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Capturing CO_2 from biogas plants

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Abstract

As a renewable energy, biogas produced from anaerobic digestion and landfill is playing a more and more important role in the energy market. Capturing CO_2 from biogas can result in a negative CO_2 emission. Depending on how biogas is utilized, there are different routes to capture CO_2. A biogas plant that uses raw biogas to produce power and heat can be retrofitted by integrating CO_2 capture. In order to identify the best option, three retrofits were compared from both technical and economic perspectives, including SYS-I, which captures CO_2 from raw gas and produces biomethane instead of electricity and heat, SYS-II, which captures CO_2 using MEA-based chemical absorption after the combustion of raw gas, and SYS-III, which captures CO_2 by using oxy-fuel combustion of the raw gas. In general, SYS-I can achieve the highest profit and shortest payback time, mainly due to the high price of biomethane. SYSII and SYS-III are clearly influenced by carbon credit. In order to have positive profits for the retrofits of SYS-II and SYS-III, carbon credit needs to exceed 750SEK (or 100USD)/ton CO_2 and 113 SEK (or 15USD)/ton CO_2 respectively.

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Keywords: biogas, negative CO_2 emission, BECCS, chemical absorption, oxy-fuel combustion, carbon credit

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1. Introduction

According to the 5th IPCC report, carbon negative technologies are necessary for the scenarios to achieve a lower than 2 degrees increase in global temperature before the end of the 21st century. Apart from brutal geo-engineering methods, the application of Carbon Capture and Sequestration (CCS) to renewable fuels, also known as Bio-CCS or Bioenergy with CCS (BECCS), appears to be the most promising approach.

As a renewable energy, biogas produced from anaerobic digestion and landfill is playing a more and more important role in the energy market [1]. Biogas has been considered as the cleanest renewable fuel for transportation by the United States and the European Union. However, since raw biogas mainly consists of methane (CH_4 ~ 65vol%) and carbon dioxide (CO_2 ~ 35vol%), an upgrading process is normally needed to remove CO_2 and other unwanted impurities before it can be used as vehicle fuel. If the CO_2 removed from the raw biogas can be captured and stored, the negative CO_2 emission can be easily realized at a low cost as CO_2 is the byproduct of upgrading. According to a report released recently by Navigant Research, the global biogas industry has an astounding nearby future, at least for the next ten years, that the annual global raw biogas production will exceed 56,6 billion cubic meter by 2024 [2]. Due to the rapid growth of biogas upgrading, there is a huge potential for CO_2 capture. For example, assuming 50% of raw gas is upgraded would result in a CO_2 capture of 19,4 Mton. Capturing CO_2 from biogas upgrading can be categorized as pre-combustion capture. Different technologies for pre-combustion CO_2 capture have been reviewed in our previous work [3]. According to the conclusion, amine based chemical absorption (Pre-CA) is the most suitable technology, considering the CO_2 purity, CO_2 capture ratio and efficiency. The advantage lies in small capture systems and low capture costs. However, this route can only achieve a low carbon capture rate as the carbon in CH_4 is not captured.

Depending on how biogas is utilized, there are also other routes to capture CO_2 from biogas, for example when raw biogas is directly used to produce power and heat, the post-combustion capture and oxy-fuel combustion capture can be applied for CCS as well, giving the opportunity to move the CO_2 capture plant from the biogas producer site to the user site. Even though engines and gas turbines can reach higher efficiency by using upgraded biogas, it is not mandatory to upgrade raw biogas [3]. Post-combustion capture means capturing CO_2 from the exhaust gas after biogas is burnt in the combustor; and oxy-fuel combustion (Oxy) capture means burning biogas in a nitrogen free environment using pure oxygen and capturing CO_2 through simply condensing exhaust gas to remove moisture. As the carbon contained in CH_4 will be captured as well, the advantage of post-combustion capture and oxy-fuel combustion capture is the larger CO_2 capture rates in comparison to that achieved through biogas upgrading. Similar to natural gas combustion, using biogas as fuel results in a low CO_2 content in the exhaust gas. Therefore, for the route of post-combustion capture, the common CO_2 capture technology is chemical absorption (Post-CA).

Currently, most of the studies about capturing CO_2 from biogas focus on how to improve the efficiency of biogas upgrading [3]. There has not been a comprehensive analysis from the perspective of overall CO_2 emission reduction during an energy conversion. To bridge the knowledge gap, the present study aims at assessing the aforementioned technologies for CO_2 capture from both technical and economic points of view. Results will provide insights and give guidelines for the selection of CO_2 capture technologies to achieve a cost-effective negative CO_2 emission.

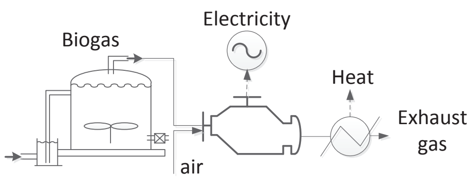
Nomenclature

A	Capacity
BECCS	Bioenergy with CCS
C	Capital cost
CCS	Carbon Capture and Sequestration
Oxy	Oxy-fuel combustion capture
Post-CA	Amine based chemical absorption for post-combustion CO_2 capture
Pre-CA	Amine based chemical absorption for pre-combustion CO_2 capture

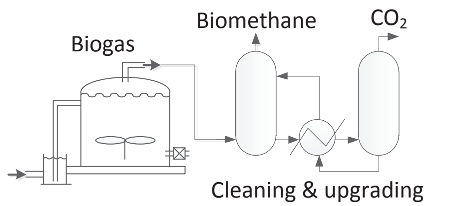
2. Systems description and methodology

Interest and public support in large scale biogas have been growing around the world, resulting in that some large scale biogas plants have been or are being built. For example, the Biogas Park in Penkun has 40 Modules at 500kW each, which gives a total capacity of 20MW (biogas) [4]. The generated biogas is utilized to produce electricity and heat and CO_2 capture is not included. The system scheme is shown in Fig 1(a), which a gas engine is used instead of a gas turbine in order to lower the investment cost. Based on such a plant, three retrofitting systems integrated with CO_2 capture were studied in this work, as shown in Fig 1(b)-(d).

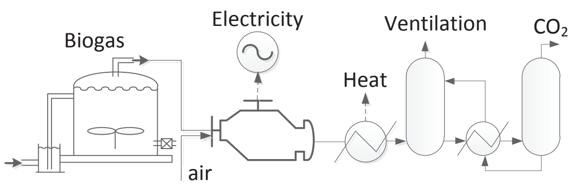
- SYS-I: instead of producing electricity and heat, biogas is upgraded to vehicle fuel (i.e. biomethane) through a chemical absorption process. Compared to electricity and heat, biomethane has a higher price. Meanwhile, negative CO_2 emission through CO_2 capture can further increase the benefit through carbon emission trading. To provide the heat demand required by the solvent regeneration, some raw gas is burnt;
- SYS-II: after raw biogas is combusted in the engine, the exhaust gas passes through a chemical absorption process and CO_2 is captured. Since the heat demand required by the solvent regeneration comes from exhaust gas too, the heat production is reduced;
- SYS-III: for oxyfuel combustion capture, air is replaced by pure oxygen. Hence, an air separation unit (ASU) is needed to produce oxygen, which results in an electricity penalty. It is assumed that the necessary re-design of a gas engine to operate with CO_2 as working fluid would provide the same power and heat production as a conventional system. Similar re-design work has been done for gas turbine [5], which shows that oxygen as a single component gas stream is a considerable advantage for controlling flame stability and the design of the oxy-fuel combustor.



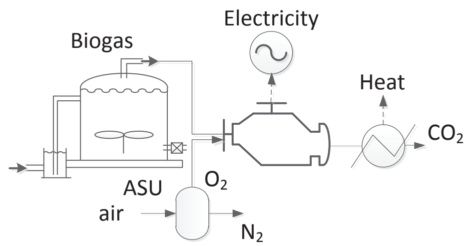
(a) SYS-Ref: System without CO2 capture



(b) SYS-I: Pre-CA



(c) SYS-II: Post-CA



(d) SYS-III: Oxy

Figure 1 System schemes

A model was developed in Excel to calculate the energy and material balance for the four systems shown in Fig 1, based on which the economic analysis was further conducted. The key input data and assumptions are listed in Table 1. The capital costs of MEA-based chemical absorption and ASU were estimated based on the information presented in [6] and [7] respectively. In order to consider the impact of system capacity on the cost, the six-tenth rule is adopted:

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^{0,6}$$

where C is the capital cost, A is capacity or size of equipment, a and b refer to the required capacity and base capacity, respectively.

Table 1. Input data and assumptions

Parameter	Unit	Value
Anaerobic digestion		
Raw gas	Nm3/hr	3100
Composition (CH4/CO2)	vol%	65/35
Gas engine [8]		
Electrical efficiency	%	46
Overall efficiency	%	90
Chemical absorption		
Solvent	-	MEA
Heat demand of regeneration	MJ/kg CO2	3,8
CO2 recovery ratio	%	90
ASU		
O2 purity	%	97 [9]
Energy consumption	MJ/kg O2	0,9 [9]
Others		
CH4 price	SEK/kg	12,7 [10]
Electricity price	SEK/MWh	500 [10]
Heat price	SEK/MWh	700 [10]
Interest	%	6
Carbon credit	SEK/ton	375
Operating hours	hr/yr	8000
Currency exchange rate	USD/SEK	7,5

3. Results

Results about the techno-economic performances are shown in Table 2. Obviously, SYS-I can achieve the highest total income, which mainly comes from the high price of biomethane; whereas it contributes less than SYS-II and III from the perspective of CO_2 emission reduction. Since SYS-II consumes a lot heat for the solvent regeneration and heat has a higher price than electricity, the economy of SYS-II is much worse than SYS-III. Such a retrofitting cannot be paid back based on the current prices of electricity and heat and carbon credit. SYS-III has the biggest capacity of negative CO_2 emission. Compared to reference system, the payback time is less than 3 years for SYS-III.

Table 2. Techno-economic performances of the studied systems

Parameter	SYS-Ref	SYS-I: Pre-CA	SYS-II: Post-CA	SYS-III: Oxy
Technical performance				
Power generation (MWh/yr)	73600	NA	73600	62336
Heat production (MWh/yr)	70400	NA	24100	70400
Biomethane production (ton/yr)	NA	10019	NA	NA
CO_2 emission (ton/yr)	48740	5500	4880	0
Captured CO_2 (ton/yr)	NA	15140	43870	48740
Economic performance				
Investment cost for retrofitting (MSEK)	NA	13	25	29
Income from selling electricity (MSEK/yr)	37	NA	37	31
Income from selling heat (MSEK/yr)	49	NA	17	49
Income from selling biomethane (MSEK/yr)	NA	127	NA	NA
Income from carbon trading (MSEK/yr)	NA	6	16	18
Total income (MEK/yr)	86	133	70	99
Payback time (yr)	-	<1	NA	<3

It is quite clear that the economy of different retrofitting systems is significantly influenced by the carbon credit. A sensitivity study was conducted to investigate its impact. Results are illustrated in Fig 2. Since SYS-I captures the least CO_2, it is not affected by carbon credit as much as SYS-II and III. On the contrary, the effect of carbon credit on SYS-III is most obvious. The gap between SYS-I and SYS-III becomes smaller as carbon credit increases. Compared to the reference system, in order to have positive profits for the retrofits of SYS-II and SYS-III, carbon credit needs to exceed 750SEK (or 100USD)/ton CO_2 and 113 SEK (or 15USD)/ton CO_2 respectively.

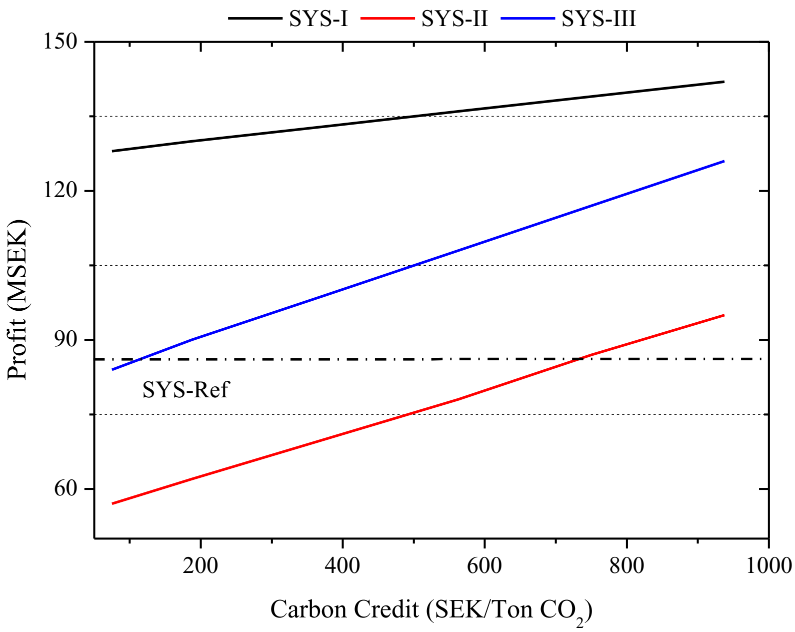


Fig 2 Sensitivity study on Carbon credit

In addition, the high profit of SYS-I, as aforementioned, mainly benefits from the high price of biomethane. If the price drops to below 8SEK/kg, SYS-I won't be able to result in a positive profit. Meanwhile, to compete with SYS-III, the price of biomethane should be kept above 9,3SEK/kg at the carbon credit of 375SEK (or 50USD)/ton CO_2.

4. Conclusions

Capturing CO_2 from biogas produced from anaerobic digestion can result in a negative CO_2 emission. In order to identify the best option for CO_2 capture, three retrofitting systems concerning the original biogas plant that uses raw biogas to produce power and heat were investigated from both technical and economic perspectives. In general, the system (SYS-I) that captures CO_2 from raw gas and produces biomethane instead of electricity and heat can achieve the highest profit and shortest payback time, mainly due to the high price of biomethane. The systems which capture CO_2 by using MEA-based chemical absorption after the combustion of raw gas (SYS-II), or using oxy-fuel combustion (SYS-III) are influenced by carbon credit clearly. In order to have positive profits for the retrofits of SYS-II and SYS-III, carbon credit needs to exceed 750SEK (or 100USD)/ton CO_2 and 113 SEK (or 15USD)/ton CO_2 respectively. It is also interesting to see that for between the two solutions with heat and power (without biofuel production), the oxy-fuel case (SYS-III) is a clear winner against the post-combustion case (SYS-II), which is somewhat counterintuitive. It shows that technologies can have very different impact depending on the environment and framework they operate in.

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