR14 is similar to other water scrubbers on the market, and can schematically be drawn as in Figure 7 below.

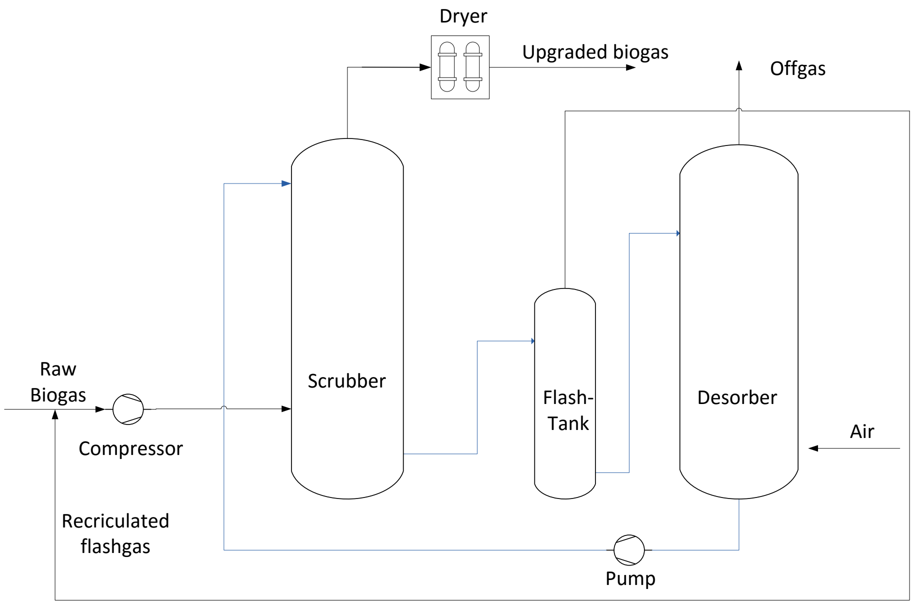

Figure 7 **Schematic process flow over a GR14**

To be able to perform simulations for the hybrid processes, the properties of the different flows in GR14 presented in Figure 7 have been determined in advance. The flow properties are presented in table 2.

Table 2 **Flow parameters of GR14 and typical gas composition of biogas from crops[12]**

	Raw biogas	Flash gas	Unit
CH4	55	15	vol-%
CO2	44	83	vol-%
O2	0,1	0,1	vol-%
N2	0,7	0,7	vol-%
H2S	40	45	ppm- vol
Gas flow	1400	350	Nm3/h
Temperature	25	14	°C
Pressure	0,03	1,3 - 1,6	bar(g)

GR14 is a water scrubber with a total upgrading capacity of 1400 Nm^3 raw biogas per hour. The capacity of the scrubber column is, as previously mentioned, mainly depending on the incoming raw gas flow and less dependent on other properties of the gas such as the methane content.

[12] Raw biogas content measured at a GR14 upgrading plant in Sweden

3.1.1 Key figures of biogas upgrading

The most important figures in order to compare the performance of a biogas upgrading unit are the specific energy consumption, specific investment cost, methane loss and the specific upgrading cost.

The specific energy consumption is a measure of how much energy in form of electricity that is needed in order to purify 1 Nm^3 of the incoming biogas of a certain quality to the required standards.

The specific investment cost is the investment cost of a certain upgrading capacity measured in SEK/(Nm^3/h raw gas flow).

The methane loss is another important factor that influences the performance of the water scrubber. In this report, methane loss is defined as the total amount of methane leaving the biogas upgrading unit with the stripper air in relation to the total amount of methane entering the unit with the raw biogas. The methane loss is expressed as a percentage. A high methane loss results in a loss of profit since less methane from the raw biogas is recovered in the product gas. Also, a high methane loss results in a higher methane concentration in the stripper air, resulting in methane emissions and a potential cost for emission reduction.

Altogether, the investment cost, the energy consumption and the methane losses represents the 3 most important figures influencing the specific upgrading cost, that is the total cost of upgrading 1 Nm^3 of raw biogas.

3.2 HYBRID CASE I - WATER SCRUBBER GR14, MEMBRANE AND INCREASED FLASH PRESSURE

In order to get a reasonable efficiency of the membrane unit, it is important to keep up the differences in partial pressure over the membranes. One way of doing so is to increase the pressure of the incoming gas. The driving pressure is too low to achieve required separation if a membrane unit is added to a traditional GR14 unit with a flash pressure of 1,3 bar(g). Therefore the driving force has to be increased in one way or another. In the first hybrid case studied, the pressure in the absorption column is increased from 5,5 to 7 bar(g) so that the pressure in the flash column can be increased from 1,3 to 2 bar(g) while maintaining the methane loss in the water scrubber, see Figure 8.

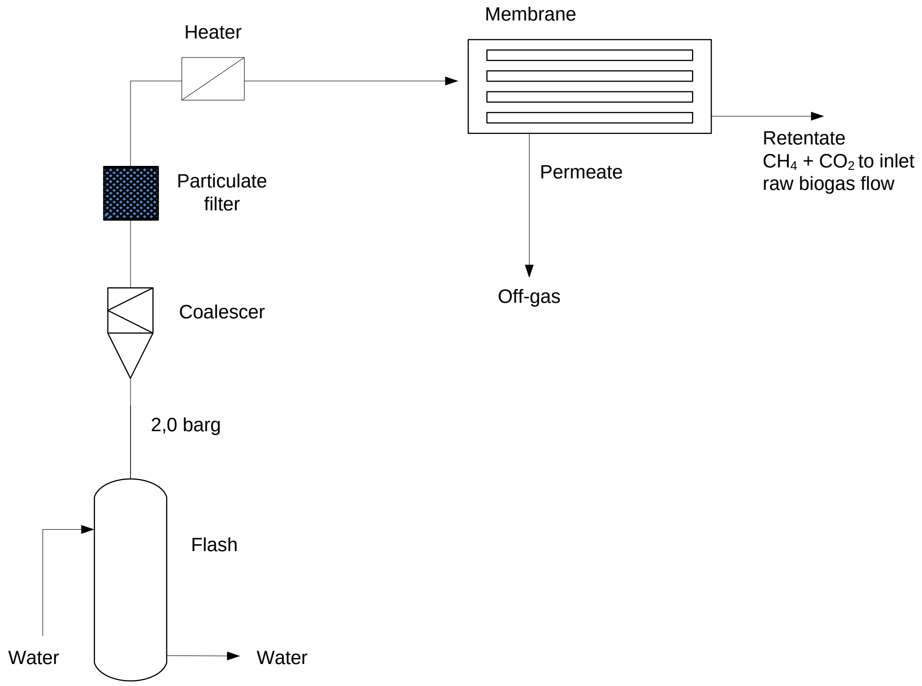

Figure 8 **Schematic process flow over hybrid system in hybrid case I**

In the hybrid case I the pressure in the flash column is increased to 2,0 bar(g) before the flash gas is led through a coalescing filter and a particulate filter to prevent contamination of particles. The flash gas is also heated to prevent condensation of water in the membrane. Moreover, the pressure in the scrubber column (not shown in Figure 8) has to be increased in order to maintain the same methane loss as in the base case. The increase of pressure in the scrubber column will lead to higher specific energy consumption in the water scrubber.

In the membrane unit, carbon dioxide is removed and released into the atmosphere whereas the more methane rich retentate is merged with the incoming gas flow before the compressor.

3.2.1 Simulations of hybrid case I

An integration of a membrane unit will increase the methane loss in comparison with a water scrubber without a hybrid solution. The hybrid case I was simulated in order to keep the methane loss from the total upgrading plant as low as possible.

In hybrid case I the water scrubber is modified to have a higher pressure in the absorption colon and flash tank so that the flash gas pressure rises from 1,3 bar(g) to 2,0 bar(g). Hence, less membrane area is needed due to the relatively high incoming pressure of the flash flow of 2 bar(g). By bulk removal of CO_2 in the flash gas, the recirculated flow of flash gas can be decreased from 350 Nm^3/h to 210 Nm^3/h. As a result of the decreased recirculation flow, an additional 140 Nm^3/h is liberated in the compressor. This free compressor capacity can be used to increase the raw biogas flow with 140 Nm^3/h. Therefore, the total capacity of hybrid case I is 1540 Nm^3/h instead of 1400 Nm^3/h for the original GR14. In order to increase the capacity of incoming raw gas flow in the GR14, extra blower power in the blower prior to the compressor is needed. Assuming a linear increase of blower power with raw gas capacity, 6.44 kW are needed for the 140 Nm^3/h extra raw gas flow.

Moreover, the specific energy consumption of the water scrubber (kW/Nm^3 raw gas) will increase with 7.8% due to the higher pressure in the absorption column, which is needed in order to maintain the methane loss even at higher pressure in the flash column. This increased energy consumption is partly compensated by the membrane solution, since the specific energy consumption in the membrane unit is lower than the specific energy consumption of a GR14.

3.3 HYBRID CASE II - WATER SCRUBBER GR14, MEMBRANE AND BLOWER

In hybrid case II, a blower is used in order to increase the flash gas pressure from 1,3 barg to 2,0 barg. See Figure 9.

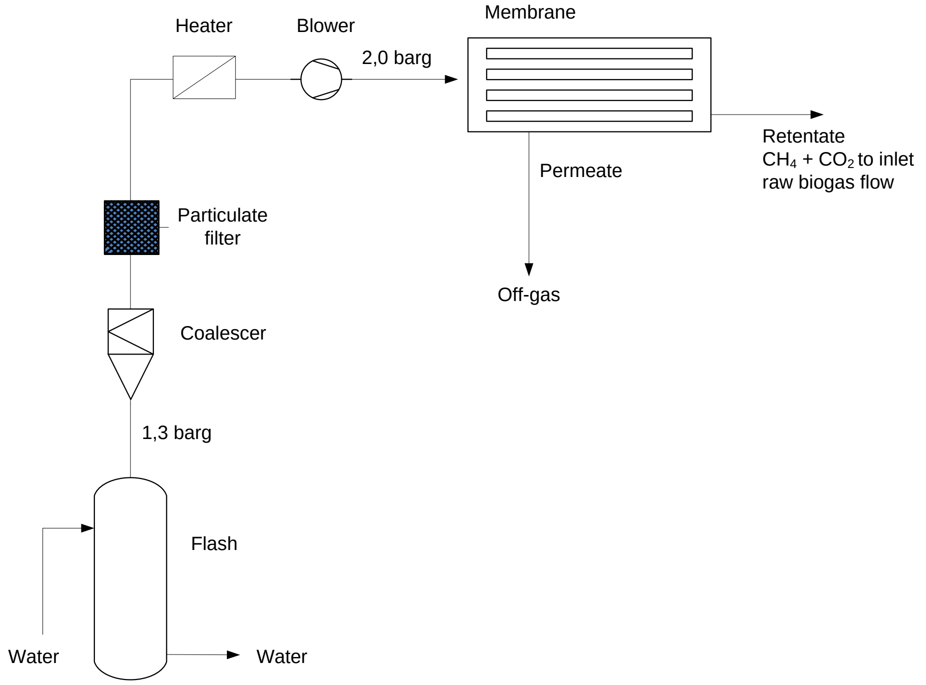

Figure 9 **Schematic process flow over hybrid system in hybrid case II**

By increasing the pressure with a blower instead of using a higher pressure in the flash column, the water scrubber can continue to operate in an optimal way regarding both energy consumption and methane losses. The blower has a rather high power load of 16,1 kW since the blower cannot utilize the pressure from the flash column. Therefor the pressure of the flow has to be decreased before it can enter the blower.

Besides how the higher pressure of the flash gas is obtained, the hybrid case II is similar to hybrid case I.

3.3.1 Simulations of hybrid case II

As with hybrid case I, also Hybrid case II will result in a total capacity increase of 140 Nm^3 raw gas/ h.

However, compared to hybrid case I the energy consumption for the water scrubber will be lower for hybrid case II since absorption and flash pressure in the water scrubber are lower in hybrid case II than in hybrid case I. A summary and compilation of simulation results is shown in chapter 4.

3.4 HYBRID CASE III - WATER SCRUBBER GR14, MEMBRANE AND VACUUM PUMP

Instead of increasing the pressure prior to the membrane unit, it is also possible to decrease the pressure of the permeate flow in order to increase the driving force in the membrane unit. The pressure of the permeate flow can be decreased by the help of a vacuum pump according to Figure 10 below.

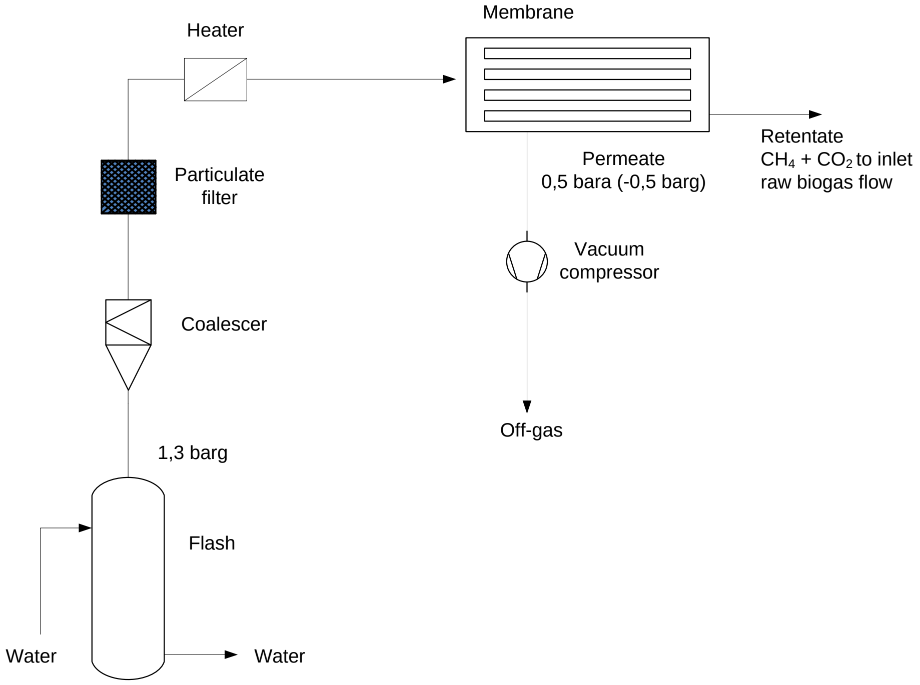

Figure 10 **Schematic process flow over hybrid system in hybrid case III**

By decreasing the pressure of the permeate flow with a vacuum pump instead of using a higher pressure prior to the membrane, the water scrubber can continue to operate in an optimal way regarding both energy consumption and methane losses and no additional blower is needed. The vacuum pump has in comparison with a blower a power load of only 5,5 kW compared to 16,1 kW for the blower in case II.

Besides the pressure of the flash gas and permeate flow, the hybrid case III is similar to hybrid case II, for instance with an additional blower capacity installed for the increased raw gas flow.

3.4.1 Simulations of hybrid case III

An optimization of membrane area and methane loss gave an optimized membrane permeate flow of 175 Nm^3/h. Compared to hybrid case I and II, the energy consumption is lower for hybrid case III since the vacuum pump demands less energy compared to the blower required in case II or the total pressure increase in the water scrubber unit in case I.

3.5 HYBRID CASE IV - WATER SCRUBBER GR14, MEMBRANE, BLOWER AND VACUUM PUMP

In order to increase the driving forces for membrane separation even further, it is possible to both increase the pressure of the flash gas and at the same time use a vacuum pump for the permeate flow. This can be done through a set up according to Figure 11.

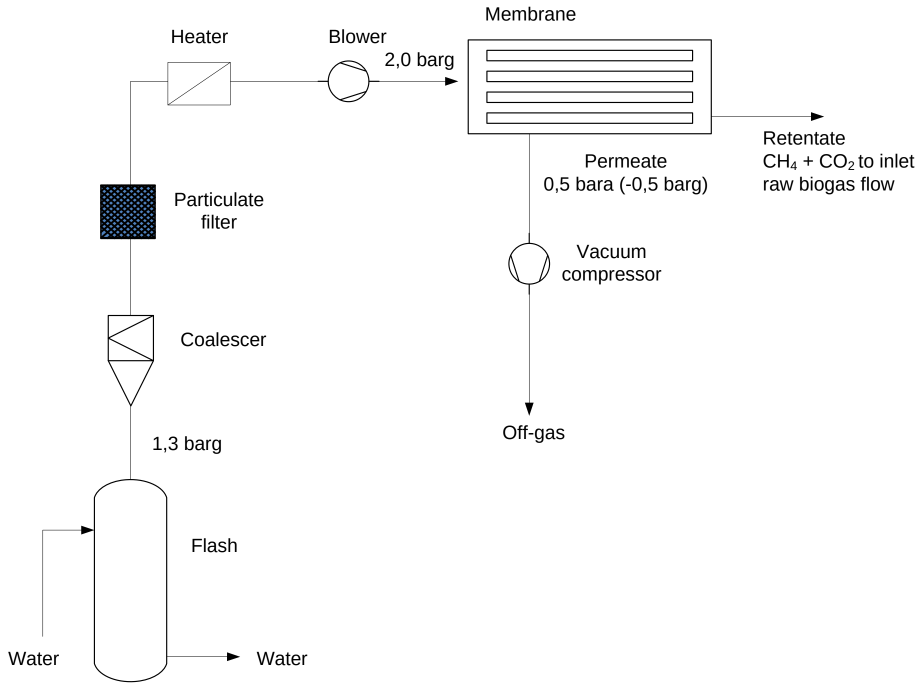

Figure 11 **Schematic process flow over hybrid system in hybrid case IV**

By combining a blower to increase the pressure the flash gas flow and a vacuum pump to decrease the pressure of the permeate flow, 8 membrane elements could be used to increase the capacity 175 Nm^3/h. This is the same number of membrane elements as in Hybrid Case I+II but with a result of a larger capacity increase compared to those cases due to the use of vacuum pump.

However, since both a blower and a vacuum pump are installed the total extra installed power load sum up to 21,6 kW.

3.5.1 Simulations of hybrid case IV

Hybrid case IV will due to the addition of membrane, vacuum pump and blower result in a total capacity increase of 175 Nm^3 raw gas/ h.

Compared to hybrid case I to III the energy consumption will be higher for hybrid case IV since both a vacuum pump and a blower is installed.

4 Comparison of Simulation Results

In this chapter the simulations results presented in chapter 3 will be compared. The comparison of specific energy consumption, specific investment cost and specific upgrading cost will be made both on the additional capacity but also between the total solutions in the different cases. Thereby it is possible to both benchmark the different solutions against each other, but also see how well the different solutions cooperate with the original GR14 to which they are integrated. When comparing these results, it is important to keep in mind that these are only four cases that have been studied and it is probable that even more attractive solutions could be found if many more cases were to be studied.

4.1 SPECIFIC ENERGY CONSUMPTION

The specific energy consumption for the added capacity as well as for the different total hybrid cases can be seen in Table 3.

Table 3 **Specific energy consumption [%] in comparison to GR14**

	Base case Normal water scrubber GR14. 1400 Nm3/h. No membranes.	**Hybrid case I** 1540 Nm3/h. 2,0 barg flashgas to membranes without blower.	**Hybrid case II** 1540 Nm3/h. Flashgas to membranes, 2.0 barg after blower.	**Hybrid case III** 1575 Nm3/h. 1.3 barg flashgas. Membranes with vacuum pump.	**Hybrid case IV** 1575 Nm3/h. 2.0 barg after blower, vacuum pump at permeate side.
Additional capacity kWhel/Nm3 raw gas	0	-0,9	-26,5	-64,5	-22,28
Total hybrid case kWhel/Nm3	0	-0,1	-2,38	-7,16	-2,48

By only comparing the energy consumption for the additional capacity it can be seen that the most favorable case from an energetic point of view is hybrid case III. Compared to the other cases hybrid case III requires less extra installed power at the same time as it does not affect the performance of the GR14 like in hybrid case I. Compared to the original GR14, the extra capacity in hybrid case III requires 64,5% less energy per Nm^3 raw gas resulting in a total hybrid upgrading unit consuming 7,16% less energy per Nm^3 raw gas.

However, it should also be concluded that hybrid case I might be a very energy efficient alternative for e.g. older operating water scrubber units that already runs with an pressure of 2,0 bar(g) in the flash column. Thereby no increase in energy consumption will be loaded onto the extra capacity and it will thereby become a very competitive alternative. In such a case the specific energy use in the added capacity will be >90% lower than for a GR14.

Moreover, it can be seen that the combination of two reasonable cases into a third case does not have to be a good solution. This result is simply due to the fact that the performance of the membrane does not increase in the same way when the two options are combined (pressure increase of flash gas and vacuum pump) as when they are used as different options in order to increase the driving forces.

4.2 SPECIFIC INVESTMENT COST

The specific investment cost for the added capacity as well as for the different hybrid total cases can be seen in Table 4.

Table 4 **Specific investment cost [%] in comparison to GR14**

	Base case Normal water scrubber GR14. 1400 Nm³/h. No membranes.	**Hybrid case I** 1540 Nm3/h. 2,0 barg flashgas to membranes without blower.	**Hybrid case II** 1540 Nm3/h. Flashgas to membranes, 2.0 barg after blower.	**Hybrid case III** 1575 Nm3/h. 1.3 barg flashgas to membranes. Vacuum pump at permeate side.	**Hybrid case IV** 1575 Nm3/h. 2.0 barg after blower, vacuum pump at membrane permeate side.
Additional capacity SEK/Nm³/h raw gas	0	-51,9	-35,5	-44,0	-44,0
Total hybrid case SEK/Nm3/h raw gas	0	-4,7	-3,2	-4,9	-4,9

The specific investment cost is lower for all cases simulated for both the additional capacity as well as the total hybrid plant, compared to GR14's investment cost.

Lowest specific investment cost for the additional capacity has hybrid case I with 50% lower specific investment cost than for GR14. Taken the whole case into consideration, hybrid case I has a specific investment cost that is about 4,7% lower than for GR14.

However, due to the impact of a larger total added upgrading capacity, hybrid case III and IV will be even more cost efficient on a total level, with 4,9% lower specific investment cost than GR14. This despite that the specific investment cost for the additional capacity in hybrid case III and IV is higher than for case I.

4.3 SPECIFIC UPGRADING COST

The specific upgrading cost is defined as all capital and operational expenses in relation to the annual upgrading raw gas capacity. The specific upgrading cost for the added capacity as well as for the different hybrid total cases can be seen in table 5.

Table 5 Specific upgrading cost cost [%] in comparison to GR14

	Base case Normal water scrubber GR14. 1400 Nm3/h. No membranes.	**Hybrid case I** 1540 Nm3/h. 2,0 barg flashgas to membranes without blower.	**Hybrid case II** 1540 Nm3/h. Flashgas to membranes, 2.0 barg after blower.	**Hybrid case III** 1575 Nm3/h. 1.3 barg flashgas to membranes. Vacuum pump at permeate side.	**Hybrid case IV** 1575 Nm3/h. 2.0 barg after blower, vacuum pump at membrane permeate side.
Additional capacity SEK/Nm3 raw gas	0	7,0	3,9	-19,2	-5,1
Total hybrid case SEK/Nm3 raw gas	0	0,6	0,4	-2,1	-0,6

Lowest upgrading cost for both the additional capacity and the total hybrid case can be found at hybrid case III when only a vacuum pump is used in order to lower the pressure of the permeate. This case is energy efficient, provides a good capacity increase in the integrated GR14 plant and is rather competitive in price. In total the specific upgrading cost for total hybrid case III is 2,1% lower than the upgrading costs of a normal GR14. Only evaluating the additional capacity of hybrid case III, it looks even better with a specific investment cost that is 19,2% lower cost than for the GR14.

Despite both lower specific energy use and lower specific investment cost for all cases compared to GR14, the specific upgrading costs are not lower in all cases. For case I and II the specific upgrading cost increases since the improvements in energy use and investment cost are not large enough to pay for the extra methane losses. However, once again, these are only four cases that have been studied and it is probable that cases with even larger reductions in costs can be found if more cases would be studied.

5 Conclusions

Based on the results in this report, it can be concluded that the combination and integration of the membrane and water scrubber upgrading technologies results in a hybrid solution interesting in many aspects. Not only does the combination of the different technologies provide a hybrid solution that provides lower specific energy use, investment cost and upgrading cost, but also an interesting alternative to extend the capacity at existing water scrubber plants that have reached their capacity limits. Many existing plants built at early stages in the development of the biogas market are operating with a higher pressure in the flash tank than new water scrubbers. This will make the integration of a membrane unit even more interesting and feasible since the higher pressure in the flash tank improves the performance in an integrated membrane unit. The market for integrations like the one mentioned here should not be underestimated, not at least since the last extra production at an existing plant heavily contributes to the profitability of a plant. By installing a membrane unit according to hybrid case I the capacity of an existing water scrubber can be increased with 10% and with hybrid case III with 12%.

The hybrid solution will make the upgrading plant more flexible. The membranes may be by-passed when the extra capacity is not necessary, while used when the raw gas production is high creating a flexible upgrading plant. The capacity range that is 700-1400 Nm^3/h in today's GR14 may be 700-1575 Nm^3/h with the membrane hybrid solution.

By integration of membranes with the water scrubber technology, the greatest advantage of each technology can be used. Membranes are very cost efficient for bulk removal of CO_2 but they need an advanced process configuration in order to separate the last percentage of CO_2 from the biogas. On the other hand, the water scrubber technology is very efficient also for fine removal of CO_2. On the one hand, the large-scale advantages of the water scrubber can be utilized on large biogas flows providing upgraded biogas of low cost. On the other hand, the advantages of price competitive bulk removal of carbon dioxide that membrane technology provides can be utilized for reduction of the recirculated flash gas flow, thus reducing upgrading costs even further than for the existing water scrubber technology.

A water scrubber upgrading plant that is integrated with membrane technology will get a specific energy consumption that is 7% lower than today's plants and a specific investment cost that is 5% lower than today. The total specific upgrading cost will be 2% lower than today's water scrubber. However, only focusing on the cost of the added capacity, the specific upgrading cost of the added capacity will be 19% lower than the specific upgrading cost of today's water scrubber. The added capacity will have a specific investment cost that is 44% lower and a specific energy consumption that is 65% lower than a water scrubber without integrated membranes.

It should also be mentioned that the simulations above only give indications of the possible performance of a hybrid solution for biogas upgrading. The simulations have been carried out for a few representative operational cases, but have not been optimized. Most likely, an optimization regarding pressures, number of membranes and methane slip will be able to improve the performance of the water scrubber membrane hybrid even more.

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MEMBRANE INTEGRATION TO SIGNIFICANTLY IMPROVE WATER SCRUBBER PERFORMANCE

Integrering av vattenskrubberteknik och membranteknik ger synergieffekter. Dessa nås genom att stora delar av koldioxiden i det återcirkulerade flashgasflödet i vattenskrubbern avskiljs med hjälp av membranteknik. Minskningen av det återcirkulerade flödet leder då till högre kapacitet och lägre specifik energiförbrukning.

Potentialen i en hybridlösning mellan vattenskrubberteknik och membranteknik undersöktes genom simuleringar av olika fall i samarbete med Malmberg Water AB, leverantör av vattenskrubbrar, och Air Products, leverantör av membran.

Det mest intressanta simuleringsfallet indikerar 7,2 % lägre specifik energikonsumtion, 4,9 % lägre specifik investeringskostnad samt 2,1 % lägre uppgraderingskostnad jämfört med en GR14-anläggning från Malmberg Water AB.

Det är troligt att vidare optimeringsarbete leder till ännu bättre resultat. Utöver att hybridlösningen mellan vattenskrubber- och membranteknik verkar intressant för nya anläggningar, innebär det även en intressant möjlighet för befintliga vattenskrubbrar att utöka sin kapacitet genom integrering av membranteknik.