Report on biogas bottling
Mobile and stationary biogas upgrading and compression

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Project: Reduction of GHG emission through promotion of commercial biogas plants (Cambodia)

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II. Executive summary

Biogas, consisting of methane, carbon dioxide and some other trace gases, can be upgraded to biomethane quality. Biomethane mainly consist of methane (typically above 95% methane purity).

Biogas and biomethane could be compressed and filled up in pressure resistant bottles. Those bottles can be transported to the location were the fuel is needed and used to fuel stoves in households, produce electricity and, if upgraded to biomethane quality, used as vehicle fuel, substituting compressed natural gas (CNG).

Due to additional investment needed and economies of scale (the bigger the plant the lower the specific production costs), biomethane plants are usually only economically interesting at high production capacities (300 m³/h biogas production or higher). The opportunities for such big biogas plants are very limited in Cambodia. Pig farms offer much smaller capacities (typically below 20 m³/h biogas production). Biogas bottling will be no option for pig farmers. For some commercial factories, e.g. tapioca processing industry, the biogas potential could be interesting. However, it will be challenging to develop a financially interesting project.

There are low-cost solutions for biogas bottling. However, the German Biogas Association sees fundamental problems connected with those technologies. Most probably they will have substantial safety issues and might be harmful for the environment due to high methane emissions.

III. Introduction

Biogas production and use in Cambodia has mainly being realised by means of small-scale domestic biogas digester and the use of the biogas for cooking, mainly being promoted by the National Biodigester Program of Cambodia (NBP). A few first larger biogas plants have been built, mainly in order to produce biogas from residues of food production (e.g. starch) or from agricultural residues (e.g. pig manure).

The Global Environment Facility (GEF) project "Reduction of GHG emission through Promotion of Commercial Biogas Plants", jointly implemented by the Cambodian Ministry of Environment, Ministry of Agriculture, Forestry and Fisheries and the United Nations Industrial Development Organization (UNIDO), aims to demonstrate and promote biogas-based energy services as a financially viable, reliable, effective and sustainable mechanism to address on-farm animal waste management, access to clean energy while reducing greenhouse gas emissions.

Under the current Cambodian circumstances, operating a commercial biogas plant that produces electricity is an enormous challenge. The main reason is that the electricity demand on pig farms is usually much lower compared with the potential electricity production by using a genset fuelled with biogas. Surplus electricity usually cannot be fed into the public grid because the grid operator sets difficult conditions (e.g. only allowing electricity in a certain period of the year and paying only a very low price for the electricity).

This report is a part of a project called "Provision of Services: Analysis of alternative uses for biogas in Cambodia" in which the German Biogas Association (GBA) is analysing the alternative usage of biogas in form of biogas bottling, biogas backpacks and biogas pipelines. The aim is to assess other options of biogas usage instead of electricity production.

In this report, biogas bottling (mobile biogas bottling facility[1] and traditional biogas bottling[2]) for commercial and household purpose (e.g. biomethane retailing for large cooking appliances) is assessed.

Following aspects will be analysed:

- Description about feasibility of the different biogas bottling options against baseline situation;
- Rough estimation of possible biogas production for locations visited in Cambodia (see Initial Assessment Report).
- Description under which circumstances the biogas bottling options might be interesting. What price would be economically feasible or competitive?
- Recommendations on biogas bottling plant, technical configuration and operation;
- Recommendations regarding financial attractiveness of an investment in a safe and environmentally friendly biogas plant.

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[1] This refer to mobile biogas upgrading and compression unit. The mobile bottling station would go from biogas producer to biogas producer and bottle the available biogas at that location. Once finished it would drive to the next biogas producer.

[2] Traditional/usual biogas bottling refers to biogas upgrading to biomethane quality, compression into bottles (150 - 250 bar).

IV. Overview on biogas production and its use in pressurized gas bottles

4.1. Biogas and biomethane

Biogas technology makes use of the natural process whereby organic material like biowaste, food leftovers or manure are transformed by microorganisms in oxygen-free digesters into biogas and digestate. Depending on the type of feedstock that is used, the methane content of biogas is between 50% to 70%. The second most abundant component is carbon dioxide (CO_2), which makes up between 30% to 50% of biogas. There are also small quantities of other components such as water, oxygen, traces of sulphur compounds, hydrogen sulphide and volatile organic compounds, as shown in Table 1.

Table 1: Chemical composition of biogas and biomethane

	Biogas	Biomethane (natural gas quality)
Methane (CH_4)	50-70%	> 95%
Carbon dioxide (CO_2)	30-45%	< 3%
Oxygen (O_2)	2-4%	< 0.5%
Hydrogen sulphide (H_2S)	< 0-6,000 ppm	< 5 ppm

For more information on biogas production, please consult the brochure Biowaste to Biogas at www.biowaste-to-biogas.com.

Biogas can be upgraded to natural gas quality, being the product of this process typically called biomethane. This is done by separating the methane from the other gas components. Further details about this process and the technology used can be consulted in the publication Biogas to Biomethane at www.biogas-to-biomethane.com

Biomethane can be used in all ways natural gas is used, such as: for heating, electricity production and as fuel for transportation. Biogas and biomethane can be stored and transported by injecting it in the natural gas grid, when there is one available. Additionally, biogas can be transported in biogas backpacks, it can be liquefied and stored in analogous manner to liquefied natural gas (LNG) or in pressurized gas bottles. This last option is the topic of this report.

4.2. Biogas / biomethane in pressurized gas bottles

There are in principle two ways to distribute biogas in pressurized gas bottles:

- Upgrading biogas to biomethane quality and its storage in pressurised bottles (in the introduction called traditional biogas bottling);
- Compression of biogas directly, without upgrading to biomethane quality.

In the following both options will be assessed further.

4.2.1. Gas pre-treatment

Pre-treatment and cleaning are necessary for the further processing and subsequent use of biogas, mainly to protect the machinery and equipment from chemical or mechanical deterioration. This is especially important if biogas is compressed to high pressures (above 200 bar). If there are corrosive chemicals in the biogas, fissures might occur with a high danger of explosion of the bottles. This is a danger that must be taken seriously, especially if the bottles will be used in households.

The presence of potential impurities in biogas depends essentially on the type of feedstock used and, on the technology, applied in the production process. Gaseous impurities in biogas that might require pre-treatment can be:

- Hydrogen sulphide;
- Water;
- Silicon organic compounds (e.g. siloxanes);
- Oxygen;
- Ammonia;
- Volatile Organic Compounds, VOC;
- Dust, oil and aerosols.

The amount of effort and costs for gas pre-treatment depends mainly on the requirements for the machines (limits on certain chemicals defined by the CHP manufacturer).

Hydrogen sulphide (H_2S) is produced in greater quantities when using feedstocks containing high amounts of sulphur. There is a wide range of H_2S concentration in biogas from below 50 ppm to above some 10,000 ppm. The need to reduce H_2S depends mainly on the requirements of the machines (e.g. the compressor). Typically, H_2S should be reduced to 50-200 ppm for use in state-of-the-art machines.

Furthermore, H_2S is corrosive and very toxic to persons. The release of sulphur dioxide into the atmosphere must be excluded. Especially if biogas/biomethane is used on household level, H_2S must be low because it is toxic to people even at low ppm concentration level[3]. During combustion, H_2S oxidises form sulphur dioxide (SO_2), which accumulates on sensitive components like catalysts) and acts as an environmental pollutant. Consequently, biogas must be

[3] https://en.wikipedia.org/wiki/Hydrogen_sulfide

subjected to a desulphurisation process before further processing and use. A variety of desulphurisation procedures are described below:

- **Biological desulphurisation**: consists in injecting air into the gas holder of the digester to provide oxygen for bacteria, which converts H_2S to elementary sulphur. This is an economic and simple procedure for the desulphurisation of biogas and is quite often implemented.
- Adding doses of **iron hydroxide** and/or **iron salts** into the digester. This method works well but its use is limited by the costs of these chemicals.
- **Catalytic oxidation** and **adsorption** with filtering materials (like activated carbon). Activated carbon is expensive, thus, this method is often used as a second (back-up) filter only.
- **Caustic treatment** with biological regeneration of the washing agent, the drawback being a higher investment cost for the additional equipment.

Water can also compromise the process considerably during the conversion of biogas to electricity or biomethane because the biogas is saturated with water vapour inside the digester. In order to avoid corrosion and other negative effects during subsequent gas treatment, it is necessary to dry the biogas. Various methods are available for drying biogas:

- **Condensation drying**: the biogas is cooled in gas coolers (refrigeration units) or underground pipes so that the water vapour condenses.
- **Adsorption dryer**: with the help of silica gel, aluminium oxides or molecular sieves.
- **Drying by increasing the pressure**. Using this method, the water is not removed but the relative humidity reduced.

Oxygen can also compromise the biogas process as well. Although biogas production in the digester takes place in the absence of oxygen, there are a number of ways in which oxygen can enter the system. Some air is brought into the digester with the feedstock, additionally some is also introduced for the biological coarse desulphurisation and for the regeneration of activated carbon during fine desulphurisation. This results in approximately 0.5 vol% of O_2 content in the biogas. These proportions are small enough to not have an adverse effect on the bottles for compressed biomethane or natural gas distribution grid and can be tolerated.

Traces of **ammonia** can also be found in biogas. Because it is highly water-soluble, it can be reduced by water removal (for example during condensation drying).

Biogas must additionally be free from impurities such as dust, oil and aerosols. Filters used in gas technology are installed for this purpose.

In sum: If biogas/biomethane is compressed into bottles it must be pre-treated to avoid damage to humans, environment and machines.

V. Traditional biogas upgrading and bottling

Before biogas is compressed into gas bottles it is usually upgraded to biomethane quality. The first reason to do this step is to ensure that the gas in the bottle is almost free from corrosive substances. The second reason is that much more energy can be stored in the bottle if pure methane is bottled instead of biogas (mixture of methane and carbon dioxide).

After undergoing a cleaning and upgrading process, biogas can be used in the form of biomethane as a renewable substitute for natural gas, with a heating value of 9.97 kWh/m³. [4]

The main process involved in the upgrading of biogas to biomethane quality is the separation of CH_4 and CO_2. There are several upgrading technologies available on the market that have been used and improved for many years. **Biogas upgrading methods** can be categorised as follows:

- Membrane separation;
- Scrubbing technologies (absorption methods);
  - Water scrubbing;
  - Physical scrubbing;
  - Chemical scrubbing;
- Pressure swing adsorption (PSA);
- Cryogenic treatment.

The aim of all upgrading technologies is to achieve high methane purity and by that high energy density of the product gas. Low methane losses and low energy consumption are the main criteria for the choice of the right technology solution. If the reader is interested in getting more on biomethane, the German Biogas Association and the United Nations Industrial Development Organisation published the publication Biogas to Biomethane in 2017, which offers a detailed overview of the topic (available under www.biogas-to-biomethane.com)

The upgrading of biogas to biomethane requires additional technology and investment. As described below from an economical point of view it makes only sense at high volume rates (some hundred m³/h biogas production). In many locations the utilisation of large quantities of energy produced is not directly feasible, or a usable gas grid infrastructure is not available. In this case, biomethane can be compressed and filled into pressurized gas cylinders, making it easy to transport. In order to achieve the highest possible energy density, the biomethane is typically compressed to 200 – 250 bar. In this case, the fuel quality is equivalent to that of compressed natural gas. Steel pressure bottles are used to store the biomethane. Increasingly, however, full-composite containers – plastic liners coated with carbon fibres – are used as storage vessels. The gas bottles are tested to ensure they are burst-proof and are offered in a wide range of sizes. Small pressurised bottles have a capacity of several kg. If trucks are used for transportation, larger cylinders containing several hundred kg of biomethane are used, sometimes fastened together in bundles. One kg of biomethane has an equivalent energy content (lower heating value) of approximately 13.9 kWh. The electricity required to compress

[4] As comparison, natural gas has heating value between 10-14 kWh/m3 (depending on the quality) and liquefied petroleum gas (LPG) has a heating value of 12.8 kWh/kg and a density of 0.54-0.60 kg/litre.

biomethane to 200 bar depends on different factors, amongst them on the gas inlet pressure before the compressor, and it is about 0.2 - 0.5 kWh_{el} per m^3 when using a highly efficient compressor. Biomethane in pressurised gas bottles is typically used in the transport but can be used in households as well.

The advantages of biogas upgrading and compression are (compared with compression of biogas directly):

- Proved technology with several hundred biomethane plants in operation worldwide,
- Safe and reliable professional process,
- Pressure typically between 200 – 250 bar, (In this case, the fuel quality is equivalent to that of compressed natural gas)
- High energy density in the bottle due to high methane content and high pressure.

The disadvantages are:

- Additional investments and costs,
- Due to economies of scale, high biogas production capacity is needed, typically some hundred m^3 per hour production.

It is important to mention, that safety aspects should be considered seriously, regarding high pressure bottles, as these can represent high risks especially if used in households. Some recommendations for safe biogas/biomethane use in pressure cylinders are (this list is not exhaustive):

- Legal requirements (e.g. handling with pressure cylinders, gas quality, etc.) must be followed.
- The gas must be dried (removal of H_2O), water promotes corrosion, for example when H_2S or CO_2 are solved and acids result.
- H_2S must be reduced. H_2S is extremely toxic for human health and corrosive.
- The biogas should be free of siloxanes and particles.
- The share of oxygen in gas must be kept as low as possible. In contact with water vapour, it has a corrosive effect.
- Gas cylinders should be connected by an authorised person.
- Gas cylinders must be controlled regularly to check if they are mechanically sound. This aspect is of upmost importance because little fissures often cannot be seen by eyes but can lead to dangerous bursts.

Picture 1: Biomethane bottling in India for own consumption (Source: Indian Biogas Association).

VI. Costs for biogas and biomethane production

This chapter highlights the most relevant conclusions from the report "Analysis of alternative uses of biogas in Cambodia" (Grope, Scholwin et. al)[5].

Each biogas plant is individual and the costs for biogas production depend mainly on the individual local conditions. Some general assumptions can be done but there will be deviations found for each single biogas plant from the general conditions. The second most important influence factor for the costs of biogas production in qualitatively manufactured[6] biogas plants is the volume rate of biogas production. The costs of biogas upgrading depend mainly on the size of the upgrading facility, e.g. in m³ biogas production per hour. Under Cambodian circumstances they are some US cents/kWh for small installations (e.g. 0.05 US$/kWh for 50 m³/h raw biogas) and can go down to below 0.01 US$/kWh for bigger volume rates (e.g. above 2000 m³/h raw biogas). In the most cases of biogas production with capacity of less than 100 m³/h, the upgrading is economically not feasible.

[5] Several data and assumptions on the calculations are summarized in the Annex of this report.
[6] It is important to stress, that there are several biogas plants constructed in Cambodia, which were erected at a cost of safety and efficiency and some of them are producing an environmental damage by emitting high amounts of methane. More details are documented in the report "Innitial assessment report on field mission in Cambodia" by Frank Hofmann and Giannina Bontempo (2018).

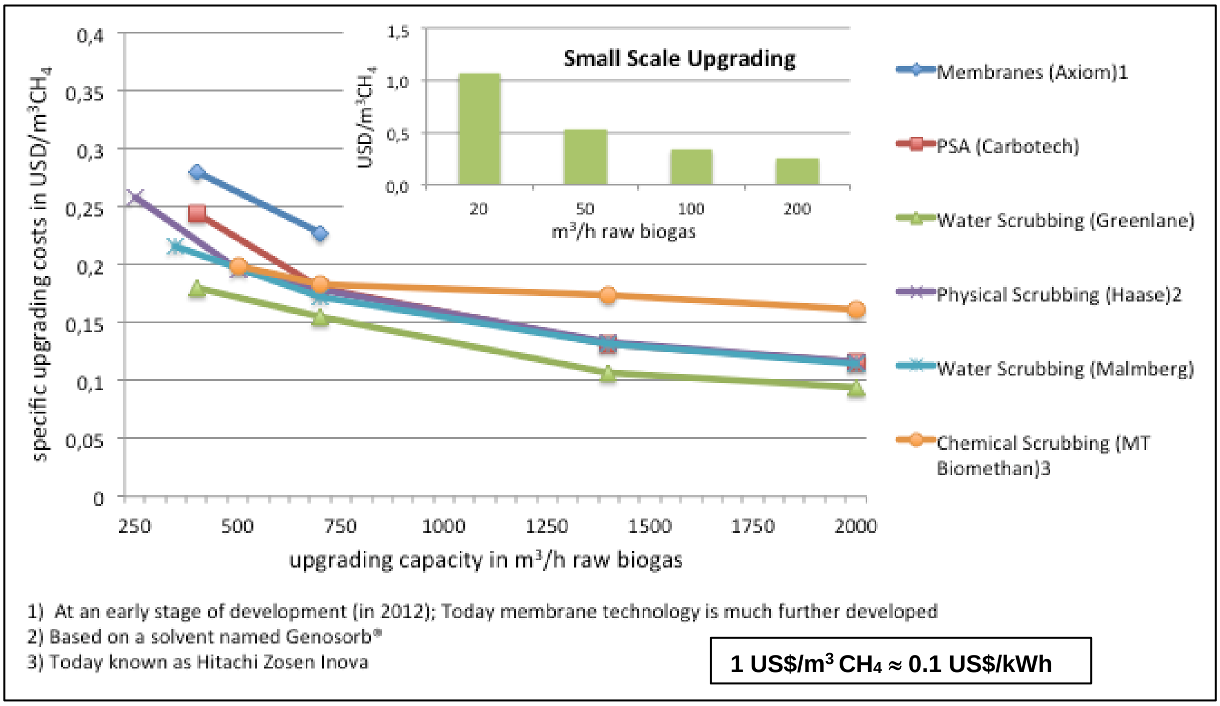

Figure 1: Cost for biogas upgrading, Source: author's own figure published in: [IRENA 2017], based on [Adler 2014]

Costs for biogas bottling (investment in equipment, compression and operation of the bottling process) are 0.039 US$/kWh (10 m³/h biogas production) or 0.026 US$/kWh, for 100 m³/h respectively.

Table 2: Overview of costs of some components for biogas, upgrading and bottling in US$/kWh

	10 m³/h	50 m³/h	100 m³/h	500 m³/h	1000 m³/h	2000 m³/h
Biogas production		0.05				0.03
Biogas upgrading		0.05			0.01	
Biogas bottling	0.039		0.026			
Total Costs			0.082 US$/kWh	0.07 US$/kWh		

The authors did not make individual calculations for each component and every volume rate because in some cases they collected data from various sources.

According to Grope, Johan et al "Analysis of alternative uses for biogas in Cambodia" the experience with the biogas upgrading and compression in gas bottles is as follows:

- Facilities of 100 m³/h: 0.082 US$/kWh.
- Higher volume rates offer lower costs. According to European experiences, capacities above 500 m³/h can require about 0.07 US$/kWh.
- Low production capacities (below 100 m³/h) are not economically interesting.

6.1. Use of bottled biogas in households

If used as fuel for cooking in households, the costs of bottled biogas can be compared to the costs of liquefied petroleum gas (LPG). The LPG retail price in Cambodia is about 0.79 US$/kg (1,900 KHR/litre) which corresponds to a price of 0.06 US$/kWh (based on a lower heating value of LPG of 12.87 kWh/kg). Grope et al. estimated the costs for 100 m^3/h raw biogas production at 0.082 US$/kWh. **As long as the LPG price is at that relatively low level and biogas plants are not supported, biogas bottling in households will not become an economically interesting alternative**.

6.2. Use of bottled biogas as a transportation fuel

Biogas as a transportation fuel can be used as substitute for diesel, which is sold for 0.80 US$/litre (0.07 US$/kWh) as average in Cambodia. According to Grope et al. the total costs both of biogas production for its usage as transportation fuel and for its transport in high-pressure gas cylinders to the fuel filling station will be 0.084 US$/kWh[7] (100 m^3/h raw biogas production). As long as the price for diesel stays at this level and biogas production is not supported bottled biogas will be more expensive compared to the use of diesel in transport sector. But there might be some potential locations, for example if the diesel must be transported for long distances from the harbour to the inner area of Cambodia, were locally produced biomethane might be cheaper than diesel.

6.3. Use of bottled biogas for industrial heat supply

Bottled biogas could be used to substitute LPG in the industry. As mentioned above, the price for LPG is about 0.06 US$/kWh. Grope et al. calculated costs for 100 m^3/h raw biogas production of 0.082 US$/kWh, see above. As long as the LPG price is at that level and biogas plants are not supported, the usage of the bottled biogas for the industrial heat supply will not become an economically interesting alternative to LPG.

It must be stressed that these calculations have been made with purified biomethane (above 95% methane content). It is not in the range of this report to calculate the bottling of partly upgraded biogas (e.g. 50% methane content) or not upgraded but compressed biogas. One reason not to calculate this is that there are other arguments (environmental and safety issues) that indicate the absences of available technology, which would offer a safe and environmentally friendly biogas bottling, except those upgrading technologies that are described above. Further details on safety and environmental issues are documented in the text below.

[7] Including cost of biomethane production, filling into high-pressure gas cylinders, transport to filling station and OPEX and CAPEX of filling station; not including cost for conversion of cars from petrol to gas

6.4. SWOT analysis for qualitative biogas upgrading and bottling under Cambodian circumstances

Strengths: Biogas upgrading and bottling is a proven and reliable technology. It offers chances to deliver renewable energy, used as transportation fuel, fuel for households or industry. It has the potential to reduce GHG emissions by substitution of fossil fuels.

Weaknesses: Advanced know-how needs to identify interesting locations, for project planning, for project financing and plant operation. High investments needed, typically biogas upgrading and bottling projects cost some million US$.

Opportunities: There are opportunities to produce own fuel instead of burning expensive fossil fuels. On a governmental perspective, biogas bottling offers rural development, technology transfer, business and job creation and GHG reduction.

Threats: From a financial perspective the value of bottled biogas is in concurrency with established fossil fuels, like LPG or diesel. The costs for those fuels will probably rise in future but it could be hardly predicted. This is a risk for biogas bottling projects. Another risk is a long-term operation of the biogas plant, especially long-term contracts for the feedstock.

VII. Mobile biogas bottling

Mobile biogas bottling refers to mobile biogas upgrading and compression unit. The mobile bottling station would go from biogas producer to biogas producer and bottle the available biogas at that location. Once finished, they would drive to the next biogas producer.

Biogas upgrading plants are typically stationary systems. The main challenge to construct a mobile biogas upgrading plant is technical reliability. Moving equipment has to be constructed in a way that vibration doesn't harm the equipment. Another challenge is of logistical nature: the biogas production is permanent (24 h/d and 365 d/a), in case of a mobile biogas upgrading plant, the produced biogas must be stored in times when the device is absent. If the upgrading plant is operated between several biogas plants, the biogas upgrading plant is in most times absent. In this case, significant biogas storage capacities are needed and the annual operational time of the upgrading plant is low due to the times lost during the plant's change of location and its connection. In consequence this technical opportunity seems to have much more disadvantages compared to advantages. In reality, there are no or only very few mobile upgrading plants in operation yet. One example is https://www.biovoicenews.com/iit-innovation-series-mobile-unit-for-biogas-enrichment-and-bottling/ but the author don't has any data on its performance (emissions; own energy demand, if it is in operation, etc.).

If there is only a mobile compressor used, again, there is a logistical challenge that the biogas produced must be stored during the absence of the compressor. If, for example, the compressor shall be used to compress biogas from four different biogas plants, its availability on each location will be only about 4.5 hours (assuming location changes per day and 0.5 hours for (dis)-connection. 24 h/d minus 4.5 h times four locations, results in 18 h present on four biogas plants, which is 1.5 operational hours per day and biogas plant. The biogas produced has to be stored for about 22 h each day and significant storage volumes are needed. From a commercial aspect such a project seems not economically justified because an overcapacity of compressor is needed (if the biogas production from 24 hours must be compressed within 4.5 hours) and the annual operation times are not optimized (operational times lost due to transport and the plant connection). Probably it is not commercially interesting to operate a mobile compressor on biogas plants. Practice shows that this approach is not implemented in professional and safe operating projects yet.

As an example, for mobile bottling UNIDO provided the following link and asked the German Biogas Association to give feedback on that technology. A particular interest was to the picture on the slide number eight, see the following link:

http://web.iitd.ac.in/~vkvijay/Biogas%20models.pdf

Slide 8 shows the following picture.

Picture 2. Mobile biogas upgrading plant

In the presentation, no performance factors are given, like upgrading and compression capacity, methane purity of pressure in the gas bottles. No information on the electricity demand of the installation and no information on experiences in practise. However some aspects can be analysed based only on the picture.

Methane emissions

The whole system is not constructed gas-tight. In order to achieve the maximum environmental effect, the biogas projects are initiated and supported to reduce greenhouse gas (GHG) emissions. UNIDO supports biogas projects in Cambodia with the intention to reduce GHG emissions. The UNIDO project's title is "Reduction of GHG emissions through Promotion of commercial biogas plants". As known, biogas contains 50-75% methane. According to recent publications of IPCC methane has a GHG potential that is about 28 times higher compared to CO_2[8] in a timeframe of 100 years. Life cycle assessments (LCA) show a huge influence of methane emissions on the GHG performance of biogas plants. The authors are not aware of any study of methane emissions of such a system like it is installed in the picture. But experiences from other emission measurements strongly indicate that those emissions from the unit shown in the picture must be very high. As comparison: biogas plants in Germany are usually technically relative gas tight between the pre-storage tank and end-storage tank (emissions should be below 1%). It is well known for such installation as in the picture that the methane emissions are very high. In the presentation mentioned, on slide 16, the authors write "High CH4 losses (low BioCH4 recovery)" but they don't quantify the level of losses. The authors of this report are quite sure that the emissions of the system are in a rage in which the GHG performance is harmful for the environment.

Safety:

The installation on the picture cannot be operated in a safe way. This is not at all an exhaustive assessment on safety but only some arguments based on one picture. In practice there will be much more to say about safety issues.

- Methane is a flammable gas. Explosive atmosphere should be avoided during plant operation. Due to high methane emissions, e.g. open digesters and not gas tight junctions, a safe operation cannot be ensured.
- Tubes for biogas are not safely installed. They are lying on the ground and workers might stumble over it. On the bottom on the right side of the pictures some stones/brigs are lying on the ground. Again, if the operator stumbles on the material lying on the ground he/she might tear down the biogas containing tubes and biogas will be emitted, which can result in an explosive atmosphere on the spot.
- The green hoses in the picture, in which the biogas is transported to the upgrading facility are for a mobile connection. The effect is that they are sometimes filled with biogas and sometimes air will flow in (in times of disconnection). As consequence there is an explosive atmosphere in the tubes every time the device is connected or disconnected.
- The operator of the system should be informed about the dangers, like explosive atmosphere and potentially H_2S in the emitting biogas. Obviously there are no warning signs and the authors of this report don't know if there has been a safety training for the workers.

In sum, there are many questions and doubts if mobile biogas upgrading plants can be constructed for reliable operation. The technology shown in the picture above is not offering safe or environmentally friendly biogas bottling.

[8] https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf Page 73.

7.1. SWOT analysis for mobile biogas upgrading and bottling under Cambodian circumstances

Strengths: It could reduce investment costs if one mobile upgrading and compression unit could be used for several biogas plants.

Weaknesses: It is a significant challenge to construct a mobile device and ensure reliable operation. In fact, it can be doubted if safe and reliable operation for years can be provided. Logistical challenge: Long-time of absence of the unit at the locations while the produced biogas must be stored. During the time of operation, the processed volume rate must be very high. The example analysed are not safe or environmentally friendly.

Opportunities: There is a huge interest in relatively cheap but safe and reliable solutions.

Threats: High risk in not reliable, not safe and not environmentally friendly projects.

VIII. Possible biogas upgrading and bottling for the locations visited

During the field mission in Cambodia several locations have been visited. In this chapter German Biogas Association compares the potential gas production on the location with opportunities for biogas bottling. The options of commercial biogas upgrading and bottling are mainly depending on the volume rate of biogas production. To remember, if the volume rate is below 100 m³/h commercial biogas upgrading will not be economical interesting.

The location and the estimated biogas production are:

- Farm No 1, biogas plant installed, about 11 m³/h biogas production
- Farm No 2, biogas plant installed, estimated biogas production is 5.7 m³/h
- Farm No 3, biogas plant installed, estimated biogas production is 5.7 m³/h
- Farm No 4, biogas plant installed, estimated biogas production is 13 m³/h
- Farm No 5, biogas plant will be installed, estimated biogas production is 3 m³/h
- Farm No 6 (tapioca factory), factory stopped operation, biogas plant installed, estimated biogas production is **450 m³/h**
- Farm No 7 (rubber factory), no reliable estimation of biogas production but might be about **300 m³/h**
- Farm No 8 (rubber factory), no reliable estimation of biogas production but might be around **150 m³/h**
- Farm No 9, no biogas plant, biogas potential 5 m³/h
- Farm No 10, no biogas plant, biogas potential 5 m³/h
- Farm No 12, biogas potential unknown but might be around **480 m³/h** plus/minus 50%.

Conclusions on the chances for biogas bottling depending on the locations are:

- None of the **pig farms** has the biogas production rate that would be needed for professional biogas upgrading and bottling.
- For estimated biogas potential at the **rubber factory** indicate that there might be a potential for biogas upgrading and bottling. But the estimations are not based on reliable data.
- The **tapioca factory** stopped its operation and with that stop the biogas plant is not in operation anymore. However, the biogas potential was in a range where biogas upgrading and bottling was economically interesting. It could be assumed that if the investment for the biogas plant is depreciated and the tapioca factory would start operation again, biomethane production costs might be very low.
- **Farm No 12**. As described in the “Initial assessment report on field mission”, there is no gas collection system installed at Battambang dump site. If in future, a gas collection system should be installed the landfill gas potential will be big enough that biogas upgrading and bottling are an interesting option. As long as the investment is not done for

environmental reasons, it will not be economically interesting to install a landfill gas collecting system and a landfill gas upgrading system.

IX. Description under which circumstances the biogas bottling options might be interesting.

As described above, biogas bottling is only economically interesting at high production rates. According to economy of scale, it can be said that the bigger the biogas plant is the specific cheaper the energy production costs are. The biogas production should be **at least 200 m³/h** better higher, to qualify a location to have a more detailed assessment.

As long as the LPG price is at a level of 0.045 ct/kWh and the price of bottled biogas is about 0.082 US$/kWh and biogas plants are not supported biogas bottling for households will not be an economically interesting.

The costs for diesel are about 0.076 US$/kWh, in Cambodia. According to Grope et al. the costs for Biogas use as vehicle fuel and transport by high-pressure gas cylinders will be 0.084 US$/kWh at 100 m^3/h raw biogas production[9]. As long as the price for diesel stays at this level and biogas production is not supported bottled biogas will be more expensive compared to the use of diesel.

X. Additional sources for information.

Additional to the analysis above UNIDO asked German Biogas Association on their opinion on this video

https://www.youtube.com/watch?v=8kIUfgbcySw

In many countries, the provision of household fuels, in particular for food preparation, is a major challenge. Billions of people around the world use wood for cooking. This leads to various problems such as deforestation and labour-intensive fuel collection, as well as lung and eye diseases caused by particle pollution or soot. Biogas has already proved its worth as an alternative to wood or LPG in several million household systems. A new development is to supply households with biomethane in compressed gas bottles. In many regions of the world this is less expensive than fossil fuels (such as LPG or kerosene) and helps to avoid problems that are prevalent when using wood.

The opinion of the authors on the technology in the video is similar like the mobile technology described above. The technical solutions have several issues:

[9] Including cost of biomethane production, filling into high-pressure gas cylinders, transport to filling station and OPEX and CAPEX of filling station; not including cost for conversion of cars from petrol to gas

Methane emissions: The biogas digesters are not gas-tight. High methane emissions will occur. Such biogas systems are a good solution to produce energy, e.g. for cooking but the GHG performance will be bad. Again, the authors don't have reliable data on emissions but it is very probable that high methane emissions occur.

Safety: The construction cannot be considered as being safe. Hoses are lying on the ground. Explosive atmosphere will occur. The system is not gas-tight. If biogas emits, there is not only danger of explosion but danger of poisoning by H_2S inhalation as well. There are no warning signs installed. In sum, the video is not showing a professional and safe operated biogas and biogas upgrading plant but only an experiment on household or University level.

Energy density: The compression in this example seems to be low (much below 200 bar) thus the energy density in the bottles is low. Additionally biogas (methane and carbon dioxide) is compressed (not upgraded to biomethane) what leads to low efficiency because CO_2 has to be compressed as well. This results in low efficiency of the process and low energy density in the bottles. Transport of the bottles is less efficient (compared to 200 bar) and costly (depending on the transport distance).

The second link, German Biogas Association was asked to give feedback to is:

https://mnre.gov.in/file-manager/UserFiles/case-study-Biogas-Generation_Purification_and_Bottling-Development-In-India.pdf

This paper is summarizing the advantages of biogas. German Biogas Association agrees completely that biogas has many advantages if done right. The arguments are, the integration of renewable energies into the energy mix high biogas production potential (in this paper in India), and many more.

Again, there is no information on performance factors (like efficiency, methane losses and several other) to deliver a qualitative estimation. In general, we have a positive impression of the potential of both biogas production and its usage for bottling. But German Biogas Association wants to stress, that in a biogas plant a high GHG potent gas - methane - is produced and the emissions must be kept as low as possible to ensure a positive influence on the climate. Second aspect is that the operation of the biogas plant, the biogas upgrading plant and the use of pressurized bottles must be safe.

XI. Final conclusions and recommendations

The evaluation of different business models for biogas in Cambodia within this study have shown many advantages and challenges. The main results are as follows:

- Biogas can be upgraded to natural gas quality, called biomethane, but that would need additional investment and operation costs. In Cambodia, biogas upgrading will be seldom done in practice, due few locations with enough substrates that allow biogas production on a large scale (above 100 m^3/h biogas) and the high specific cost of biogas upgrading, especially for small biogas production capacities.
- In case biogas has to be upgraded to biomethane, e.g. in order to transport it by high-pressure gas bottles and/or to use it as transportation fuel, high biogas production capacities (> 100 m^3/h raw biogas) are necessary in most cases in order to be competitive with other energy carriers.
- Transporting biogas in high-pressure gas bottles gives the most flexibility (interchangeability of customers and biogas storing) and allows biogas transport at long distances, but is very costly, especially at low production capacities. As long as the LPG price is at a level of 0.06 ct/kWh and the price of bottled biogas is about 0.082 US$/kWh and biogas plants are not supported, biogas bottling for households will not be an economically interesting option.
- The analysis has shown that using biogas for cooking, as vehicle fuel or for thermal application can be competitive in Cambodia under certain circumstances. Nevertheless, each biogas project may have very different circumstances and its suitability needs to be evaluated from case to case. The costs for diesel are about 0.076 US$/kWh in Cambodia. According to Grope et al. the costs for Biogas use as vehicle fuel and transport by high-pressure gas cylinders will be 0.084 US$/kWh at 100 m^3/h raw biogas production[10]. As long as the price for diesel stays at this level and biogas production is not supported bottled biogas will be more expensive compared to the use of diesel.

Recommendations for next steps:

- If UNIDO wants to identify locations in Cambodia were biogas upgrading and bottling might be interesting, the potential biogas production volume rate is the most important influence factor. Biogas upgrading and bottling is only in locations with high biogas potential an economical interesting option, on locations with above 100 m^3/h biogas production.
- If UNIDO is intending to support biogas projects in Cambodia, German Biogas Association recommends to support safe and environmentally friendly projects only. Many biogas plants we assessed in these projects do not comply with this recommendation.

[10] Including cost of biomethane production, filling into high-pressure gas cylinders, transport to filling station and OPEX and CAPEX of filling station; not including cost for conversion of cars from petrol to gas

- German Biogas Association doesn’t see options for safe and reliable mobile biogas upgrading and bottling plants.
- If biogas shall be bottled, it is of a significant importance that the whole technology chain is safe, from biogas production to its use and to the maintenance of pressurised bottles.
- There is a huge lack of information on the safe biogas production and usage in Cambodia. It is to recommend to have studies and training to BTIC on safe and environmentally friendly performance of biogas plants.

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XIII. Annex

Background data used in the report “Analysis of alternative uses for biogas in Cambodia” by Grope, Scholwin and Hofmann (2018)

Table 1: Data used for economic evaluation of the concepts

	Value	Unit	Source
Material parameters			
Heating value of LPG	46.33 12.87 6,950	MJ/kg kWh/kg kWh/m³	https://en.wikipedia.org/wiki/Liquefied_petroleum_gas
Heating value of biogas (with 58 % methane)	17.35 4.82 5.78	MJ/kg kWh/kg kWh/m³	
Financial parameters			
Amortisation	10	years	Own assumption
Interest rate	9.25	%	List of question filled by BTIC and UNIDO
Cost for maintenance	2	% of total invest p.a.	Own assumption
Electricity price for electricity need[11]	16	USct/kWh$_e$	Price list of commodities by Ministry of Commerce
Biogas consumption per household for cooking	1.5	m³/day	[El-Halwagi 2012]
Salaries: • Worker with qualification • Engineer	430 250 to 2,500	US$ per month	List of question filled by BTIC and UNIDO

Table 1: Cost of biogas transport by high-pressure gas cylinders

item	**Biogas production**		**unit**	**Comments / sources**
	100	**10**	**m³/h**	
Energy for compression	0.25	0.25	kWh$_e$ per m³	from 10 to 250 bar
Transport distance (one way)	100	10	km	Own assumption
Cylinder volume	176	45	liter	Own assumption

[11] e.g. for gas compression

Cylinders to be transported per year	12,824	5,015	[-]	calculated
Number of cylinders per truck* / tuk-tuk**	*50	**10	[-]	Own assumption
Tours per year	256	502	[-]	calculated[12]
Number of trucks* / tuk-tuk	*1	**3		calculated
Fuel cost of transport vehicle	0.16	0.04	US$ per km	[13]
Working hours per tour	12	2	hours	Incl. filling, un- and uploading, driving
Investment cost				
Cylinders	200	150	US$ per cylinder	Own assumptions
Truck / tuk-tuk	10,000	4,000	US$ per vehicle	Information by COMPED
Gas compressor	85,000	15,000	US$	[U.S. Department of Energy 2014]
Gas dryer	70,000	25,000	US$	[U.S. Department of Energy 2014]
Overall investment	325,000	64,800	US$	
Amortization	32,500	6,480	US$/year	Over 10 years
Interests	15,031	2,997	US$/year	9.25 % p.a.
Maintenance	6,500	1,296	US$/year	2 % of investment
Energy cost for gas compression	20,636	2,064	US$/year	Calculated with 0.15 US$/kWh$_e$
Total transport cost	16,708	3,187	US$/year	
CAPEX	47,531	9,477	US$/year	
OPEX	38,362	6,547	US$/year	
Yearly overall cost	91,376	16,024	US$/year	
Specific cost	**0.026**	**0.039**	**US$/kWh**	

[12] Note larger capacity of cylinders and vehicle in case of the larger plant
[13] based on the following assumptions: fuel consumption a) of truck: 20 litres per 100 km and b) of tuk-tuk: 5 litres per 100 km; diesel price: 0.80 US$/litre

Overview of costs for biogas filling stations

Location	in a town	on-site	units	Comments / sources
Biogas production	**100**	**100**	**m^3/h**	
Capacity storage cyl-inder	28	28	m^3	Own assumption
Cylinders per day	85,7	85,7	[-]	
Investment per stor-age cylinder	2,500	2,500	US$	[Western United Dair-ymen 2005b]
Investment storage in total	214,286	214,286	US$	
Investment compressors	0	85,000	US$	[U.S. Department of Energy 2014]
Investment gas dryer	0	70,000	US$	[U.S. Department of Energy 2014]
Investment other components	60,000	60,000	US$	[U.S. Department of Energy 2014]
Amortisation	27,429	42,929	US$/year	Over 10 years
Interests	12,686	19,854	US$/year	9.25 % p.a.
Maintanance	5,486	8,586	US$/year	2 % of investment
Energy cost for compression	0	20,636	US$/year	Calculated with 0.15 $US\$/kWh_e$
CAPEX	40,114	62,783	US$/year	
OPEX	5,486	29,222	US$/year	
Total yearly costs	45,600	92,005	US$/year	
Specific cost	**0.008**	**0.016**	**US$/kWh**	

A.3 – Biogas use for cooking and transport in high-pressure gas cylinders by truck	
- high-pressure gas cylinders (e.g. at 250 bar) - transport by truck or tuk tuk to households and / or to stores selling the cylinders - refilling of 176 litres cylinder about once every 1.5 months necessary for a family	- 100 m^3/h raw biogas production: 0.082 US$/kWh - 10 m^3/h raw biogas production: much too expensive because of very high up-grading cost for small capacities

Potential business models of using biogas as vehicle fuel

Cleaning and upgrading required	Concept of distribution	Associated cost
B.1 – Biogas use as vehicle fuel and transport by high-pressure gas cylinders		
- fine desulphurisation and drying - upgrading - odorisation	- high-pressure gas cylinders (at 250 bar) - transport by truck to filling station (in towns) - fuelling of about 80 passenger cars and tuk-tuk a day	- 100 m^3/h raw biogas production: 0.084 US$/kWh[14]
B.2 – Biogas use as vehicle fuel with filling station on-site (high pressure gas cylinders as storage)		
- fine desulphurisation and drying - odorisation - upgrading required	- high-pressure gas cylinders (at 250 bar) - storage and filling on-site - fuelling of about 80 passenger cars and tuk-tuks a day	- 100 m^3/h raw biogas production: 0.072 US$/kWh

C.3 – Biogas use for heat supply and transport in high-pressure gas cylinders by truck	
- high-pressure gas cylinders (e.g. at 250 bar) - transport by truck to the customer	- 100 m^3/h raw biogas production: 0.082 US$/kWh

[14] Including cost of biomethane production, filling into high-pressure gas cylinders, transport to filling station and OPEX and CAPEX of filling station; nit including cost for conversion of cars from petrol to gas