Vienna University of Technology
Continuing Education Center

GAS PERMEATION BIOGAS UPGRADING TECHNOLOGY - Business development analysis

A Master Thesis submitted for the degree of
"Master of Science"

MSc Renewable Energy in Central and Eastern Europe

Supervised by
Ass.Prof. Dipl.-Ing. Dr.techn. Michael Harasek

DI Martina Prechtl
Student ID: 9440209

Wien, February.2008

Affidavit

Martina Prechtl, hereby declare

1. that I am the sole author of the present Master Thesis, "GAS PERMEATION BIOGAS UPGRADING TECHNOLOGY - Business development analysis" 76 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The aim of this master's thesis is to analyse the potential market for a new biogas upgrading technology based on gas permeation that has been developed in Austria.

An overview of the basics of biogas production is given, such as, the positive environmental effects, the basics of the fermentation process, the chemical composition of raw biogas, the conventional energetic usage of biogas and the basics of biogas purification and upgrading. The advantages of the decoupling of the biogas production and the conversion by biogas upgrading and feeding into the gas grid are highlighted. They lead to a more efficient usage of the energy content of biogas.

The technical potential for biogas in European countries was estimated by experts in the range of 3.7 - 30% of the natural gas consumption.

Highly relevant for the market of upgraded biogas, on both an international and national level, are the frameworks for the net integration of the biogas and the requirements of the gas quality which differs across European countries.

The reference market for the availability of natural gas helps determine the economic context of biogas upgrading and the net integration and is therefore discussed in more detail.

The new gas permeation process is presented. The steps involved in the development of this new technology are highlighted, along with an overview of the main competitor technologies, such as, PSA, water scrubbing, and amine scrubbing. The functional principles are explained, characteristics analysed and compared and the recent market position roughly outlined according to the plant diffusion. For the evaluation and the benchmarking of these technologies the special site conditions have to be taken into account. Reliability of the technology, maintenance costs due to the consumption of process energy and other maintenance resources, the obtained

gas quality and the overall costs provide the basis for the comparison of the technologies mentioned.

According to the sensitivity analysis methodology, an analysis of the new gas permeation technology is done. The analysis results in a better understanding of the complex system “market for biogas gas permeation technology”.
As a result the investment and upgrading costs for gas permeation, niche products for gas permeation, qualified man power and service for gas permeation, and confidence in gas permeation technology are the factors which need to be investigated further in the market introduction phase.

The market share for gas permeation technology and its competitor technologies are influenced by various other factors which can be identified as the crucial elements within the system. Similarly, the parameters directly linked to the marked share of biogas gas permeation technology, such as, niche products for gas permeation and the investment and upgrading costs for gas permeation support this.

The only parameter that is free from external influences but influences others is the availability of natural gas. It needs to be continuously observed, however, cannot be actively acted upon.

The political support for upgraded biogas has a substantial influence on other parameters which can be influenced externally by lobbying measures and are indirectly influenced by the availability of natural gas.

Qualified man power and services for gas permeation and confidence in gas permeation technology illustrate a prevalence of influencing effects. They are the key drivers for successful positioning of the new technology on the market.

For further strategic decisions relating to the successful market introduction of the new biogas upgrading technology, a detailed discussion of the results presented in this master’s thesis is recommended. Advisable is a group of representatives consisting of all the relevant parties.

Table of content

List of figures

List of tables

List of pictures

1. Introduction

1.1. Aim

The last few years has seen a new biogas upgrading technology based on gas permeation under development. The leader of this technological development process is the Vienna University of Technology together in association with a small Austrian engineering enterprise. Thus far, successful test operation phases in a bench-scale unit and in a pilot plant have already taken place. The results obtained were very promising and have attracted a great deal of interest in this technology from experts and also from the biogas market itself. The market for upgraded biogas in Europe is expected to grow substantially due to establishment of several international and national goals and frameworks for the promotion of sustainable energy systems. The next steps toward a commercial launch of the new technology need to be prepared quickly. The next steps are based on the following questions:

- What are the major competitor technologies? What is their market position, what are their strengths and weaknesses?
- What are the main advantages and disadvantages of the new technology?
- What is the present market situation for upgraded biogas and which development scenarios can be expected for this market?
- What are the frameworks influencing the biogas market?
- Which organisational and strategic aspects have to be taken into account when starting a new enterprise for the assembling and offering of the new biogas upgrading technology? What are the risks?
- What is the long term vision on the new enterprise?

This master thesis aims to answer these questions and attempts to provide some base information for further strategic decisions in connection with the intended business development

In chapter 1, an overview of the basics of biogas production are given, such as, the positive environmental effects, the basics of the fermentation process, the chemical composition of raw biogas, the conventional energetic usage of biogas and the basics of biogas purification and upgrading.

In chapter 2, an outline of the influencing frameworks for upgraded biogas is discussed. The Austrian and European situation is taken into consideration along with a rough overview on the reference market for natural gas.

In chapter 3, the new gas permeation process is explained and analysed. The development steps of this new technology are highlighted, along with an overview on the main competitor technologies. The functional principles are explained, characteristics analysed and compared and the recent market position roughly outlined according to the plant diffusion.

Chapter 4 deals with the key factors necessary for a successful introduction into the market of the new biogas upgrading technology. Here, a sensitive analysis of the market systems where the new technology has to be lounged and the main risks associated therewith are highlighted.

Chapter 5 discusses possible outlooks for the further development of the biogas market by giving a rough overview of its potential.

The conclusion, in chapter 6, summarises the main points discussed throughout the entire master thesis.

This master thesis is no business plan. However, it contains some important strategic analysis, information and evidence which provide the basis for which future business plan can be developed.

1.2. Energy source biogas – pros and cons

1.2.1. Biogas and emissions

Strategies against climate change caused by green house gases are considered the greatest challenges towards a sustainable development. The largest amount of anthropogenic green house gas emissions are caused by energy production based on fossil fuel sources. Thus, climate protection also means changes to our current energy system.

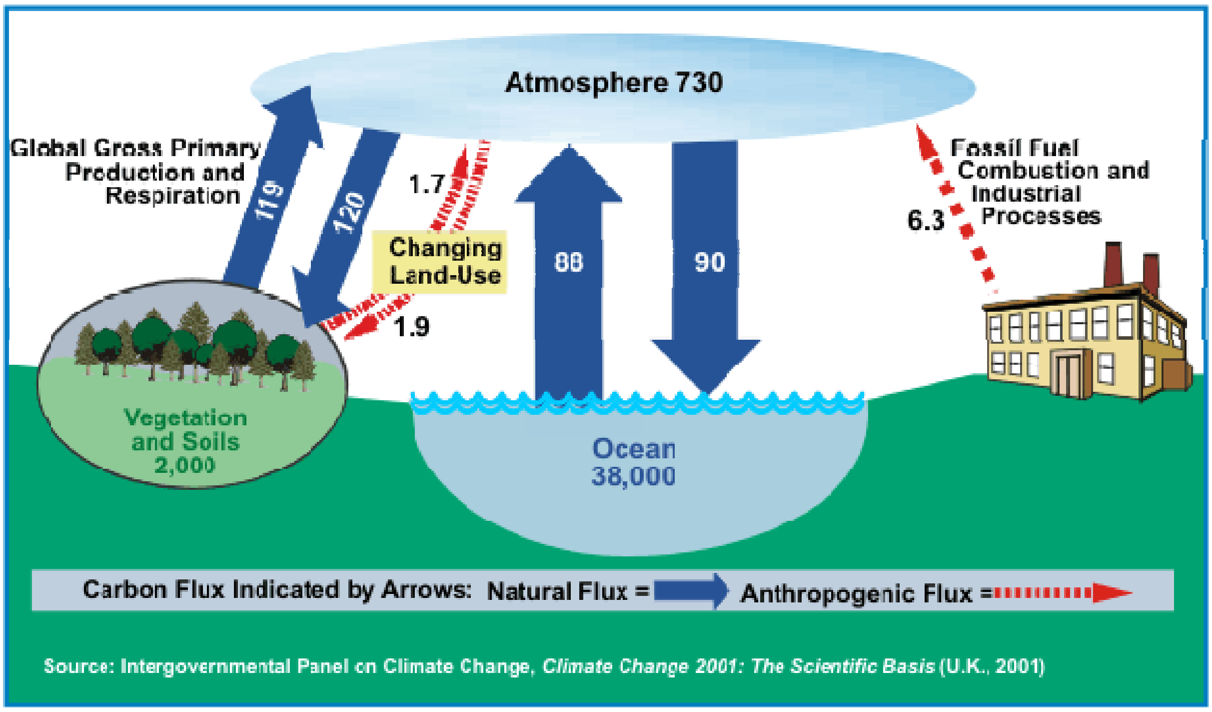


Figure 1: Global carbon cycle (billion metric tons carbon)

A sustainable energy system is based on two main strategies: efficient use of energy, which leads to a reduction of the total energy consumption; and change towards an energy production system based on renewable sources.

One component of this renewable energy system is biogas. Biogas is considered to be CO_2-neutral. That is, the CO_2 emitted while burning biogas is equal to that assumed during the growth process by plants at the beginning of the biogas production life cycle.

When talking about other climate relevant gases, several investigations have shown that the usage of fermented manure as a fertilizer leads to less emission of the climate relevant gas methane (CH_4), ammonia (NH_3) and nitrous oxide (N_2O) than the direct usage of non-fermented manure on agricultural fields or by use of chemical fertilizers. (Arlt, 2001)

1.2.2. Biogas residues as fertilizer

The usage of biogas manure as an agricultural fertilizer not only leads to less emissions, less costs for mineral fertilizers, but also has much more favourable characteristics. The biogas production process is a very smooth one for nutrients, partly enhanced by fertilizers.

When compared with non-treated manure, it is shown to be less aggressive towards plants, provides easier absorption of nutrients by the plants and enhances the quality of the soil (more humus, higher water retention capacity, less erosion, etc.). Fermented manure is proven to have a less intense odour than unfermented manure. (Tretter 2003; Plöcking et. al. 2006)

1.2.3. Biogas - a high potential energy source

With the biogas technology a wide range of organic substances can be used for energy production. Not only agricultural products, but also agricultural residues such as manure and harvesting residues, organic residues from food industry, households and gastronomy and the waste water treatment can all be used as raw materials of the biogas production process. Therefore, biogas production has a great potential which is not fully utilised at this stage.

1.3. Principles of biogas production

1.3.1 Biogas components

Biogas is the end product from a fermentation process where oxygen is absent, and consists mainly of methane (CH_4) and carbon dioxide (CO_2). The concentration of the energy source methane in the biogas is approximately 50 - 60%. Beside CH_4 and CO_2, biogas contains small amounts of water (H_2O), hydrogen sulphide (H_2S), ammonia (NH_3) and trace amounts of hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO), oxygen (O_2) and saturated or halogenated hydrocarbons. The biogas is usually saturated with water vapour and may contain dust, particles and siloxanes. The energy content is defined by the concentration of methane – 10% of methane in the dry gas corresponds to approximately one kWh/m³ (IEA Bioenergy, Task 24).

The composition of biogas depends strongly on the raw material and the fermentation process.

The following table illustrates the average composition of biogas (Hofbauer 2002, SGC et. al. 2001, E.V.A. 2001)

Components	**wood gas**		**sewage gas**	**landfill gas**	**biogas**	*** biogas - average**
Fumigator	air	steam				
CH_4	3 - 6 %	9 - 11 %	60 - 75 %	45 - 55 %	50 - 75 %	**60%**
CO_2	12 - 16 %	20 - 25 %	30 - 40 %	30 - 40 %	25 - 45 %	**38,90%**
H_2S			< 1 %	50 - 300 ppm	0 - 1 %	**0,05%**
H_2O			saturated	saturated	saturated	**saturated**
H_2	11 - 16 %	33 - 40 %	traces		0 - 1 %	**0,50%**
O_2			< 1 %		0 - 1 %	**0,10%**
N_2	45 - 60 %	< 3 %	< 4 %	5 - 15 %	0 - 3 %	**0,40%**
NH_3					0 - 0,5 %	**0,05%**
CO	13 - 18 %	25 - 30 %	traces		-	**-**
calorific value [kWh/m³]	**1,1 - 1,7**	**3,3 - 4,2**	**6 - 7,5**	**4,5 - 5,5**	**5 - 7,5**	**6,00%**

* The indication of vol-% in the last column relates to dry gas

Table 1: Average gas compositions of biogas based on different feedstocks

1.3.2 Fermentation process

The biogas fermentation process occurs in four stages: the hydrolysis, in which complex molecules are broken down to constituent monomers; the acidogenesis, in which acids are formed; the acetogenesis or the production of acetate; and the methanogenesis, the stage in which methane is produced from either acetate or hydrogen. Digestion is not complete until the substrate has undergone all of these stages. Each stage contains a responsible physiologically unique bacteria population that requires disparate environmental conditions. (Wellinger 2006)

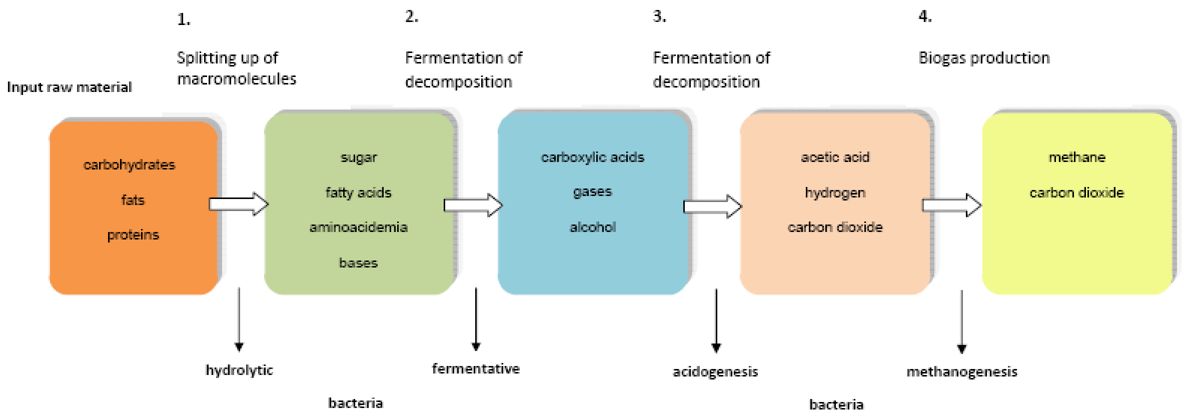


Figure 2: Stages of fermentation process

The process is governed and limited by four parameters: temperature, hydraulic retention time (average time the substrate remains in the digester), organic load rate (amount of organic material which is fed daily per m^3 of digester volume) and ammonia concentration. To guarantee an optimised gas production they can be altered only within very narrow limits. (Wellinger 2006)

The main task for an optimised anaerobic degradation process is to provide optimal conditions for each bacteria culture within the different process stages. The following conditions need to be taken into consideration:

Process	Input	Output	Influencing Conditions
Hydrolyses	**Complex structures (Polymers):** Proteine fat complex carbohydrates.	**Soluble monomers** amino acids fatty acids, simple sugars	Choice of feed material preparation of feed material residues time (limiting factor)
Acidogenesis	**Soluble monomers** amino acids fatty acids, simple sugars	**Simple organic** short chain acids ketones alcohols	type of bacteria, culture conditions: temperature and pH < 4,5 to 5,5
Acetagenesis	**Simple organic** short chain acids ketones alcohols	Acetate CO2 H2	concentration of hydrogen (inhibits oxidation to acetate and propionate) pH < 4,5 to 5,5
Methanogenesis	Acetate CO2 H2	CH4 CO2 H20	Reduction of CO2 by H2 (1/3) acetate conversion (2/3) pH <7 rate controlling – slower growth rate than acitogenes Ammonia concentration → inhibitor

Table 2: Influencing conditions on 4 stages of biogas production (Machan et. al. 2006)

1.3.3. Digestion systems

The digestion systems can basically be distinguished in wet and dry digestion systems. Wet systems usually operate in between 6 and 12% total solids (TS), dry systems above 30% TS at the inlet. In both systems, three genuine modes of feeding: batch-fed, continuous-flow and accumulation systems exist. (Wellinger 2006)

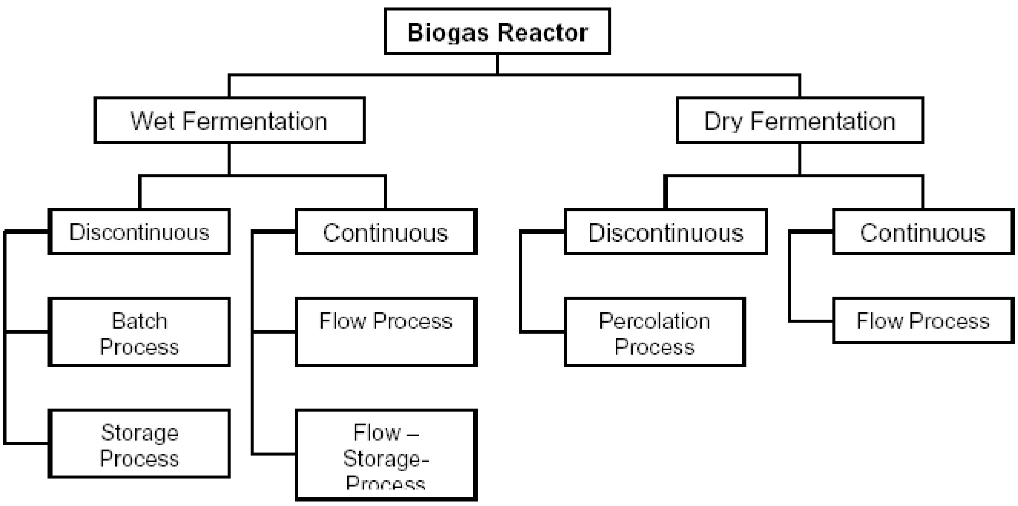


Figure 3: Scheme of different reactor principles (Wellinger 2006)

1.3.4. Biogas raw material

The anaerobic digestion of manure and sewage sludge is the most common application of biogas production performed in many small farmer digesters and sewage plants. Today, biogas production has become a standard technology in wastewater treatment and in the upgrading of bio waste from households, food industry and agriculture. Due to the implementation of profitable feed in tariffs for green electricity in different countries and the utilisation as transport fuel, the efficiency of the plant becomes more important and standardisation, especially for agriculture substrates and organic waste, increases. (Wellinger 2006)

The possible feedstocks for biogas production can roughly be divided into three categories:

Industrial feedstocks, such as, waste from the food industry, slaughter houses etc.
Agricultural feedstock, such as, animal manure, harvesting residues and energy crops, and
Municipality feedstocks, such as, urban sewage sludge and municipal solid waste.

1.4. Biogas utilisation

Biogas can be used for all applications for which natural gas is also designed, such as, for heating purposes, in CHP plants or as fuel for vehicles. Not all gas appliances require the same gas standards. There is a considerable difference between the requirements of stationary biogas applications and fuel gas or pipeline quality. (Persson et. al 2006)

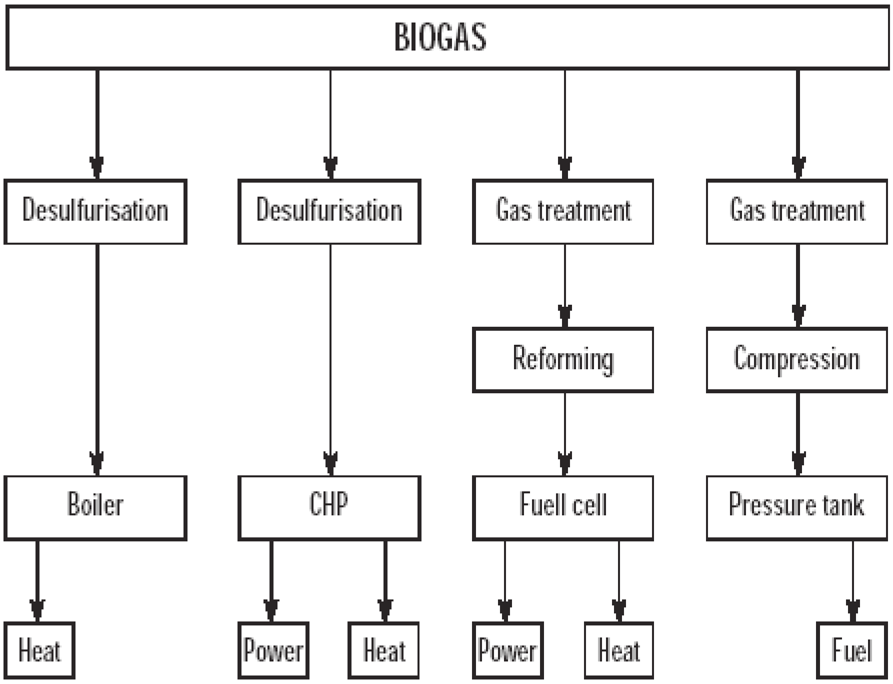


Figure 4: Different treatment procedures for different biogas applications (Persson et. al. IEA Task 37 2006)

There are four basic ways biogas can be utilised:

- Production of heat and steam
- Electricity production/ co-generation
- Vehicle fuel
- Production of chemicals.

In the following text, the several biogas applications are only briefly discussed. A differentiation is made between the conversion and the utilisation on site, and a decoupling of fermentation, conversion and utilisation according to their relevance in biogas upgrading procedures.

1.4.1. Conversion on production site

In Central and Eastern Europe, biogas is mainly used for the production of electricity. Due to the European Framework Directive on Renewable Energy and the resulting national legal framework conditions, most of the member states have implemented support mechanisms for this application. In the case of electricity production, about 30 to 40% of the energy content of biogas is transformed into electricity, heat being a by-product of this biogas conversion process. 40 to 60% of the energy content produced by the biogas needs to be utilised in close proximity to the actual biogas plant otherwise the losses are too high. About 10 to 15% of the energy content is, however, made up of non-usable energy losses. Possible usages for the "biogas waste heat" are, for example, heating of private households, public buildings, industry, drying purposes, such as, the drying of the biogas manure or other agricultural or industrial products, or for cooling purposes through the application of absorption technologies. Due to the fact that a modern and economically efficient biogas plant has an average working load of about 7.000 full load hours per year, the continuous use of the whole amount of the by-product heat is often hard to obtain. For a more efficient utilisation of biogas, a decoupling of the location of production and the location of conversion would be more suitable. (Tretter 2003)

1.4.2. Decoupling of biogas conversion

Decoupling of the biogas conversion and utilisation processes would support a more efficient usage of the biogas energy content and thus increase the utilisation possibilities beyond just electricity to include, for example, transport fuels or other substitutions of natural gas that could be used for several purposes. The decoupling can be achieved by feeding biogas into gas grids and transporting it over notable distances. Using this method, biogas can be used for a majority of applications that are developed for natural gas.

In comparison with the transportation of electricity and heat, there are fewer losses in the transportation of gas. (Persson et. al 2006)

1.5. Biogas treatment

Prior to the feeding biogas into gas pipelines and the actual utilisation of biogas as a fuel, a two step treatment is required. Firstly, purification of the biogas needs to occur. Most of the impurities need to be removed, as they may cause corrosion, deposits and wear of the equipment or may even harm the end-users. Secondly, the biogas must be upgraded. For biogas to be effectively used, it needs to be enriched in methane. This is primarily achieved by the removal of carbon dioxide, which then enhances the energy value of the gas. The removal of carbon dioxide also provides a consistent gas quality with respect to energy value. (Tretter 2003)

The treatment steps and the intensity of the applied treatment gradually improve the quality of the biogas.

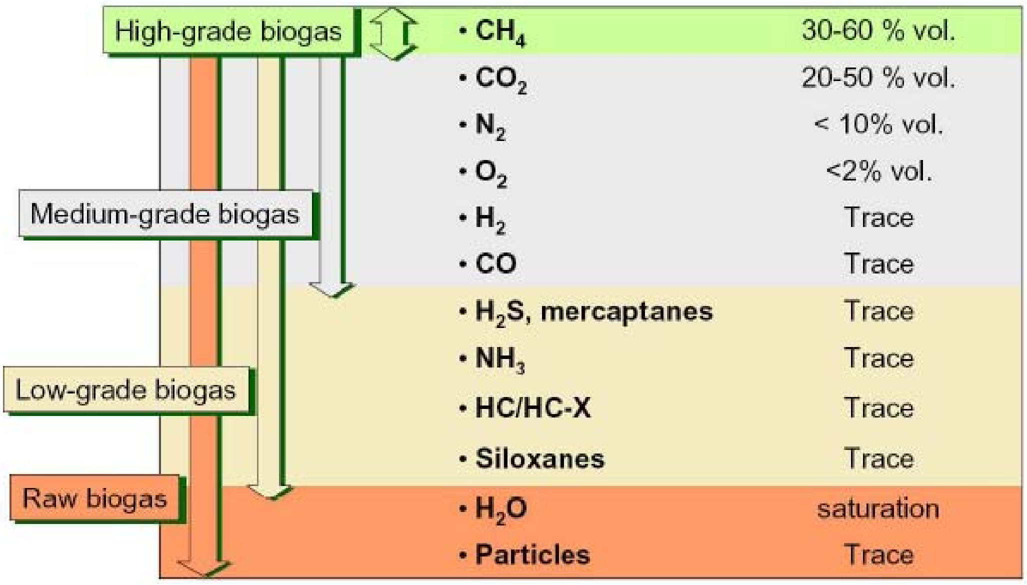


Figure 5: Quality steps of biogas referred to the components (Ferreira 2004)

1.5.1. Biogas purification

In the biogas purification process, substances requiring attention are: hydrogen sulphide, water, ammonia, halogen compounds (chlorides, fluorides), siloxanes, aromatic compounds, oxygen, and nitrogen. Purification usually takes place prior to or in conjunction with the upgrading of the methane content by the separation of CO_2.

The separation of H_2O and H_2S often occurs in separate process steps prior to the actual upgrading process of biogas. The following table illustrates several possible processes for the separation of H_2O and H_2S:

Separation principle	**Process**
Absorption (physical)	Rectisol (methanol) Sultinol (alkaline solution) Purisol, potassiumphosphate, sodiumphenolate, Alkazid, Girbotol Water scrubbing
Absorption (chemical)	Salt solutions (iron salts) Potassiumcarbonate Stertford Process MEA (mono ethanolamine)
Adsorption	Activated carbon Activated carbon + catalyst (e.g. iodine/potassiumiodide) Silica gel Zinc oxide Molecular sieves
Reactive desulphurization	Iron oxide, iron hydroxide
Bioreactor	Needs air for oxidative removal by thiobazillus bacteria
Trickle bed bioreactor	Needs air for oxidative removal by thiobazillus bacteria
Selective gaspermeation	

Table 3: Separation of H_2O (Harasek, Wukovits 2001)

Hydrogen sulphide is always present in biogas, although its concentration varies according to the feedstock. It must be removed in order to avoid corrosion in compressors, gas storage tanks and engines. Hydrogen sulphide is highly reactive with most metals, with its reactivity enhanced through concentration and pressure, the presence of water and elevated temperatures. It is therefore recommended, that hydrogen sulphide be removed early in the biogas upgrading process.

Separation principle	Process
Absorption (glycol scrubbing)	MEG (monoethyleneglycol) TEG (triethyleneglycol)
Adsorption	Silica gel Alumina Ceramic molecular sieves
Condensation	

Table 4: Separation of H_2S (Harasek, Wukovits 2001)

1.5.2. Biogas upgrading

For the biogas upgrading process, there exist several technical possibilities. In principle, the entire process portfolio of the thermal separation technologies exists. In chapter 4 some of these are explained in detail.

The following table shows a list of the possible separation techniques.

Separation principle	Process
Absorption (physical)	**Water scrubbing** Rectisol Purisol (n-methylpyrrolidone) Selexol (ethylene glycol)
Absorption (chemical)	Carbonate scrubbing (potassium carbonate) **Monoethanolamine (MEA)** Diethanolamine (DEA) Diisopropylamine (DIPA) Methyldiethanolamine (MDEA) Diglycolamine
Adsorption (pressure swing)	Carbon molecular sieve Ceramic molecular sieve Natural zeolites Silica gel Alumina
Membrane separation (gas permeation)	Cellulose acetate Polysulfone Polyetherimide Polycarbonate, Polyimide
Membrane separation (liquid membranes)	Water DEA / DIPA dissolved in polyethylene glycol (PEG)
Condensation (cryogenic separation	Methane / carbon dioxide condensation / distillation Micro structured heat exchangers

Table 5: Overview on biogas upgrading technologies (Harasek, Wukovits 2001)

2. Economic and legal framework for biogas net integration

In the following chapter, an overview of the main economic and legal frameworks influencing the net integration of biogas is discussed. The main influencing frameworks, the guidelines concerning net access and those concerning gas quality standards have all been identified. The reference market for natural gas having a great influence on biogas net integration is also roughly illustrated.

There are several European and national legal frameworks which state favourable usage of renewable energy sources. These frameworks are not subject of this master thesis. This master thesis deals only with frameworks influencing the net integration of biogas.

2.1. European and national frameworks concerning gas net integration and quality standards

2.1.1. General European frameworks

The supply of petroleum fuels will gradually decrease in the future and these will need to be replaced by sustainable fuels. This has been addressed by the European Commission in the directive 2003/30/EG where the following targets have been set:

- 2% bio fuels by the end of 2005
- 5,75% bio fuels by the end of 2010

Biogas is one of the possible substitutes for petroleum.

2.1.2. European frameworks concerning biogas feed in

In 2003, the European Parliament adopted the Directive 2003/55/EC, repealing Directive 98/30/EC, concerning common rules for internal market in natural gas. The scope of this new Directive covers natural gas and liquefied natural gas, along with biogas, gas from biomass and all other types of gases that can meet the necessary quality requirements. Whereas, § 24 of Directive 2003/55/EC, calls for admission to the gas network for biogas and gas from biomass for environmental reasons provided it is compatible with the secure and efficient operation of the network on environmental grounds: "*Member States should ensure that, taking into account the necessary quality requirements, biogas and gas from biomass or other types of gas, are granted non-discriminatory access to the gas system, provided such access is permanently compatible with the relevant technical rules and safety standards. These rules and standards should ensure, that these gases can technically and safely be delivered into, and transported, through the natural gas system and should also address the chemical characteristics of these gases".* Directive 2003/55/EC, Chapter 1, Article 1 defines the scope of the Directive: "*The rules established by this Directive for natural gas, including liquefied natural gas, shall also apply to biogas and gas from biomass or other types of gas in so far such gases can technically and safely be delivered into, and transported through, the natural gas system*."

2.1.3. European frameworks concerning gas quality

There is no international technical standard for biogas injection. Several gas companies and national authorities adopt different approaches concerning addition of non-conventional gases to natural gas networks. In the future, with networks becoming increasingly interconnected, a pan-European approach and a common position on the definition of "*technical rules and safety standards*" are required.

Injecting biogas into the gas grid raises concerns about the risk of transmitting disease via the gas. The Swedish Institute of Infectious Disease Control, National Veterinary Institute and the Swedish University of Agricultural Science have evaluated this risk. The study concluded that the risk of spreading disease via biogas was judged to be very low; the number of micro organisms found in biogas was equal to the level found in natural gas. (IEA, Task 37)

MARCOGAZ, the technical association of the European Natural Gas Industry has adopted a recommendation concerning technical and gas quality requirements for the delivery of non-conventional gases e.g. biogas into gas networks. This recommendation contains on the one hand the below-mentioned proposal for a harmonisation of the natural gas quality and on the other hand, a recommendation concerning limitations for impurities, concerns relating to quality control and insurance, such as measurements, shut downs, etc. (MARCOGAZ 2006 Cigni et. al)

Within the European Union there is a proposal to harmonise natural gas quality specifications. A specification has been produced by EASEE-Gas. The table below indicates the parameters that form part of the harmonised specification together with status and value limits.

Non-conventional supplies of gas must comply with prevailing national and European legislation and must be compatible with the gas quality specifications of the gas to which the non-conventional gas is being added.

Parameter	Value	Status
Wobbe Index	13.6 ÷15.81 KWh/m^3 (25°C/0°C)	Recommended. A difficulty has been recognised with the lower WI value and as a result a starting range of 13.76 ÷15.81 has been recommended.
Relative Density	0,555 ÷0,7	
Total sulphur	Maximum 30 mg S/m^3	
(H_2S + COS)	Maximum 5 mg S/m^3	
Mercaptans	Maximum 6 mg S/m^3	
Oxygen	Maximum 100 ppm molar	Under discussion at the time of publication of this report
Carbon dioxide	Maximum 2.5 % molar	
Water dewpoint	Maximum – 8°C at 70 bar a	
Hydrocarbon dewpoint	Maximum – 2°C over 1 ÷70 bar a	
Hydrogen		Currently unspecified, but it is recognised that the above WI and RD limits are only valid for "insignificant" amounts of hydrogen and may need to be changed if hydrogen content is significant.

Table 6: Gas quality parameters currently considered in proposed harmonised EU specification (MARCOGAZ 2006)

2.1.4. Situation in Austria

The Austrian gas economics act ensures that distribution network enterprises have to permit net connection to producers of biogas providing they fulfil the required quality standards. The detailed quality standards are mainly listed in the ÖVGW directive G31. The standards were originally defined for natural gas. The standards ensure secure transportation of the gas via the Austrian gas pipeline without harming it in any way. A certain minimum calorific value is guaranteed to the customers.

Gas components	
Hydrocarbons (dewpoint)	< 0°C at operating pressure
Water (dewpoint)	<-8°C at a pressure of 40 bar
Oxygen	< 5vol%
Carbon dioxide	< 2vol%
Nitrogen	< 5vol%
Hydrogen	< 4vol%
Total sulphur	< 10 mg S/m³ (continuous) < 30 mg S/m³ (peak)
Mercaptane sulphur	< 6 mg S/m³
Hydrogen sulphide	< 5 mg/m³
Halogenated compounds	0 mg/m³
Ammonia	Technically free
Solid and liquid constituents	Technically free
Other components with negative effects on safe operation and grid stability (corrosion) are not allowed	

Table 7: ÖVGW G31 limits for gas impurity

Calorific Data	
Wobbe Index	13,3 – 15,7 kWh/m³
Upper heating value	10,7 – 12,8 kWh/m³
Relative density	0,55 – 0,65

Table 8: ÖVGW G31 limits concerning the calorific value of gas

The Wobbe-Index defines the maximum thermal load of blower.

The new directive, ÖVGW G33, includes the integration of biogas and states the same quality standards as fixed in the directive, ÖVGW G31, also for biogas but with some additional limitations:

- CH_4 > 96% if H_2 is present
- CH_4 > 97% if no H_2 is present
- Total silica (siloxanes, silanes) <= 10 mg/m³N

Included in the new directive are measurement procedures, regulations concerning the feed amount and several technical issues for biogas net integration:

- H_2S, methane and dew point must to be measured regularly (every 15 minutes)
- Measurements of gas quantity must ensure that there is to be no flow back of natural gas to the biogas plant
- Pressure control need to be done
- The feed amount has to be less or equal to the consumption; other feed in points in the same section need to be taken into consideration
- Several technical issues have to be settled with the local grid operator, such as, the odorisation of biogas
- Immediate feed discontinuation takes place should the required quality standards not be met.

The following table shows a comparison of the average biogas quality and the quality standards as required by the ÖVGW G31 directive.

	Raw biogas	ÖVGW G31	Unit
Methane	50 - 75	97	vol.%
Carbon dioxide	25 - 50	2	vol.%
Water vapour	1 - 5	0	vol.%
Notrogen	5	5	vol.%
Oxygen	0 - 5	0,5	vol.%
Hydrogen	< 1	4	vol.%
Ammonia	< 1	free	vol.%
Hydrogen sulphide	< 1	0,0003	vol.%
Calorific value	5,52 - 8,27	10,7 - 12,8	kWh/m³
Wobbe index	5,9 - 8,15	13,3 - 15,7	kWh/m³

Table 9: Comparison of average biogas quality and gas quality required by the ÖVGW G31 Directive

2.1.5. Comparison of several national quality standards in Europe

In only a few European countries, standards for the integration of biogas into the gas grid have been defined. Following a comparison of the quality standards in Austria, Germany, Sweden, Denmark and Switzerland, an overview on the range of regulations can be seen and the main differences noted. Quality standards have great influence on the requirements of the biogas treatment technology and on treatment costs.

The main differences can be assumed as followed:

- The basis of comparison is different in the several countries. For example, Austria focuses on the natural gas quality in gas from Russia, the reference for quality for Netherlands is the natural gas from the North Sea.
- Austria, Germany and Switzerland refer to quality at the feed-in point, while Sweden refers to quality as that of the mixed gas in the network.
- Switzerland also allows a net integration of biogas with minimum treatment as an additional gas up to an amount of 5%. (Hornbachner et. al 2005)

	Austria	France	Germany	Netherlands	Sweden	Switzerland	
Property						Unlimited Injection	Limited injection
CH_4	> 96 %	/	-	85%	>97%	>96%	>50%
CO_2	< 3 %	<2,5%	#6%	/	<3%	<4%	<6%
CO		<2%	/	/	/	/	/
Total S	< 10 mg/m³	< 30mg/m³	#30 mg/m³	<45 mg/m³	< 23 mg/m³	< 30mg/m³	< 30mg/m³
H_2S	< 5 mg/m³	< 5 mg/m³ (H_2S+COS)	# 5 mg/m³	< 5 mg/m³	10 ppm	< 5 mg/m³	< 5 mg/m³
Mercaptans	< 6 mg/m³	<6 mg/m³	15 mg/m³	/	/	/	/
O_2	< 0,5 %	<0,01%	<0,5%	<0,5%	<1%	<0,5%	<0,5%
H_2	< 4 %	<6%	#5 %	/	<0,5%	<5%	<5%
H_2O	Water dew point -8°C/40 bar	Water dew point <-5°C at MOP	Water dew point: Ground temperature	<32 mg/m³	<32 mg/m³	<60%	<60%
Hydrocarbon dew point	0°C at OP	<-2°C (1-70 bar)	Ground temperature	/	/	/	/
Wobbe index	13,3 - 15,7 kWh/m³	13,64-15,7 kWh/m³ for H gas 12,01- 13 kWh/m³ for B gas	10,5 -15,7 kWh/m³	43,6-44,41 MJ/m³	45,5 - 48,5 MJ/m³	13,3-15,7 kWh/m³	/
Pressure			Pressure of pipeline to be injected into				
Gross calorific value	10,7- 12,8 kWh/m³	10,7- 12,8 kWh/m³ for H gas 9,5 -10,5 kWh/m³ for B gas	/	35,1 MJ/m³	/	10,7-13,1 kWh/m³	/
Relative density	0,55 - 0,65	0,555-0,70	/	/	/	0,55-0,70	/
Odorant	Gas to be odorized at consumer	15-40 mg THT/m³	Gas to be odorized at consumer	Gas to be odorized at consumer	/	15-25 mg THT/m³	15-25 mg THT/m³
Impurities	Technically pure	Technically pure				Technically pure	Technically pure
Halogenated compounds	0 mg/m³	< 1 mg Cl /m³ < 10 mg F /m³	nil	< 25 mg Cl/m³	/	/	
Ammonia	Technically pure	/	/	<3 mg/Nm³	<20 mg/Nm³	/	/
Dust	Technically pure	/	No dust	No dust			
Mercury		< 1 µg/m³	/	/	/	/	/
Benzene							
Siloxanes	< 10 mg/m³						

Table 10: Specific requirements for the injection of non-conventional gases into natural gas networks in some European countries (Marcogaz 2006)

2.2. Reference market - natural gas

The natural gas pipeline network is a great technological achievement. Over 1.400.000 kilometres of pipeline extend across Europe, with thousands of kilometres of pipeline interconnections and extensions currently being built or planned to ensure a secure and reliable supply of energy in the future. (Eurogas 2007)

Europe is mainly dependent upon natural gas imports from Russia.

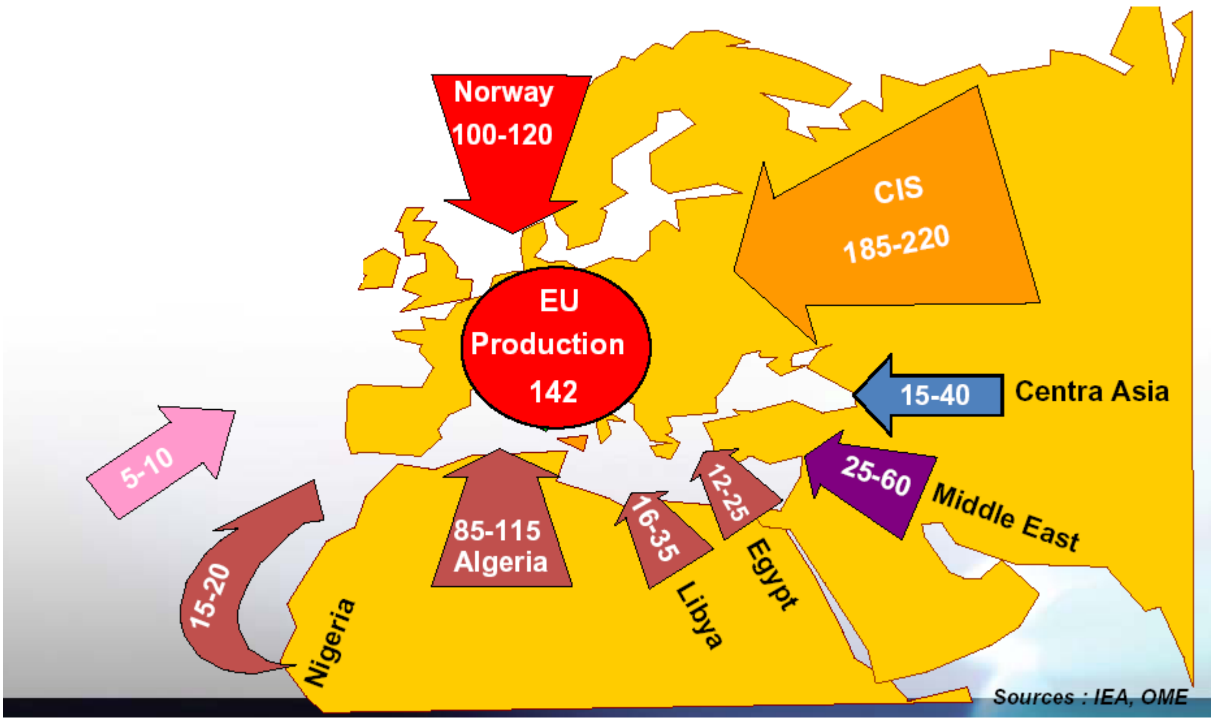


Figure 6: European natural gas balance (Eurogas 2007)

Biogas production could decrease the dependency on imports. If through the treatment process, the discussed quality standards are obtained, then the existing infrastructure for natural gas can be used for the distribution of biogas.

The gas grid consists of pipes with different pressure levels and several functions. Austria distinguishes between 3 gas grid levels:

- Level 1: trans-regional transport and transit pipes operating on a high pressure level from 70 to 120 bars

- Level 2: distribution net, supply of big costumers, pressure level from 6 to 70 bars
- Level 3: distribution net on a local level, supply of small customers, pressure level up to 6 bars.

Net integration of biogas occurs on level 2 or 3. The use of a higher network level has the advantage that less operating pressure required which subsequently lowers the net integration costs. The lower net level allows the integration of higher quantities of biogas. There is no seasonal oscillation on this level. (Hornbachner et. al 2005)

3. Gas upgrading technologies

This chapter describes the new biogas upgrading technology based on gas permeation. The recently most applied technologies for the upgrading of biogas are described and analysed as these can be considered the main competitors for the new biogas upgrading technology.
The analysis consists of the description of the upgrading process, the known advantages and disadvantages of these technologies, including quality results, the upgrading costs, the energy consumption of the process along with a list of suppliers of the technology and the technology diffusion currently available on the market.

3.1. Gas permeation process

This document is based upon the concept for the gas permeation process developed by the Vienna University of Technology. For this new technology the first steps of a business development concept shall be developed.

3.1.1. Description of the process

The gas permeation process takes advantage of the different permeability of polymer membranes to separate unwanted gas components. Some of these polymer membranes, such as cellulose acetate and aromatic polyimides, have a very high permeability for CO_2, H_2O, NH_3 and H_2S in comparison to those for methane. These characteristics are used in the upgrading process of biogas. The biogas can be rid of the unwanted CO_2 using the gas permeation process, whilst being dried at the same time, thus eliminating the additional drying step normally required at the end of the process by other upgrading technologies.

The main process components are:

- gas compression to create the required process pressure for the membrane units and for the transportation of the upgraded biogas

- gas pre-treatment, such as, condensation and H_2S adsorption for the elimination of impurities which may disturb the function of the gas permeation units
- gas permeation units based on hollow fibre and flat membranes
- control engineering to control pressures, temperature and stream volumes for the compliance of the required product specification.

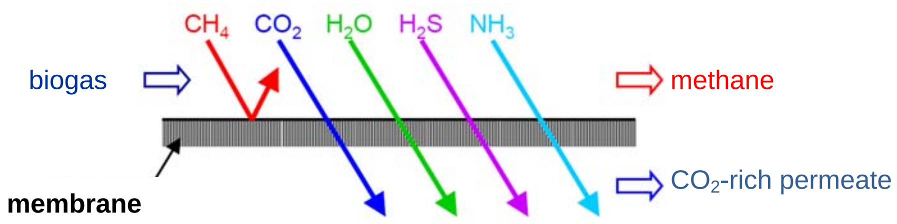


Figure 7: Principles of biogas upgrading by membrane technology

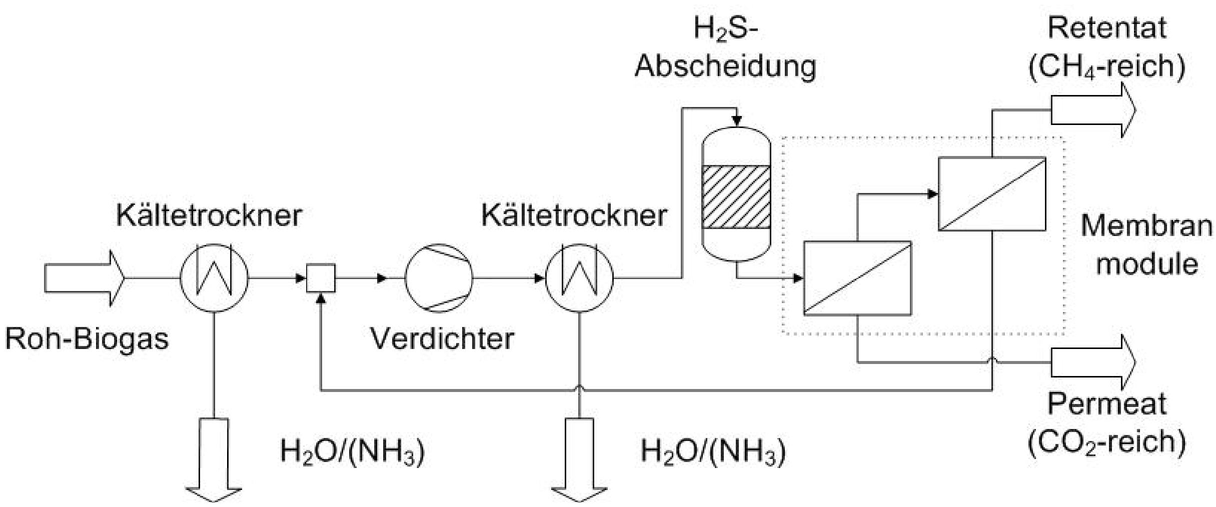


Figure 8: Gas-permeation flow-sheet

The following diagrams illustrate the processes and their data. Firstly, an overview is given (figure 9 & 10) followed by a detailed illustration of several process points with the figures obtained from the process control system (figure 11 to 17). The process is controlled automatically. Each process step shown allows the measures to be manually made.

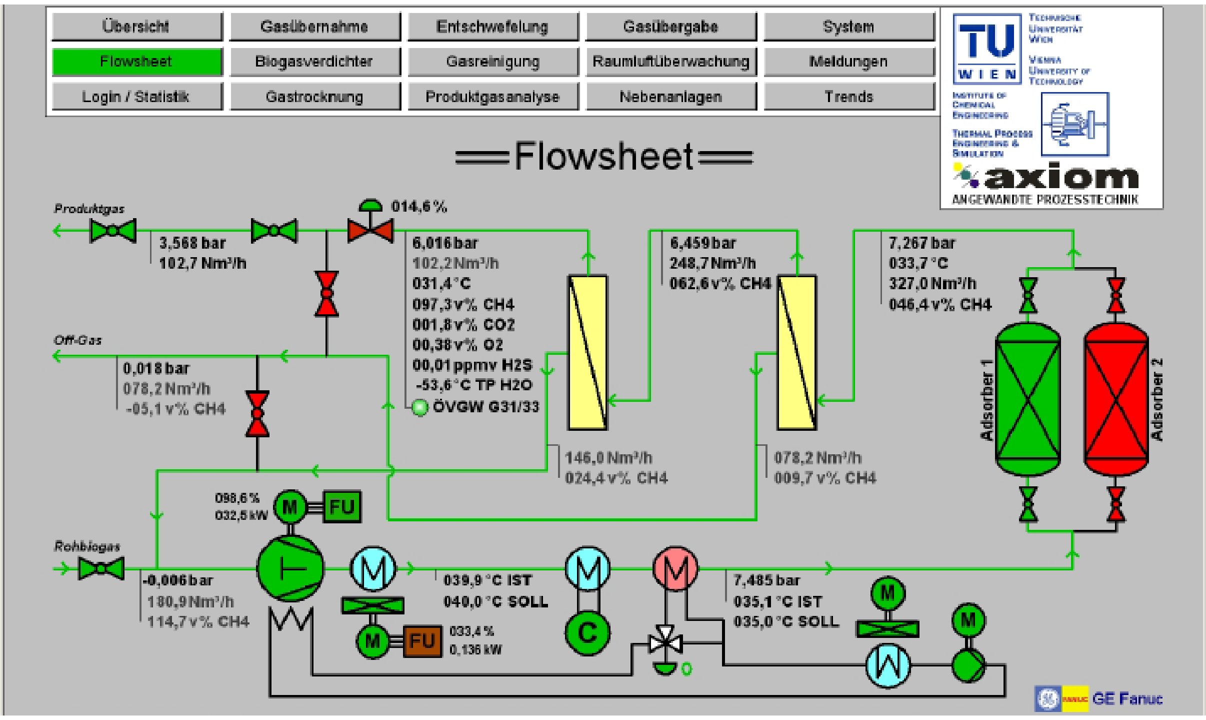


Figure 9: Flow-sheet – gas-permeation in Bruck/Leitha – average process data

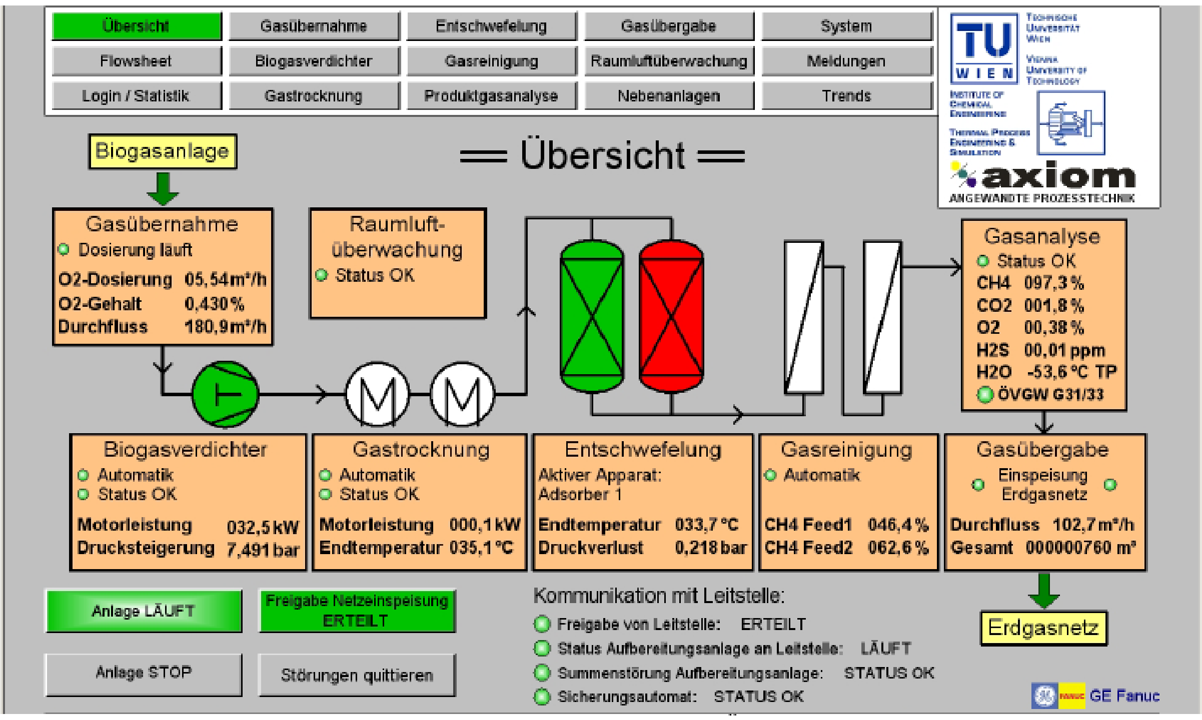


Figure 10: Overview – front page of the process control system – overview on the actual plant status

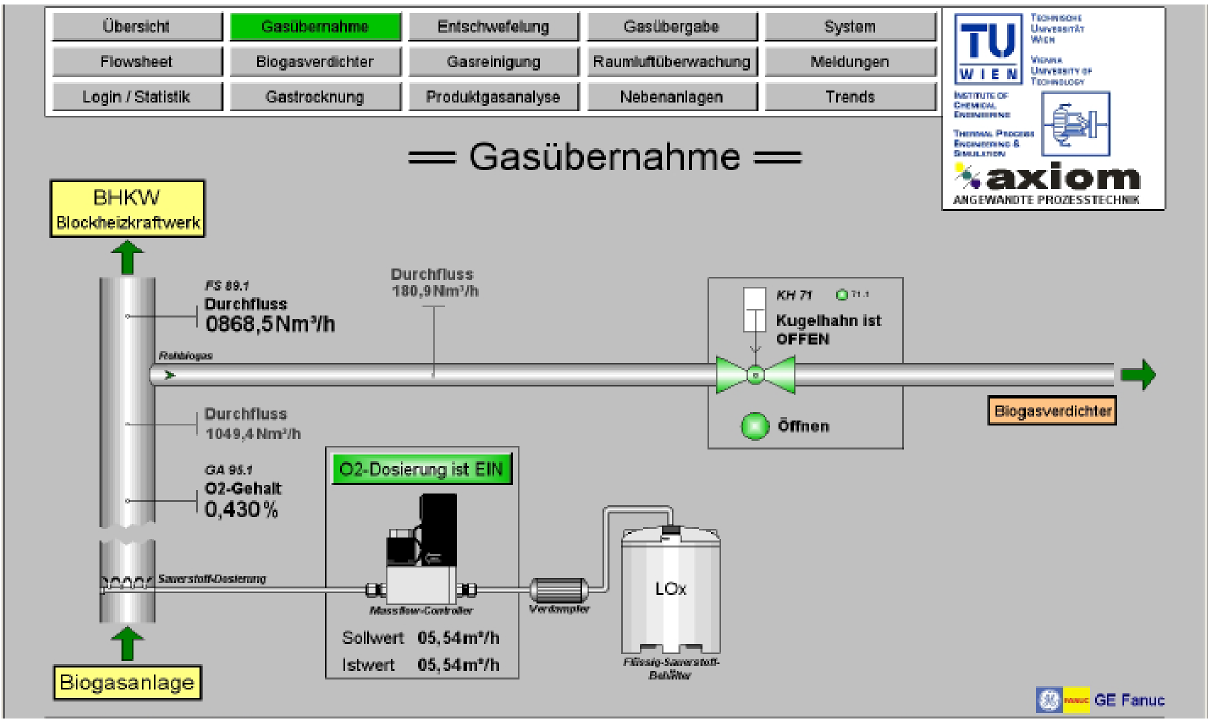


Figure 11: Gas take–over from the biogas plant

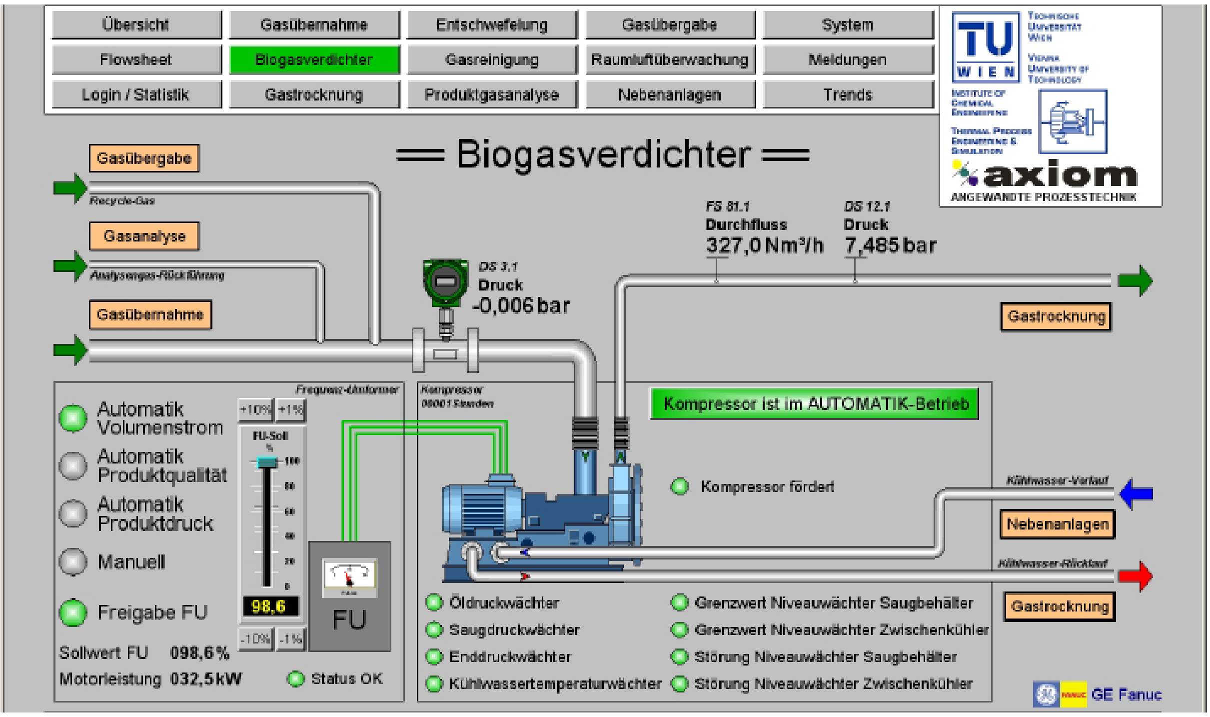


Figure 12: Gas-compressor

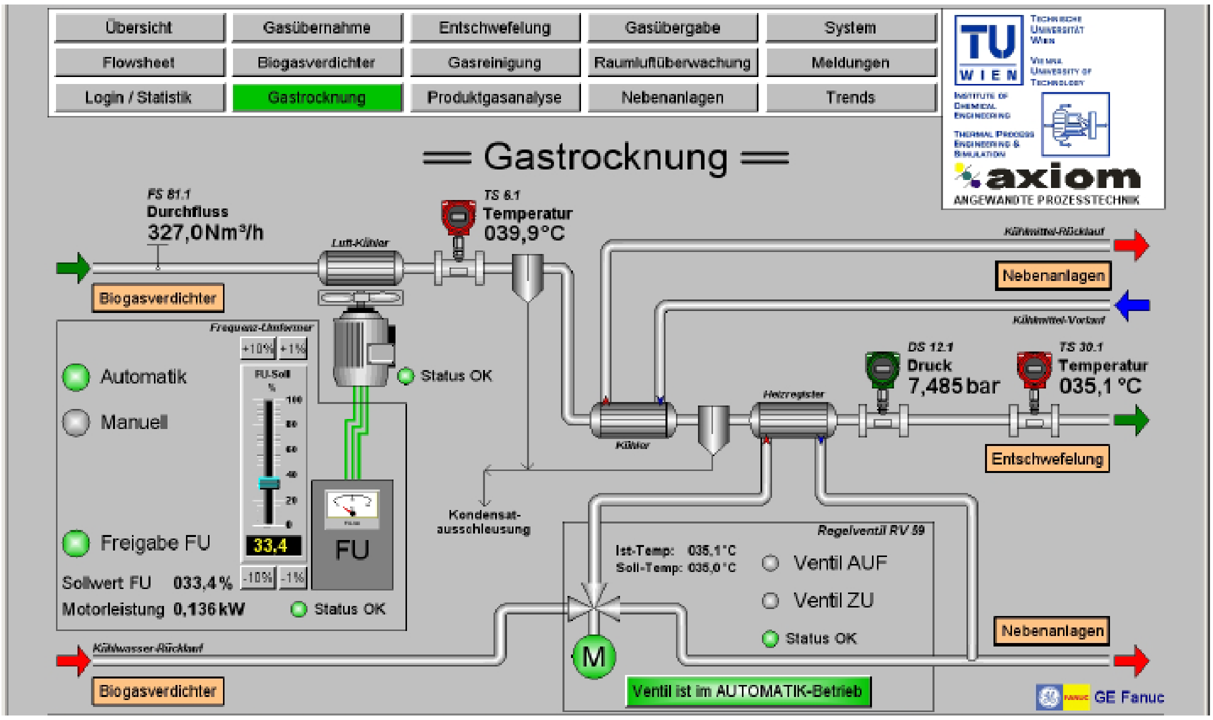


Figure 13: Gas-drying

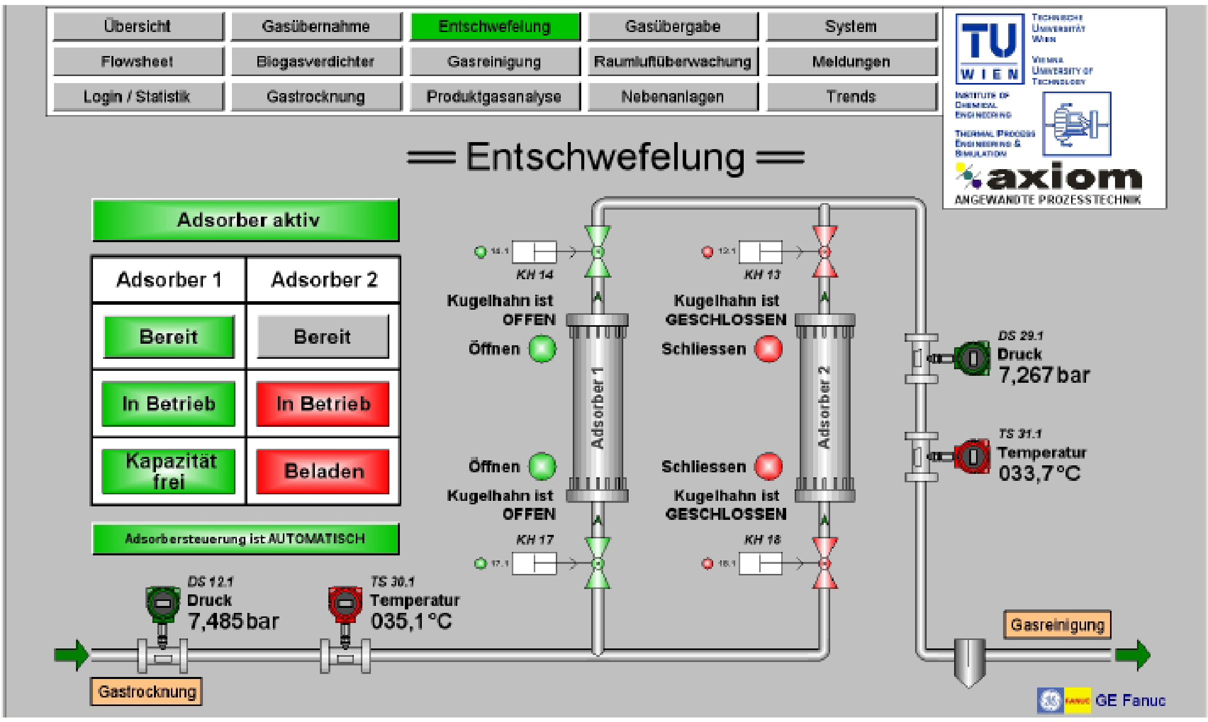


Figure 14: Desulphorisation

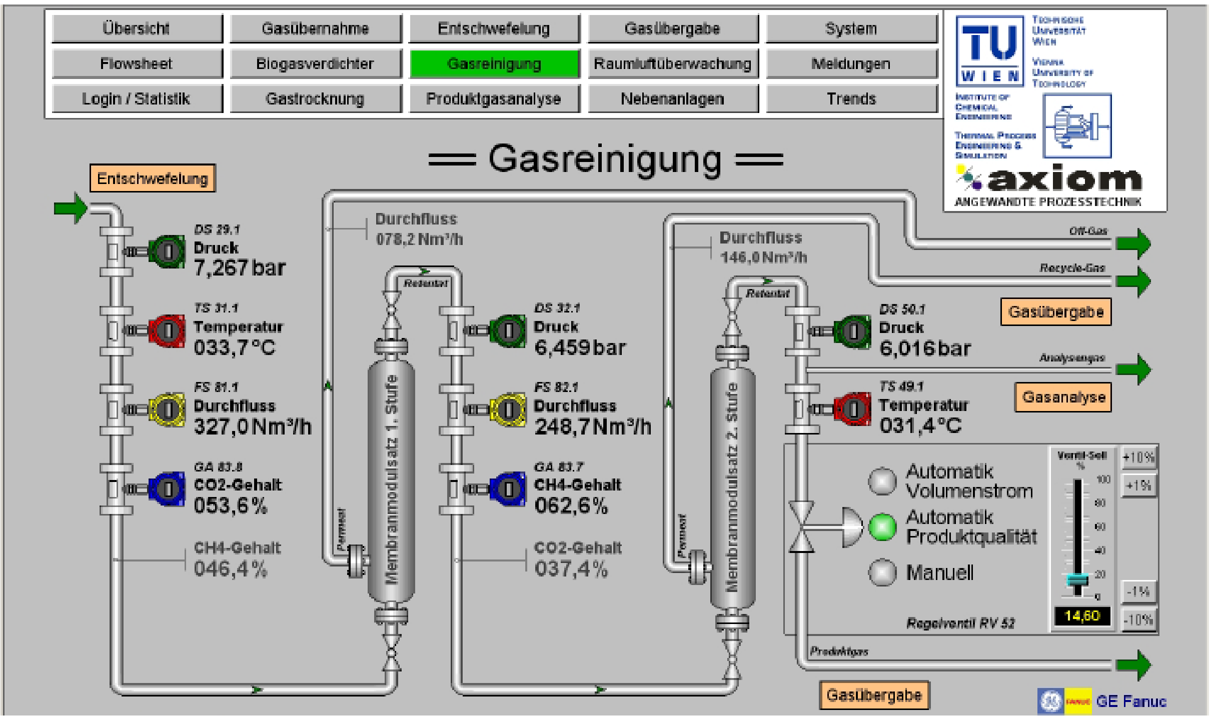


Figure 15: Gas-purification

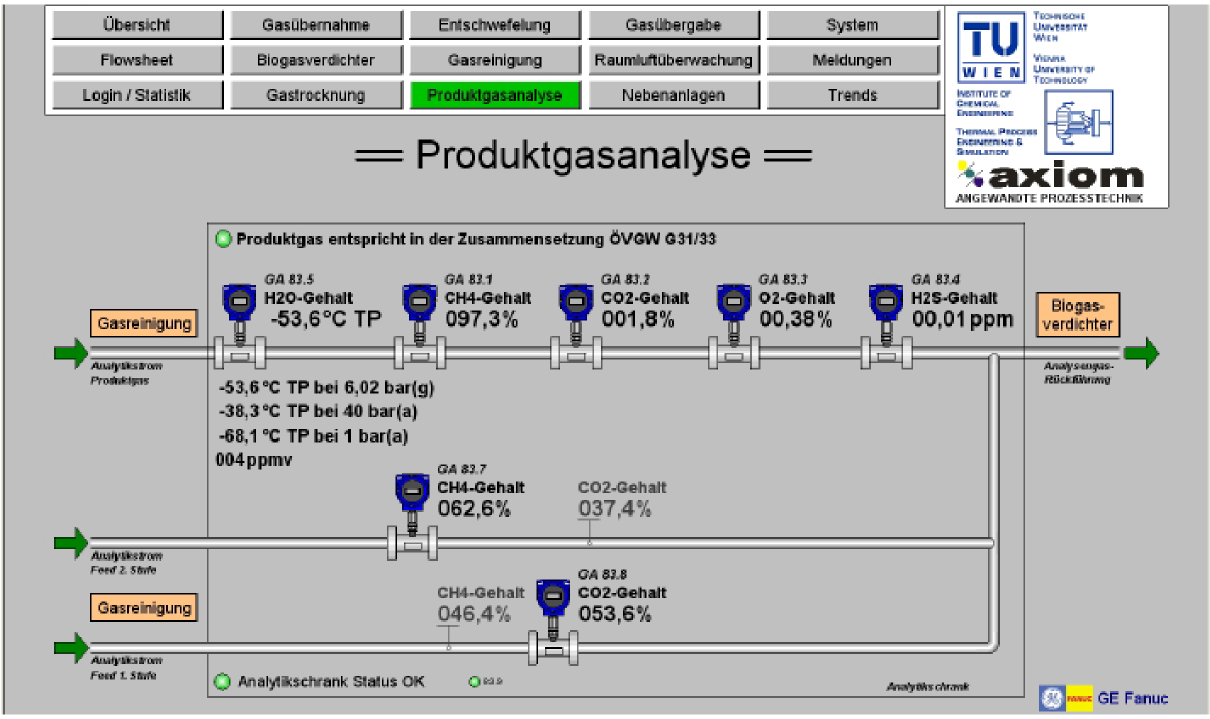


Figure 16: Product gas – analysis

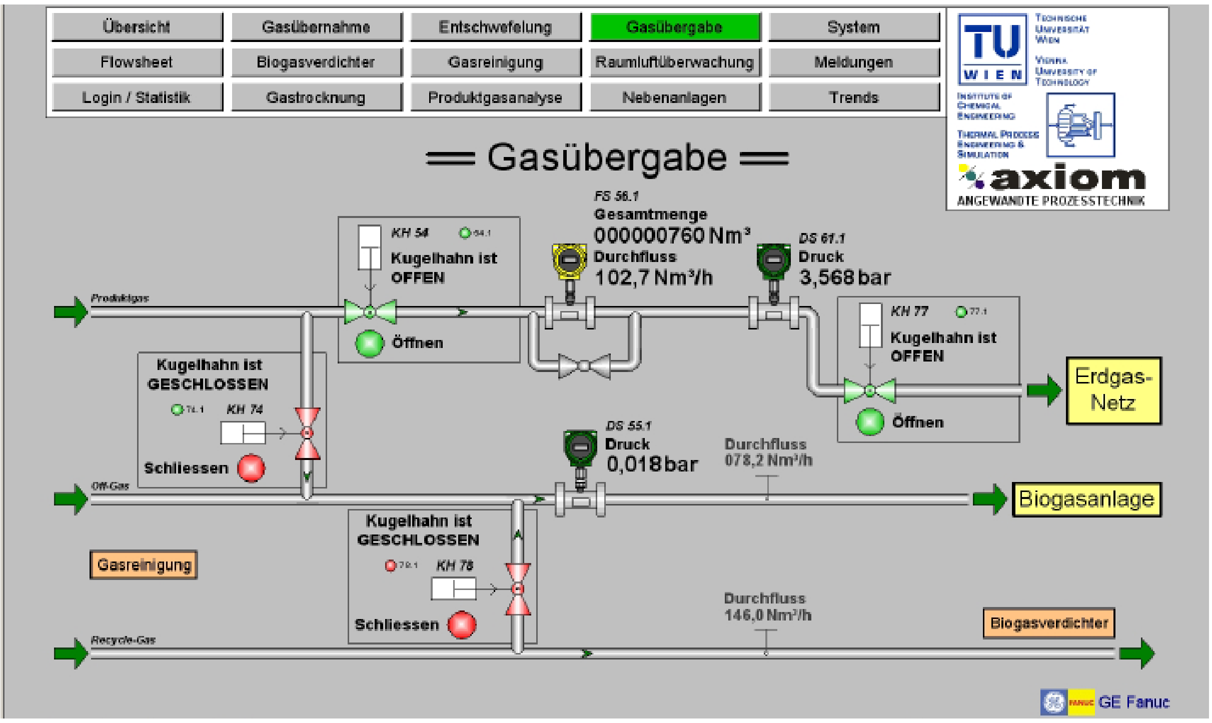


Figure 17: Feed-in point

A control system for the ambient air is installed in the container where the upgrading facility is placed. This control system measures and analyses the ambient air composition in relation to burnable substances and their actual concentration. If these reach a pre-defined critical limit then air ventilation commences automatically. If the concentration reaches 40% of the defined lower explosion limit then the entire plant is disconnected from all forms of electricity. Temperature measurements provide a further fire safety control measure. In the case of a fire, the entire plant is shut down.

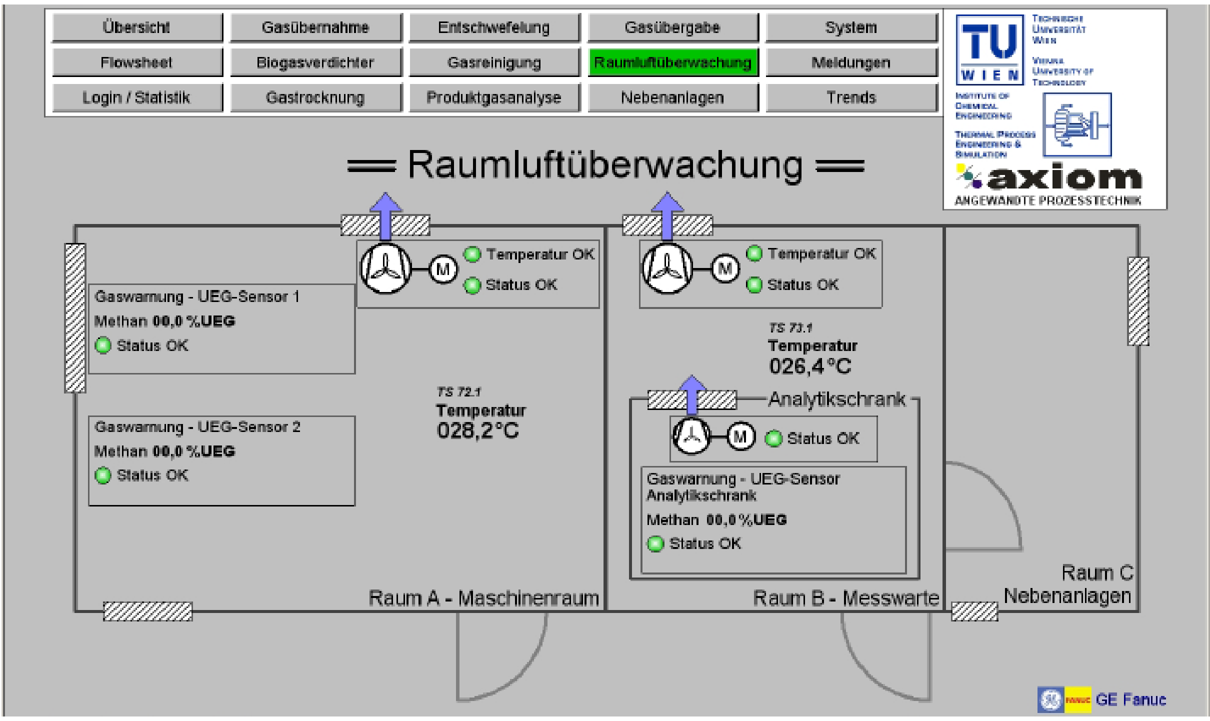


Figure 18: Ambient air control system

The measured process data and system failures are recorded, documented and retained for a period of time enabling further process analysis to occur.

The plant is almost automatically regulated. This ensures a stable gas quality of the output gas, fulfilling the requirements of gas quality in the grid and an adapted integration to pressure and stream flows from the raw biogas to the grid.

3.1.2. Technology development process

The technology was mainly developed by Dr. Michael Harasek, from the Vienna University of Technology, in cooperation with a small Austrian engineering enterprise. Throughout the development process various other interested parties were involved in projects to aid further development of the technology.

Bench scale unit

After the development of the new biogas process, the first practical application using a bench scaled unit was realised within the Austrian development program “Energiesysteme der Zukunft”. The project was lead by the Vienna University of Technology and performed in association with project partners Wien Energie Gasnetz GmbH, Axiom Angewandte Prozesstechnik Ges.m.b.H., and Biogas Produktionsges.m.b.H.

The main goal of this project was to develop a modern and efficient method based on membrane separation technology and to test the new method in combination with biogas fermentation for the digestion of energy crops. An innovative process design required only one compressor. Additionally, the methane losses could be reduced to below 2%.

A mobile pilot plant unit was designed, built and transported to an agricultural biogas production facility where energy crops were used as the fermentation feed source. During the demonstration phase of the project, a small bypass raw biogas stream of up to 1 m^3/h was upgraded to meet the requirements of the Austrian natural gas quality directive ÖVGW G31. The quality of the produced gas was analyzed by an independent laboratory. The results are used as the basis for the design of a future full-scale biogas upgrading facility. Even though the lifetime of the membrane cannot be estimated from the number of runs thus far, only a small decline in the performance of the membrane modules was observed.

Another project goal involved screening the new gas analysis techniques for online monitoring of the product gas. A new technology based on a photo acoustic signal generation was tested through the development of a suitable prototype for the measurement of carbon dioxide. The results obtained are promising and may be used as the basis for further development.

Safety measures were investigated for the scale up of the technology and suitable control techniques. Recommendations were given for the fully automated plant operation. A concept was developed for the quick shutdown of the upgrading facility.

Finally, a simulation tool was developed to model and scale-up the investigated technology. The simulation model considered all the individual unit operations (compression, condensation, gas permeation, and adsorption) and was to be the basis for a future scale-up. (Harasek 2005)

Pilot plant with net integration

The next step involved the further development for the upgrading technology based on membrane permeation. This was to be scaled up and applied for upgrading 180m³/h raw biogas, a side stream of the biogas plant in Bruck/Leitha. The quality of the gas corresponds to the requirements of the ÖVGW G33 directive. A quantity of about 100 m³/h pure gas was injected under pressure into the local gas grid operated by the EVN network. During summer, a part of the biogas has to be injected directly in the lower grid level which then requires a further compression station. The injected biogas is then virtually delivered to the customers.

There are three steps in this process:

1. Desulphurisation of the raw biogas by the injection of pure oxygen into the existing desulphurisation column. This replacement of the former desulphurisation with air avoids a too high load of nitrogen (maximum of 50ppm). The Vienna University of Technology developed a control concept which adapts the amount of oxygen demand automatically to the hydrogen sulphide content of the processed raw biogas.
2. Biogas upgrading process with membrane technology. This process step contains the compression and fine purification of the H_2S contents through mixed oxides, two gas permeation steps with recycling and the regulation of

product quality to fulfil the quality requirements (patent registered). The entire treatment plant is placed in a container system.

3. Delivery point to the gas grid with measurements for gas quantity and gas quality, regulation of pressure and odorisation for winter operation. In summer a share of the about 50 m³/h upgraded biogas gets injected into the higher pressure grid which is situated about 2.8 km away from the plant site. An odorisation procedure is not required for this stream.

The connection of the gas permeation facility to the biogas plant follows a zero CH_4-concept by the installation of a two tube system. This enables recycling of the permeate in the biogas CHP motors.

The pilot plant in Bruck/Leitha is equipped with a very sophisticated control engineering which detects measures and visualises continuously the gas streams and their quality, as well as, the temperature and pressure at several different process points. This allows very detailed documentation and a tight control of the plant behaviour. This sophisticated control system was specifically designed for this pilot plant. It is not required in its full complexity for standard plants in the future. Therefore, the investment costs in further gas permeation plants will be lower in this part of the facility.

Picture 1: Membrane gas permeation – Bruck/Leitha

Commencement of this operation began in June 2007. In December 2007 the upgrading plant commenced continuous operation.
Project partners were the Vienna University of Technology, Biogas Bruck/Leitha GmbH, der Energiepark Bruck /Leitha, Axiom Angewandte Prozesstechnik GmbH, OMV AG, EVN AG and Wien Energie Gasnetz GmbH. The project received financial support from the project partners in the gas industry, the FFG, the Austrian support program “Energiesysteme der Zukunft” and the OMV Future Energy Fund.

The diagrams below illustrate the volume streams and the gas quality reached by the upgrading plant in its commencement phase.

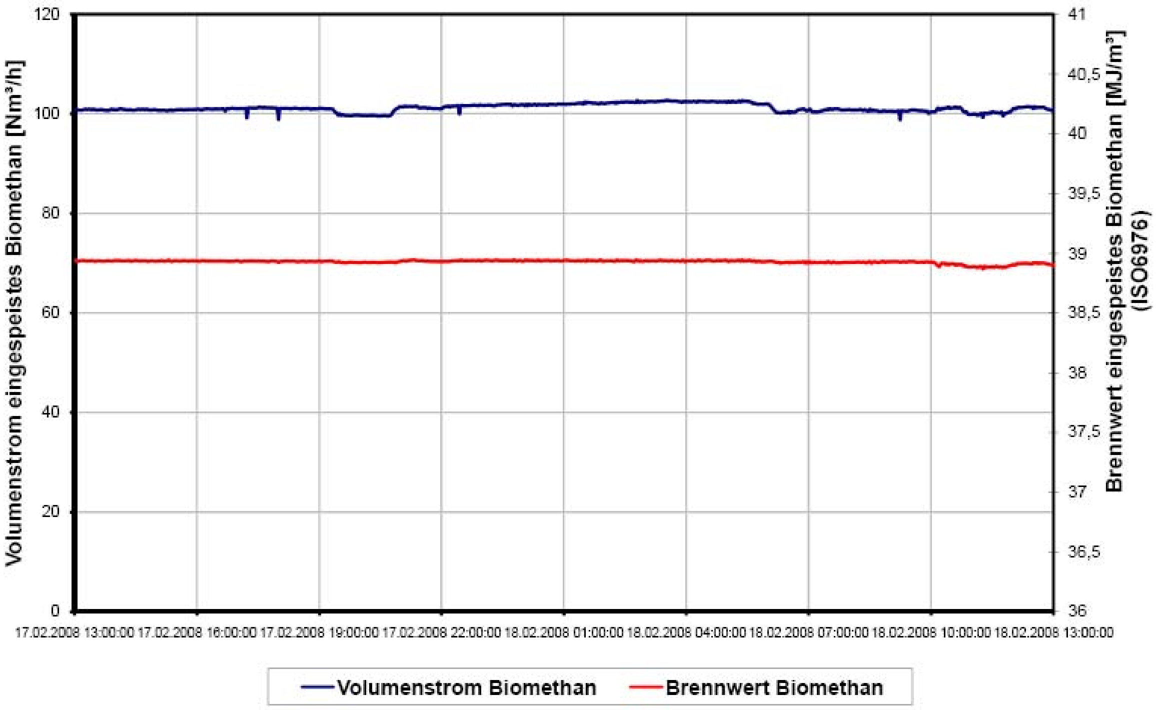


Figure 19: Volume stream and caloric value at commencement of the plant

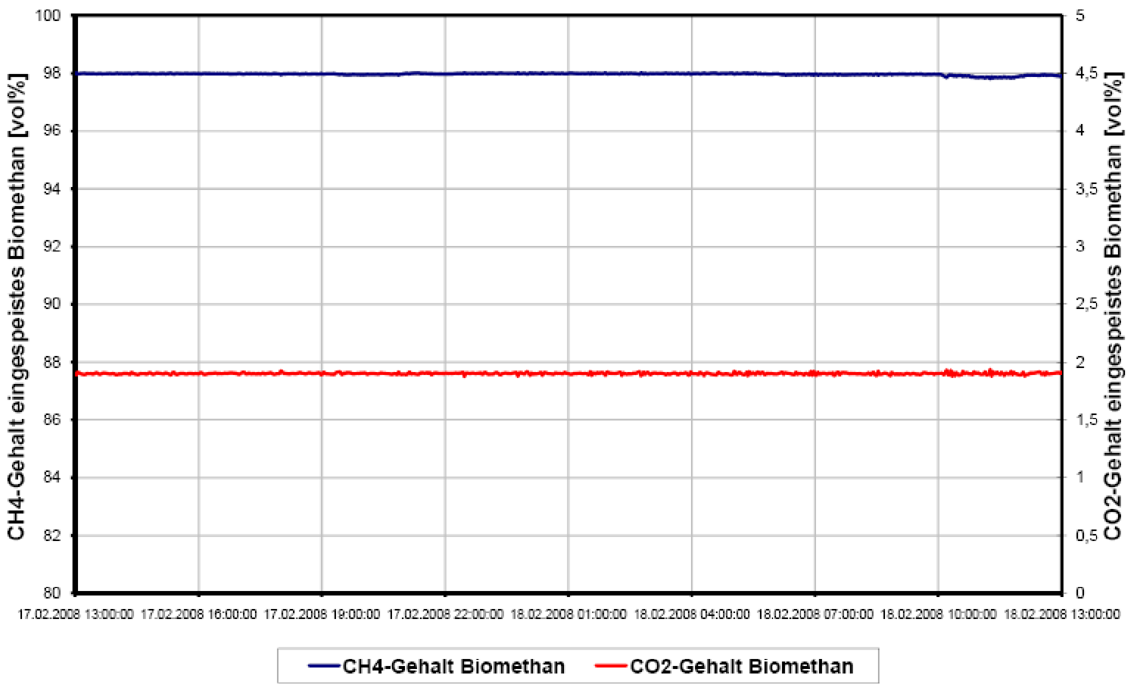


Figure 20: Quality results at commencement of the plant – CH_4 and CO_2

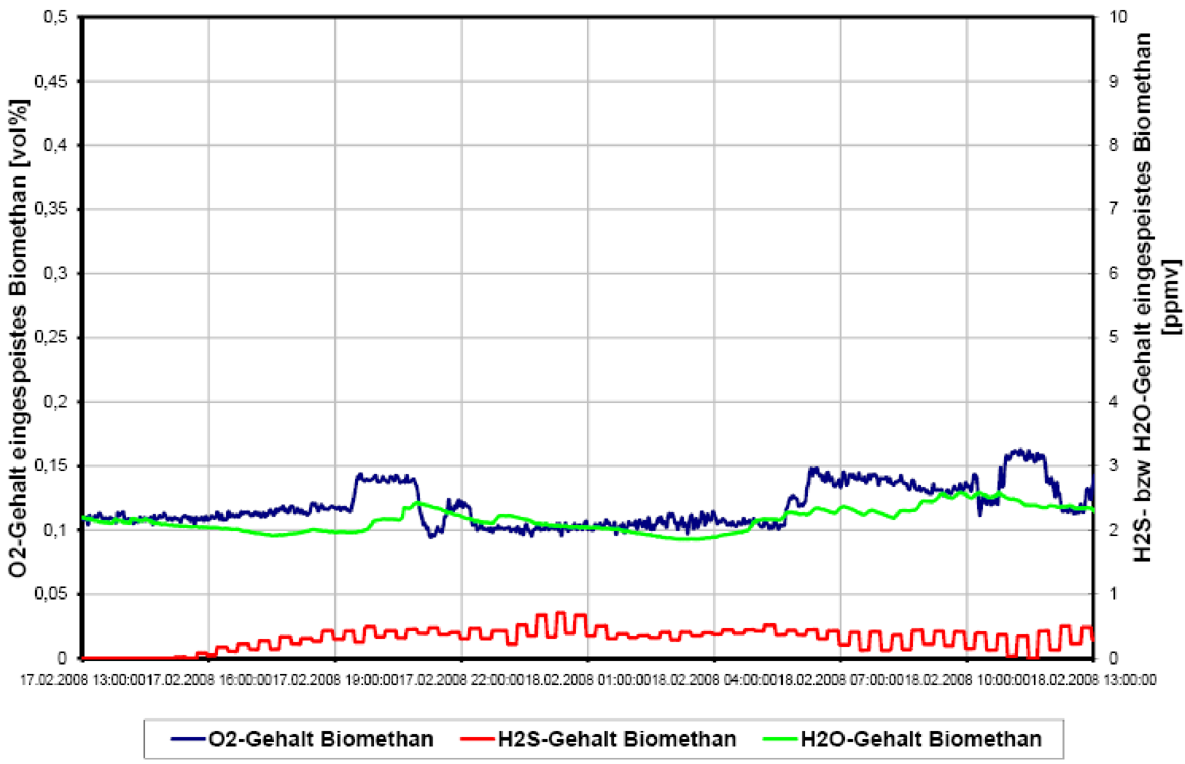


Figure 21: Quality results at commencement of the plant – O_2, H_2S and H_2O

The project has been integrated into an overall project where the economics involved and the degree of added-value are analysed and optimised. Commencing with the optimisation of the feedstock production by special crop rotation methods and special harvesting methods and ending with the optimisation of the biogas as vehicle fuels through the optimisation of gas vehicles.

3.1.3. Technology evaluation

Approximately, 5 biogas upgrading sites throughout Europe applied a gas permeation process. Evidence shows that relative high losses of methane occur through use of this technology. These losses can be decreased through serial connection of more membranes. (Hornbachner et. al. 2005)
The pilot plant Bruck/Leitha's experiences with the gas permeation technology have proven to be very stable. The gas is of a high quality with an extremely high availability ratio. Methane losses of the conducted methane load were found to fall within the range of about 2 - 3 Vol.-% but did not exceed this amount.
The whole process occurs under pressure (about 7 – 8 bar) which leads to a higher electricity consumption compared to low pressure processes, such as amine scrubbing.

The main advantage of gas permeation technology in relation to other upgrading technologies is its low maintenance costs. These can be attributed to a lower consumption of maintenance resources. Until the wear of membranes in contact with biogas is proven, it is impossible to precisely predict the lifetime of the technology.

3.2. Pressure Swing Adsorption with Carbon Molecular Sieve (PSA)

The PSA process with carbon molecular sieves takes advantage of the different adsorption attitudes of CO_2 and CH_4 - CO_2 which links faster and stronger to the solid than CH_4.

3.2.1. Description of the process

To ensure a continuous and efficient biogas upgrading process, the PSA plants operate mostly with four standing columns.
The whole process can be divided into for steps – pre-purification and compression, H_2S separation, conditioning (cooling and drying) and methanisation.

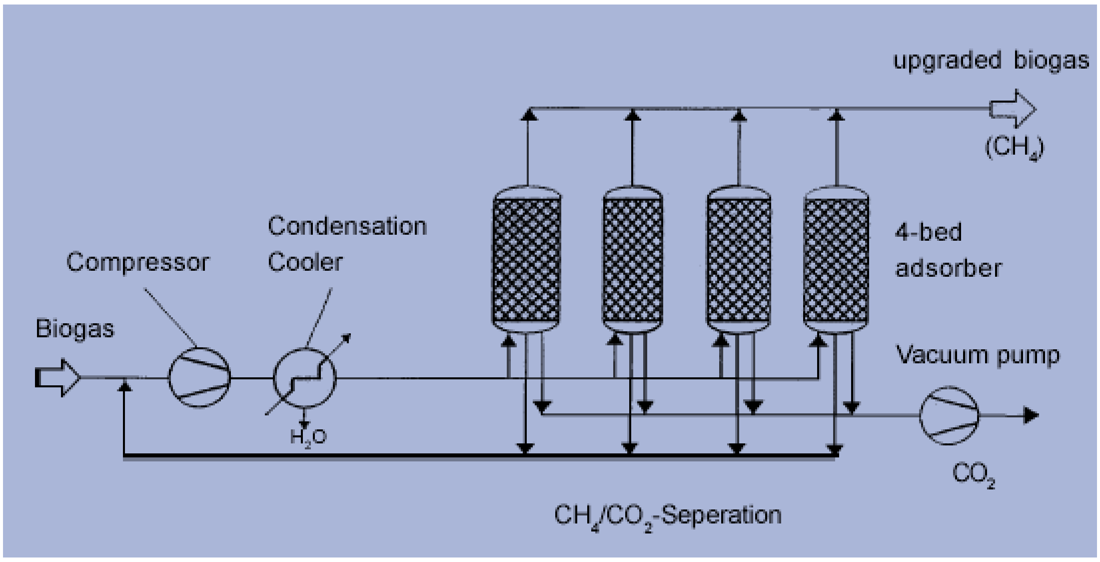


Figure 22: Scheme of PSA process (IEA task 24)

After the separation of particles and water drops, the biogas gets compressed to a process pressure of approximately 5 - 10 bar and enters into the H_2S separation with a temperature between 60 - 90 °C. H_2S needs to be largely separated prior to the biogas commencing CO_2 separation, otherwise the H_2S becomes irreversibly attached to the carbon molecular sieves and hinders the process quality. As explained in the first chapter of this master thesis, there are several technical processes available for the separation of H_2S. After the H_2S purification step has been completed, the hydrogen sulphide content is mostly clear under 5mg/Nm³. In the following conditioning process, the gas temperature is lowered to fall between 20 - 30 °C and the biogas is dried to a pressure dew point of 3 - 5 °C via cooling dehydration (H_2O separation). This drying step avoids condensation and corrosion in the successive plant components, minimizes the adsorption size and also the size of the required vacuum pump. Thereafter, the pre-dried and nearly H_2S free biogas is transported into the PSA plant. At the front of every adsorber in this PSA plant there is an additional preliminary filter containing activated carbon to ensure separation of all possible additional impurities. As mentioned, the methanisation with carbon molecular sieves takes advantage of the different adsorption attitude of CO_2 and CH_4 with an increased operating pressure. During the process one adsorption column is streamed through with biogas under increased pressure. CO_2 and small amounts of methane are adsorbed until the carbon molecular sieve is nearly saturated. This process requires approximately 3 to 5 minutes. While this adsorption column enters a phase of regeneration, the biogas flow is directed into the next column. Regeneration of an adsorption column occurs by lowering the pressure which leads to desorption of CO_2 and the small amounts of adsorbed methane. The desorbed gas stream is exhausted and re-injected into the untreated raw biogas. The total regeneration process is affected by the creation of under-pressure using a vacuum pump and by flushing with a pure gas. Once the total regeneration of the column is complete, the creation of the adsorption pressure commences by first flowing gas in from the column in the regeneration phase and then the entering of a fresh biogas stream.

Picture 2: 350 m³ upgrading plant with PSA technology - Helsingborg, Sweden (Jönsson)

3.2.2. Technology evaluation

Due to the upstream connection of additional preliminary filters with activated carbon to the adsorption columns for the separation of possible impurities, the life time of the main absorbers is approximately 10 years, which is considered relatively long. Thus, a longer life span implies lower maintenance costs. The entire process occurs under pressure, resulting in a high consumption of electricity.

The gas stream in the process shows a decline of pressure between the several columns. This can have positive impact on the efficiency of energy usage throughout the entire process.

The circulation and re-injection of the off-gas helps to lower methane losses in the process. Methane losses were found to fall within the range of 2 - 5 Vol.-% of the conducted methane load, but not exceed this amount.

PSA units between 15 and 350 m³/h have been built in Sweden. Here the operational aspects have been considered generally positive with only some disturbances in operation being caused by dust from the adsorption material getting stuck in the valves. (Jönsson 2003)

It can be deduced, that the PSA technology is a relatively advanced and a well developed technology. There are numerous reference plants in Europe. More than 25% of the European biogas upgrading plants worked with PSA technology in 2003. (Hornbachner et. al. 2005)

Several studies have analysed the specific upgrading costs per m³. As is true for other technologies, these costs depend on the plant size. To show this is so, plant sizes with a purification capacity within the range of approximately 50 - 1000 m³/h have been compared. The graphical representation below shows that the application of PSA technology in relation to the specific upgrading costs per m³ product gas lies in the range of approx. 0,1 - 0,47 €, comparison analysis of Tretter 2003. (Hornbachner et. al. 2005)

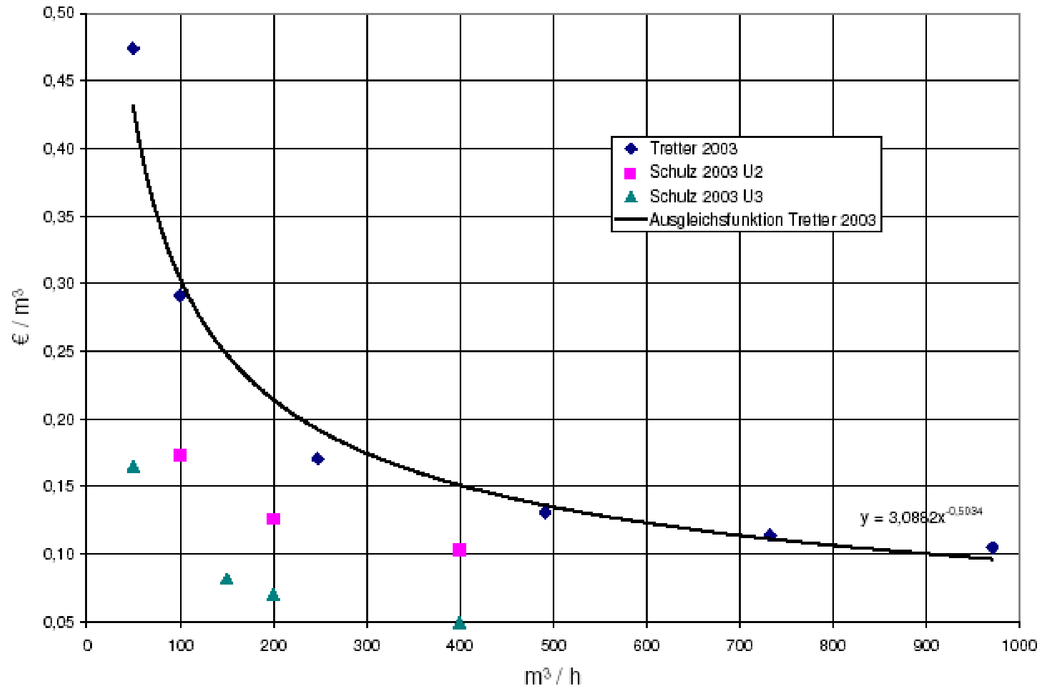


Figure 23: Specific upgrading costs (€/m³) for pure gas processed in PSA plants in different scaled plants (m³/h) analysed by Tretter 2003 and Schulz 2003 (Hornbachner et. al. 2005)

3.3. Water scrubbing

Water scrubbing is used to remove carbon dioxide and hydrogen sulphide from biogas as their solubility is greater in water than methane in water. The absorption process is purely physical. The solubility increases with increased pressure, therefore, the process is performed with compressed biogas.

3.3.1. Description of the process

Modern water scrubbing processes can be divided into four process steps – coarse filtering, raw biogas compression, gas upgrading and gas drying.

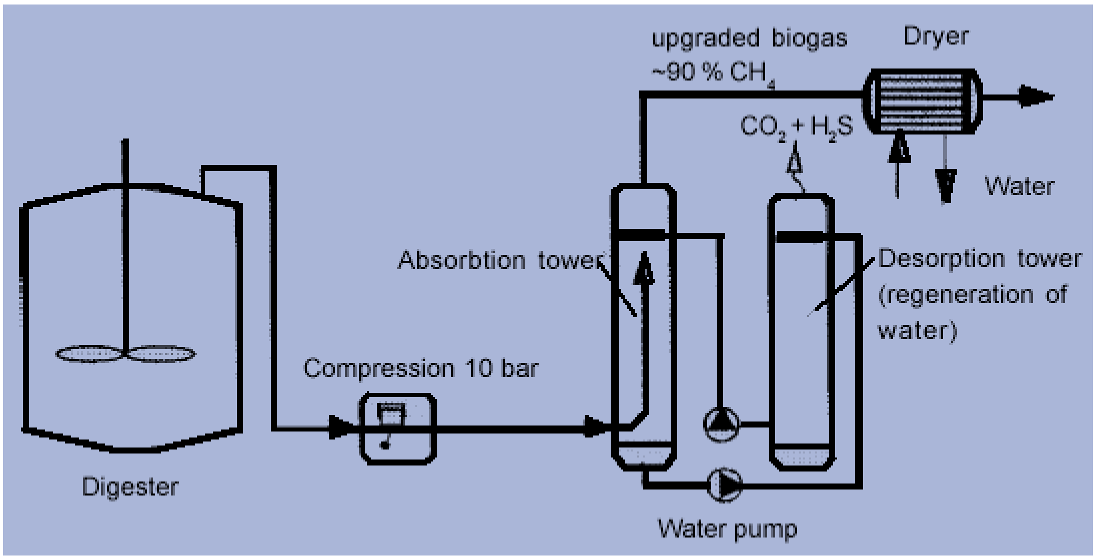


Figure 24: Scheme of water scrubbing process (IEA task 24)

Coarse filtering, rough drying and eventually a rough desulphurisation need to be performed before upgrading of the biogas occurs in the water scrubber. A first desulphurisation only needs to be done when the H_2S concentration of the raw biogas lies above 300 mg/Nm³, otherwise, the desulphurisation through the water scrubbing process is sufficient to obtain the required gas quality. After this pre-treatment, the biogas is pressurised to obtain approximately 6 - 8 bar. The pressuring of biogas leads to a heating up of the biogas to a temperature of 100 °C. Thereafter, cooling is required. The produced waste heat can be used, for example, for heating the biogas fermenters. The compressed biogas gets fed to the bottom of a packed column where water is then fed on the top so that the absorption process is operated counter-currently. The absorption column is filled with a carrier material to optimise the use of the reaction surfaces for the gas-liquid contacts. The alkaline and acid components are dissolved in water. The dust and micro organisms become separated. The gas flow produced is saturated with water vapour and needs to be dried. Drying usually occurs through pressure swing adsorption with molecular sieves. Oxygen and nitrogen do not dissolve in water and need to be removed by activated carbon or membranes. The upgraded biogas comes out of the system with a pressure of approximately 8 bars. Along with CO_2 and H_2S, a small amount of methane also gets dissolved in the water. This methane content can be regained to a certain degree by the desorption column which follows the absorption column. The pressure of the processed water is decreased in the first part of this column (or flashing tower) leading to most of the dissolved methane being released. The gained off-gas is then re-injected into the process at the station where compression occurs to avoid large losses of methane. The second part of the desorption tower is the stripper-tower. While the gas stream is fed into the column on top, air is blown in with ambient pressure from the bottom. This leads to desorption of CO_2 and H_2S from the water, which means a regeneration of the process water, thus allowing a recirculation of the processed water. Small amounts of water losses occur in the desorption column. It is at this point that fresh water gets injected into the process. The off-gas from the desorption column needs to undergo special treatment due to the high H_2S content, for example, through the use of a bio filter.

Picture 3: 600 m³/h upgrading plant with water scrubbing technology – Henriksdal sewage plant, Stockholm (Jönsson)

3.3.2. Technology evaluation

The upgraded biogas has a CO_2 concentration of less than 2 vol. percent and a H_2S content of less than 5 mg/Nm³.
The process described is not able to separate nitrogen or oxygen. Therefore, the gained methane content depends upon the amount of the gas components. If the amount of N_2 and O_2 are less than 1vol.%, then the obtained methane content can reach 97 vol.%. If the amount of nitrogen and oxygen is higher than the amount of methane obtained, the concentration is accordingly less. It is therefore important to avoid air entry in this process. (Tretter 2003)
The circulation and re-injection of the off-gas helps to lower methane losses in the process. Methane losses usually do not exceed 2 - 4 vol.-% of the conducted methane load.
During the absorption process the water increases in temperature. This heat needs to be discharged from the system and is done so by either cooling or by changing the processed water providing enough fresh water is available to do so. A substantial amount of water is needed in the water scrubbing process which is seen as the main disadvantage of this technology. This technology is often used for upgrading the biogas from sewage treatment plants and also in working with the treated sewage. Here deposits may occur in the water column.
Water scrubber units with capacities of 75 – 800 m³/h capacity have been installed at different locations in Sweden. The technology has proven to be very robust, however, some plants have shown operational disturbances due to the contamination of organic substances from the packing in the columns. (Jönsson 2003)
In Europe, the water scrubbing technology is widespread and well advanced. More than 55% of the biogas upgrading sites applied this technology in 2003 (Hornbachner et. al. 2005).

Several studies analyse the specific upgrading costs per m³ for the water scrubbing process. The costs depend strongly upon the size of the plant. Plant sizes with a purification capacity in the range of approximately 50 - 1150 m³/h have been compared. As shown in the graphical representation below, where PSA technology has been applied, the specific upgrading costs per m³ product gas lie in the average range of approximately 0,1 to 0,3 € - comparison analysis from Tretter 2003. (Hornbachner et. al. 2005)

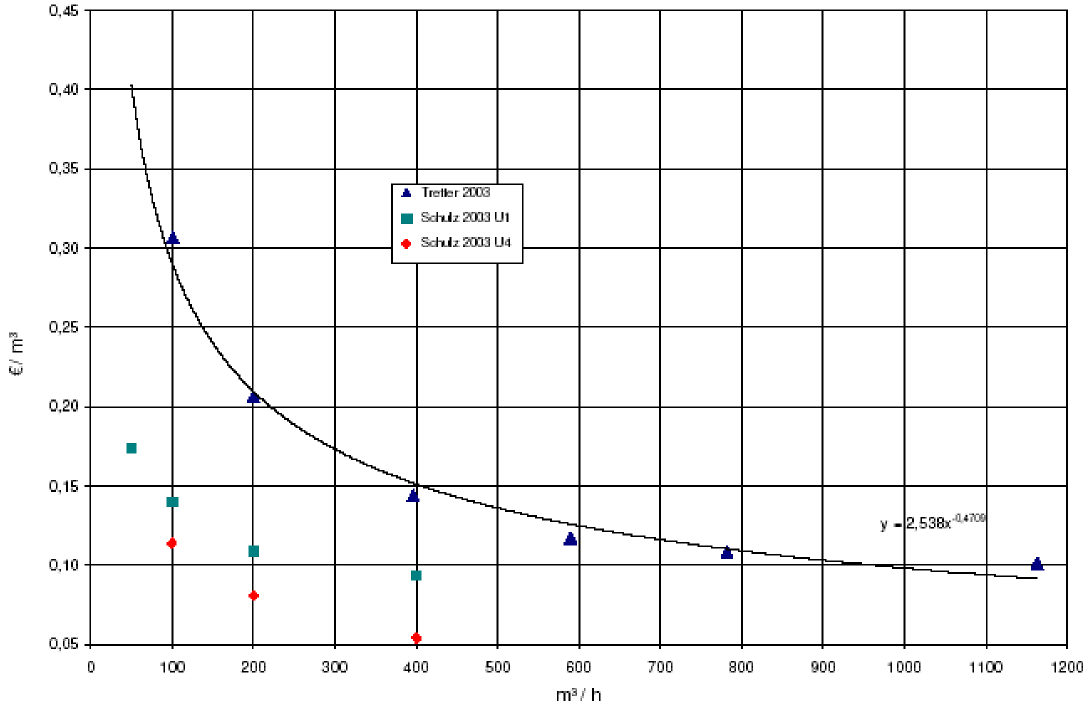


Figure 25: Specific upgrading costs (€/m³) for pure gas processed water scrubbing plants in different scaled plants (m³/h) analysed by Tretter 2003 and Schulz 2003 (Hornbachner et. al. 2005)

3.4. Amine scrubbing

Amine scrubbing is widely used as the preferred technology for large scale systems that recove CO_2 from natural gas wells. The process uses organic amines (monoethanolamine [MEA], diethanolamines [DEA], and diglycolamines [DGA]) as absorbers for CO_2 at only slightly elevated pressures (typically less than 150 psi).

The principle of amine scrubbing is represented by the following general chemical equations:

CO_2 sorption: $RNH_2 + H_2O + CO_2 > RNH_3 + HCO_3$ – (under pressure) (1)

CO_2 desorption: $RNH_3 + HCO_3 > RNH_2 + H_2O + CO_2$ (low pressure, some heat) (2)

(R represents the remaining organic component of the molecule that is not relevant to this equation.)

3.4.1. Description of the process

A system offered by CIRMAC is used to best describe the principles of this process.

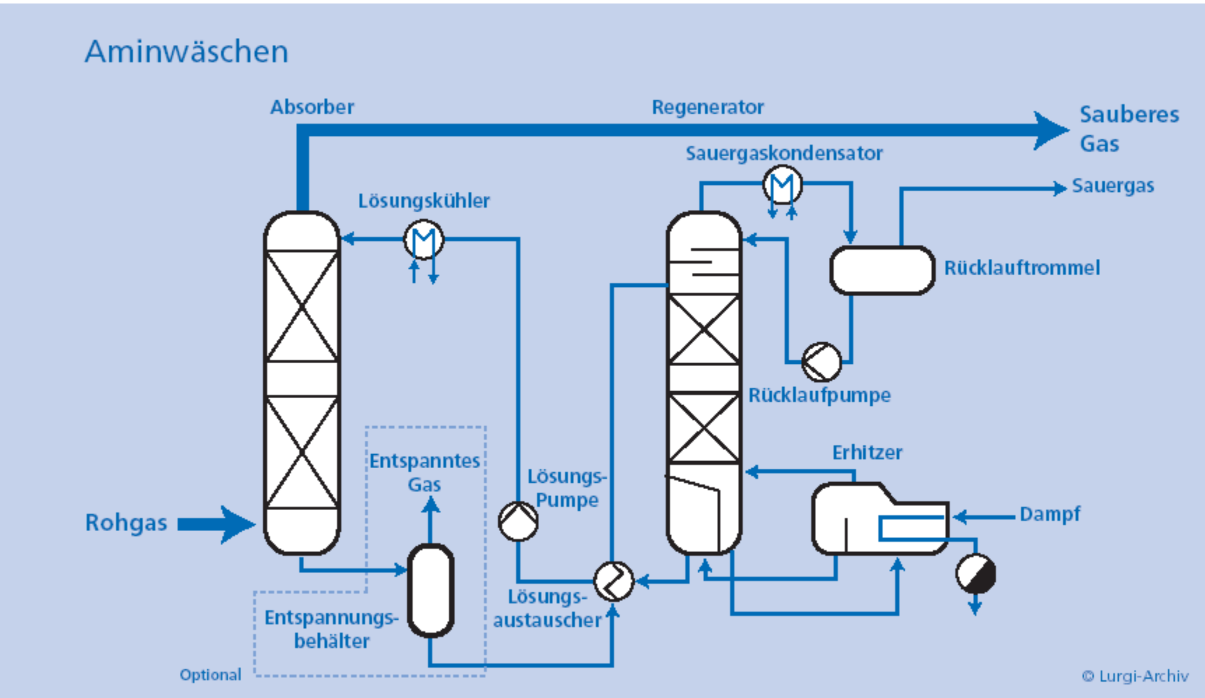


Figure 26: Scheme of amine scrubbing process (Lurgi 2007)

The incoming biogas from the gas storage is slightly over pressure, is free from dust and water droplets and then saturated with water. In most cases this slight over pressure needs to be increased in order to overcome the pressure lost from the system, for which purpose a blower is installed.

Prior to removing CO_2, H_2S and other impurities, such as, ammonia (NH_3) need to be removed. The H_2S is removed by activated carbon (occurring mostly in two columns) and if required, combined with the removal of NH_3. The activated carbon process is attractive for relatively low concentrations of up to 500 ppm. For extremely high concentrations of H_2S an alternative pre-cleaning step, like a biological process, needs to be installed to mainly reduce the high costs involved for activated carbon. The adsorption of hydrogen sulphide (H_2S) on activated carbon is catalytic. The chemical reaction is: $2H_2S + O_2$. $2S + 2H_2O$. The formed elementary sulphur will be adsorbed on the activated carbon. The activated carbon needs to be replaced after it is loaded with sulphur. The purified gas contains less than 1 ppm H_2S.

The CO_2 removal unit consists of:

– one contactor column,

– one stripper unit, and

– heat exchangers with pumps.

The gas flows in the contactor from the bottom through a packed bed to the top of the contactor. In the packed bed of the contactor the absorption liquid flows in counter current to the gas. The amine liquid stream absorbs the CO_2 via a chemical reaction, thereafter, the loaded amine liquid leaves the contactor at the bottom. The upgraded biogas leaves the contactor column at the top. It needs to be dried, odorised and pressurised to the required grid pressure. Drying takes place by means of a PSA or TSA type adsorption drier. A small flow of the product gas is used for purging the drier and returned afterwards to the inlet of the blower.

The loaded amine liquid is fed to the top of the stripper. On its way down the CO_2 will be removed from the amine liquid on the packed bed in the stripper column by increasing the temperature. The required heat for CO_2 removal is produced in the boiler at the bottom of the stripper column where the amine liquid is heated by wet steam to reach boiling point. The amine liquid vapour together with the released CO_2 leaves the boiler and heats the CO_2 saturated amine liquid on the packed bed in the stripper. The lean amine liquid almost free from CO_2 leaves the stripper at the base. Almost pure CO_2 leaves the stripper at the top after cooling down in the condenser.

The CO_2 can be directly used in greenhouses or it can be upgraded to industrial or food grade quality for sale.

Two heat exchangers are installed in the system, a 'lean' heat exchanger and a liquid cooler. In the lean heat exchanger, from the contactor to the stripper, the temperature is heated by the lean amine liquid leaving the stripping column. The process is optimised to use the lowest possible amount of energy whilst capturing the maximum amount of heat. After leaving the lean heat exchanger, the lean amine liquid is cooled down to the required temperature. This process occurs in the amine liquid cooler. The exchanged heat can be recovered and used elsewhere.

Picture 4: 300 m³/h upgrading plant with chemical adsorption technology – Boras, Sweden (Jönsson)

3.4.2. Technology evaluation

An advantage of the amine approach is the extremely high selectivity for CO_2 and the reduced volume of the process, that is, one to two orders of magnitude more of CO_2 can be dissolved per unit volume using this process than with water scrubbing. If waste heat is available for the amine scrubbing stage, the overall energy use is lower than for other processes. The process has been scaled-down for landfill applications and is proven to work relatively well. The main problems are corrosion, amine breakdown and contaminant build up, which make it problematic to apply this process to small-scale systems such as dairy farms. However, dairy manure biogas typically has fewer contaminants of concern than other biogas sources such as landfills. Here steel pipes can be used to minimize the corrosion. Cirmac, a Dutch company, has developed a proprietary amine (COOAB™) scrubbing process. One advantage of this process is its very low CH_4 loss, which is found to be less than 0.1%. The disadvantage being that the technology is more complex. However, most of the system complexities are not visible to the operator of the COOAB packaged unit and Cirmac is actively promoting its technology for small-scale biogas upgrading. The purity level of CO_2 is very high (99.5%) and can therefore be re-used.
Chemical adsorption technologies seem an attractive solution due to low methane losses and high selectivity. The process requires a rather high input of thermal energy for the regeneration of the chemical but operates at low pressure, reducing the amount of electrical energy in the process.
A chemical absorption plant with the capacity of 300 m³/h has been in operation in Borås, Sweden since 2002. (Jönsson 2003)

Information relating to the specific upgrading costs appears not to be openly available.

3.5. Comparison of the technologies

One important factor for a successful market positioning of biogas upgrading technologies is its reliability. Its reliability can be traced back to the supplier of the technology or to the technology itself. The reliability of the technology itself can be measured over time through information and documentation provided from various reference plants.

The following table shows the applied upgrading technologies in Europe in 2003. If reliability is dependant upon the number of reference plants, then the most reliable technologies would be the water scrubbing process and the PSA process. The numerous reference plants favour their market position. The total number of plants in Europe is still relatively small.

Technology **Countries**

Technology	**CH**	**CZ**	**DE**	**DK**	**FR**	**GB**	**IS**	**IT**	**NL**	**SE**	**Summe**	**A - 2008**
Water scrubbing	1	5		1	4		1	1	1	18	**32**	
PSA	5		1						3	6	**15**	2
Membranes										1	**1**	
Selexol scrubbing										1	**1**	
Gas permeation						1			4		**5**	2
Kryo technology			1								**1**	
Unknown	1		1					1			**3**	
Summe	7	5	3	1	4	1	1	2	8	26	**58**	**4**

Table 11: Overview on the installed biogas upgrading plants in Europe 2003 (Tretter 2003) Additionally the present Situation in Austria is shown.

The varying results of benchmarking of several technologies can be attributed to the specific local conditions. The applied technology always needs to be adapted to the special conditions within each project, e.g. water scrubbing for biogas upgrading is done in conjunction with sewage water treatment plants due to the availability of water, however, it may not be the favoured technology for sites where water is not that easily available.

Some major factors need to be taken into consideration when evaluating and comparing several technologies:

- Reliability and availability of the technology
- Maintenance costs resulting from maintenance resources and energy consumption within the process
- Reachable gas quality
- Overall upgrading costs.

Upgrading process	Output quality	Electricity consumption (kWel/Nm³ pure gas)	Advantages	Disadvantages
Water scrubbing	<= 2% CO_2 <= 5mg/³ H_2S	0,3 (in water scrubbing plants with water regeneration) 0,36 – 0,6 (in water scrubbing plants without water regeneration) delivery pressure unknown	- high experience - several reference plants - no chemical waste material - adapted process for waste water treatment plants	- water connection required - high water consumption - relatively high electricity consumption (process under pressure) - methane losses (2 – 4%) - may occur problems deposits in the water column
PSA	<= 2% CO_2 <= 5mg/m³ H_2S 0,07 g/m³ H_2O	0,5 (supplier: 0,35 – 0,4) delivery pressure unknown	- dry process - therefore no waste water - reference plants - good quality results	- relatively high electricity consumption (process under pressure) - disposal of activated carbon - methane losses (2 – 5%)

Amine scrubbing	<= 2% CO_2 <= 5 mg/m³ H_2S	0,15 at a delivery pressure of 0 bar (g) – can not be compared with other technologies	- standardised process for the treatment of natural gas - few methane losses (less than 0,1%) - high methane content in the product gas possible - compact process - can be operated at low pressure which means a low electricity consumption	- expensive, high costs for operational supplements and their disposal - high heat consumption - not adapted to small scaled applications - problems with corrosion, amine breakdown, and contaminant build up - complex process
Gas permeation	<= 2% CO_2, about 0,001 ppm H_2S	0,35 at a delivery pressure of 5.5 bar (g)	Few methane losses by the recirculation of the permeate, High methane content in the product gas possible, High availability Low maintenance resource consumption	High electrictity consumption (process under pressure)

Table 12: Comparison of several upgrading technologies (Theißing 2006)

4. Sensitivity Analysis for the Market Introduction of a New Biogas Upgrading Technology

(Vester F. 2002/2007)

To guarantee a successful market introduction of the new biogas upgrading technology, the market in which this new technology will be positioned needs to be analysed to identify the main risks associated therewith and to understand the dynamics within this market.

This chapter presents a methodology for market analysis and applies the knowledge gained from the market for biogas gas permeation facilities. The results outline the dynamics and trends within the system "market for biogas gas permeation facilities" and can be used as basis information for a more detailed analysis and for strategic market decision making.

4.1. Introduction of the market analysis methodology according to Frederic Vester

In this master's thesis, the theory for sensitivity analysis according to Frederic Vester was applied to analyse the market for biogas gas permeation technology.

In Frederic Vester's works and publications relating to cross-linking mental activities he describes a new way of dealing with complex systems. Working and planning with cross-linking systems simulates reality more closely than simplified cause and effect chains do. Simplified approaches do not imply indirect effects, dependency networks and time delays. In real life, single and standing alone events do not occur without any interaction in between themselves. As is for organisms, complex systems are composed of several parts connected in a certain dynamic order to each other. It is almost impossible to act on a part of a system without influencing the relationship between the individual parts of a system and the system itself. As systems are in constant intercommunication with their surroundings it is only natural that they are influenced by their surroundings.

Any market can be identified as a complex system. When making decisions with regard to this system, one has to be aware of all the possible influences and effects. Acting on one without keeping in mind the entire complexity can result in imbalances and erroneous trends. Keeping in mind the entire system and acting within this system by integrating disturbances has been proven to control fault tolerance and ensure a better survival of the overall system. The main aim of the following analysis was the better survivability of the system "market for the new gas permeation technology". The result being the steps required to be taken towards the market.

Before starting the system analysis some general comments on the methodology and the application within this master's thesis need to be determined:

- The sensitivity analysis according to F. Vester can be described as an open process. A major characteristic is the involvement of the concerned parties in the analysis itself. The involvement of all the concerned parties in all the analysis steps is highly relevant for high quality results, a common view and a common language, a widening of the mind and ensuring a complete and balanced picture of the situation of the concerned parties, acceptance of decisions and success of further actions.
  Within this master's thesis there is no possibility to do this analysis interactively as mentioned above. Therefore, the sensitive analysis within this master's thesis aims to provide an idea of the principles of this methodology and anticipates possible results of such an analysis using the biogas gas permeation technology market according to F. Vester.
- Special computer software exists for detailed sensitivity analysis according to F. Vester. This software is outside the scope of this master's thesis. Within the scope a simplified manual application of several of the analysis steps were performed.
- Within the master's thesis only parts of the whole analysis toolbox such as the "influence matrix" and the analysis of system structures were applied. A further step in the sensitivity analysis model would be, for example, a policy test. The complete sum of analysis tools is valuable for the strategic preparation of concrete actions for the system.

- When using the results for further market entering decisions, it would be advisable to evaluate the analysis and to discuss the single steps in the mentioned process with all the concerned parties.

4.2. Analysis of the market for biogas gas permeation facility

4.2.1. System description

The first step in the sensitive analysis is the description of the system. It should be performed in a brainstorming session ideally involving all the concerned parties.

Not only facts and concrete data are valuable for a sensitivity analysis, but also soft factors have an important influence on the system. A very detailed system description often leads to a mixing of components from different system levels.

The description of the system is not a description of a problem but rather of the context where problems can occur. The system on which the analysis is based upon needs to be identified with an open mind and include all concerned life areas applicable to the system.

The system description can also be represented in graphical form. This tool helps find an alternative approach and leads to a combined effect of coherences.

The focus of the analysis within this master's thesis is the market for biogas upgrading facilities where the new technology should be lounged. Thus, the potential market for the biogas gas permeation facility is the system of concern.
The last chapters of the master's thesis can be viewed as base information for the system description "biogas upgrading facility market". The main parts of the system are described below in the form of a brainstorming exercise.

<u>Brainstorming</u>
Biogas production, raw material, production site, competitors upgrading facilities, gas industry, infrastructure – gas pipelines, transport, energy demand, agriculture, reference plants, maintenance resources and costs, qualified labour, climate protection, political support schemes, European and national frameworks, strategic cooperation, niche markets, shareholders, costumers, component subcontractors,

climate change, food industry, costs and revenues, extension are of upgrading technologies all over Europe, ...

Visualisation of the system

Picture 5: System visualisation – biogas upgrading

4.2.2. Definition of the system relevant variables with influence evaluation

To be able to work with the described system, the identified components need to be transformed into a list of system variables. The next steps of the analysis describe their influence on the entire system. The following attributes need to be fulfilled when modelling the variables:

- They have to be variable and describe a certain direction of change. They can increase or decrease;

- The variables have to exist in the same system. Variables from higher-level systems and lower-level systems cannot be combined, they must remain separate;
- The aggregated variables have to fulfil criteria which ensure a complete description of the whole system and thus avoid imbalance. The criteria can be summarised under the following headings: economies, involved parties, activities in the system, system area, human criteria, ecology, communication and information actions, infrastructure, commonwealth and society, involved material and energy flows, system, time dimensions, system inflow and outflow, influences;
- The discussion and definition of the variables ensures a good balance and leads to a common view of the system by all parties involved;
- 20 – 40 variables need to be nominated;
- A detailed description of the various variables needs to be documented and their significance kept in mind.

The role of the defined variables in the system is evaluated in several steps.
Step one, the direct influence of one variable on the others is assessed via an influence matrix where influence values are given. When the impact of a low change on a variable results in a high impact on another variable the value given is 3; when the action on a variable is as high as the reaction on another variable, the value given is 2; when a positive change of one variable causes only a slight impact on another variable the value given is 1; if there is no reaction by changing a variable on another variable the value given is 0;
The resulting active sum indicates the influence of a variable on the rest of the system. The resulting passive sum indicates the sensitivity of the variable itself.

To evaluate the active or the reactive character of a variable in the system, a quotient of the active and passive sum needs to be calculated. The highly active variables are those important to control the system or those where the highest risk for the system can be identified. The most reactive variables are the most inert ones. Under certain circumstances they are able to intercept the system in critical periods.

The involvement of a variable within the system is illustrated by the active sum and the passive sum.

In the analysis of the system “market for biogas gas permeation facilities”, the involved variables are listed in the table below and an influence matrix with active and passive sums, their quotients and products is provided.

Table 13: Influence matrix

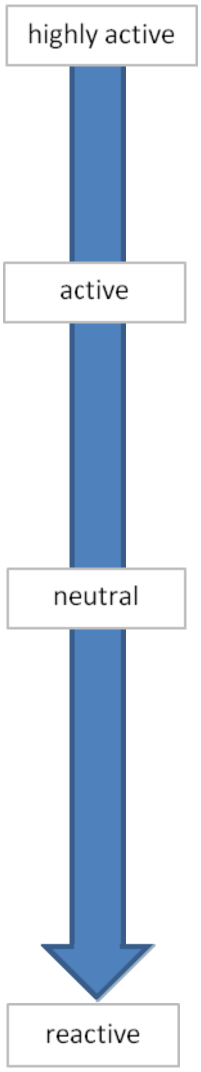
Influence matrix – system „market biogas gas permeation technology

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	AS	P
1	market share gas permeation	x	2	2	2	0	0	0	0	0	2	2	1	0	1	1	2	2	2	0	1	2	2	1	0	2	0	**27**	**945**
2	market share PSA	2	x	2	2	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	1	1	2	1	0	0	0	**13**	**312**
3	market share water scrubbing	2	2	x	2	0	0	0	0	2	2	2	0	0	0	0	0	0	0	0	1	1	2	1	0	0	0	**15**	**360**
4	market share amine scrubbing	2	2	2	x	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	1	1	2	1	0	0	0	**14**	**336**
5	availability of biogas raw material	0	0	0	0	x	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	**5**	**15**
6	costs of biogas	2	2	2	2	1	x	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	2	0	0	**13**	**78**
7	costs of natural gas	1	1	1	1	0	0	x	2	0	0	0	0	1	0	0	0	0	1	2	1	0	0	2	0	0	1	**13**	**52**
8	availability of natural gas	2	2	2	2	0	0	2	x	0	0	0	0	1	0	0	0	0	1	2	2	0	1	2	0	0	2	**19**	**114**
9	consumption process water	0	0	0	0	0	0	0	0	x	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**	**5**
10	consumption other maintenance resources	0	0	0	0	0	0	0	0	0	x	0	2	1	0	0	1	0	0	0	0	1	0	0	0	0	0	**5**	**50**
11	consumption process energy	0	0	0	0	0	0	0	0	0	0	x	2	1	0	0	1	0	0	0	0	1	2	0	0	0	0	**7**	**84**
12	costs of biogas upgrading with gas permeation	2	2	2	2	0	0	0	0	0	0	0	x	2	1	0	2	0	1	0	2	1	0	1	0	2	0	**18**	**270**
13	gas quality of upgraded biogas	0	0	0	0	0	0	0	0	1	1	1	2	x	0	1	0	1	2	0	1	3	0	1	0	1	0	**15**	**210**
14	qualified manpower for gas permeation	2	0	0	0	0	0	0	0	0	0	0	1	1	x	1	0	1	1	0	1	2	0	0	0	2	0	**10**	**50**
15	investment cost gas permeation facility	2	1	1	1	0	0	0	0	0	0	0	2	1	0	x	1	0	1	0	1	1	0	1	0	1	0	**12**	**96**
16	financial potential of shareholders gas permeation	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	x	2	1	0	1	0	0	0	0	1	0	**6**	**60**
17	possible strategic partnerships for gas permeation	2	1	1	1	0	0	0	0	0	0	0	1	0	1	1	0	x	2	0	1	1	0	0	0	1	0	**11**	**132**
18	niche products for gas permeation	2	1	1	1	0	0	0	0	0	1	1	1	1	0	1	1	2	x	0	1	1	0	0	0	1	0	**14**	**238**
19	general gas consumption	1	1	1	1	0	0	1	2	0	0	0	0	0	0	0	0	0	0	x	1	0	2	1	0	0	2	**12**	**72**
20	extension area biogas upgrading facilities	2	2	2	2	0	0	0	0	2	2	2	1	1	1	1	2	2	2	0	x	1	2	1	0	1	1	**28**	**728**
21	confidence in gas permeation technology	2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	2	x	0	1	0	1	0	**9**	**162**
22	CO2-emisson reduction	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	x	2	0	0	0	**8**	**128**
23	political support for upgraded biogas	2	2	2	2	0	2	0	0	0	0	0	2	1	0	2	2	0	1	0	2	0	2	x	1	0	0	**21**	**399**
24	agricultural innovation power	1	1	1	1	2	2	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1	1	x	0	0	**12**	**60**
25	service of gas permeation technology supplier	2	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	0	1	2	0	0	0	x	0	**8**	**88**
26	availability gas net infrastructure	2	2	2	2	0	0	1	2	0	0	0	0	1	0	1	0	1	1	2	2	0	0	0	0	0	x	**17**	**102**
	PS	**35**	**24**	**24**	**24**	**3**	**6**	**4**	**6**	**5**	**10**	**12**	**15**	**14**	**5**	**8**	**10**	**12**	**17**	**6**	**26**	**18**	**16**	**19**	**5**	**11**	**6**		
	Q	**0,77**	**0,54**	**0,63**	**0,58**	**1,67**	**2,17**	**3,25**	**3,17**	**0,20**	**0,50**	**0,58**	**1,20**	**1,07**	**2,00**	**1,50**	**0,60**	**0,92**	**0,82**	**2,00**	**1,08**	**0,50**	**0,50**	**1,11**	**2,40**	**0,73**	**2,83**		

AS = active sum
PS = passive sum
P = product of AS and PS
Q = quotient of AS and PS

Influence index analysis

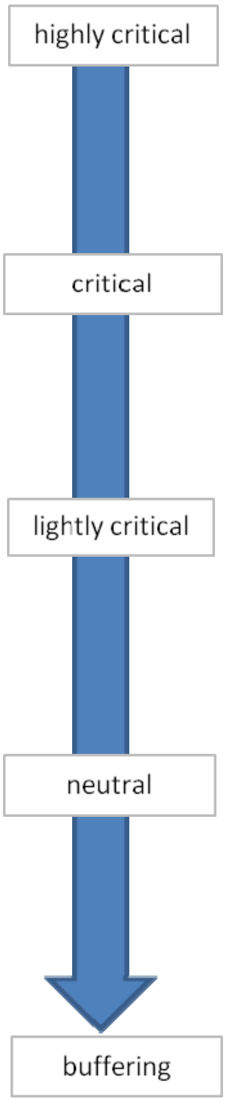
ACTIVE - REACTIVE



costs of natural gas	3,25
availability of natural gas	3,17
available gas net infrastructure	2,83
agricultural innovation power	2,4
costs of biogas	2,17
qualified manpower for gas permeation	2
general gas consumption	2
availability of biogas raw material	1,67
investment cost gas permeation	1,5
costs of biogas upgrading with gas permeation	1,2
political support for upgraded biogas	1,11
extension area biogas upgrading facilities	1,08
gas quality of upgraded biogas	1,07
possible strategic partnerships for gas permeation	0,92
niche products for gas permeation	0,82
market share gas permeation	0,77
service of gas permeation technology supplier	0,73
market share water scrubbing	0,63
financial potential of shareholders gas permeation	0,6
market share amine scrubbing	0,58
consumption of process energy	0,58
market share PSA	0,54
consumption other maintenance resources	0,5
confidence in gas permeation technology	0,5
CO2-emisson reduction	0,5
consumption process water	0,2

Table 14: Activity and reactivity of variables

HIGHLY CRITICAL - BUFFERING



market share gas permeation	945
extension area biogas upgrading facilities	728
political support for upgraded biogas	399
market share water scrubbing	360
market share amine scrubbing	336
market share PSA	312
costs of biogas upgrading with gas permeation	270
niche products for gas permeation	238
gas quality of upgraded biogas	210
confidence in gas permeation technology	162
possible strategic partnerships for gas permeation	132
CO2-emisson reduction	128
availability of natural gas	114
available gas net infrastructure	102
investment cost gas permeation facility	96
service of gas permeation technology supplier	88
consumption of process energy	84
costs of biogas	78
general gas consumption	72
financial potential of shareholders gas permeation	60
agricultural innovation power	60
costs of natural gas	52
qualified manpower for gas permeation	50
consumption other maintenance resources	50
availability of biogas raw material	15
consumption process water	5

Table 15: Critical and buffering variables

The summarised results of the influence analysis of variables in the system "market for biogas gas permeation facilities" are as follows:

- The most active variables in the system are the costs and the availability of natural gas, the available gas net infrastructure, the agricultural innovation power, costs of biogas and qualified manpower for gas permeation technology. Changes to these variables result in a high influence on other variables and are potentially the variables that exert the greatest power and control over the system, particularly, if they are very prominent in the system.

- The most reactive variables are CO_2-emissions, consumption maintenance resources, such as, process water, process energy and other process resources, the confidence in gas permeation technology, the market share of the competitor technologies and the financial potential of the shareholders. These variables are greatly influenced by other variables of the analysed system and therefore are unable to control the system dynamics. Under certain circumstances they can be used to intercept the system in critical periods.
- A high involvement in the system attitude was identified for the market share of gas permeation technology, the extension area of biogas upgrading facilities, the political support for upgraded biogas, the market share of the competitor technologies, costs of biogas upgrading and niche products for gas permeation; Their effect on the system is very clear, whether active or reactive.
- A low involvement in the system attitude was identified for the consumption of maintenance resources and process water, the availability of biogas raw material, qualified man power for gas permeation technology, costs of natural gas, agricultural innovation power and financial potential of the shareholders; These influences have a very low impact on the system.

The combination of this results leads to a better understanding of the role of the variables within the system. Are they very involved in the reaction of the system and also very active? Are they very involved but mostly reactive? Are they highly active but only slightly involved? The analysis of the role provides insight for strategic decisions. How can I act on the system to get a desired effect? Which are the variables able to control the system? A detailed analysis of the system attitudes of the several variables can be done via a two dimensional visualisation of the calculated influences.
This visualisation process is out of scope of this master's thesis, due to the software being unavailable. However, a rough interpretation according to the influence matrix was done instead.

One remarkable result is that there was no very active and involved variable able to be identified. Changes on those would have mainly destabilising effects on the system. Changes on those very active and not very involved variables have mainly stabilising effects on the system. In relation to the system "market for biogas gas permeation technology" the costs of natural gas, the qualified man power for gas permeation and the agricultural innovation power would be relevant.

The variables that have a major impact, yet are reactive in nature, are the market shares for the competitor technologies. These can be seen as quite critical for the overall system dynamics. Changes either accelerate or slow down the market for biogas gas permeation technology. Variables which are mainly reactive yet not very involved in the system itself can also be indicators for the system. However, they have no real impact on the whole system. Applicable to the system "market for biogas gas permeation technologies" would be, the consumption of maintenance resources such as process water and other maintenance resources and the financial potential of shareholders.

4.2.3. Analysis of the effect structure of a system

The analysis of the structure effect of a system illustrates the modality of actual effects of the variables within a system and assesses the effect chains. If there is a rectified relation between variables, an increase or decrease of one variable leads to an increase or decrease of the other variable. If the relation between variables is in the opposite direction, an increase or decrease leads to a decrease or increase. In a system the relation of variables can also be alternating. In this case, a reaction feedback is given. This feedback can be positive, when the reaction of both variables is similar – both are increasing or decreasing. These relations are self-energising and therefore destabilising for a system. If the reaction of the variables is of a different nature the feedback is negative. These relations have a self-regulating character and are therefore stabilising for a system. In a stable system, negative feedbacks should dominate the positive ones. Positive feedbacks are important to initiate development dynamics.

The analysis of the effect structure according to F. Vester is also supported by computer software. It can be not only be applied to the entire system but also to parts of it. The results are illustrated below:

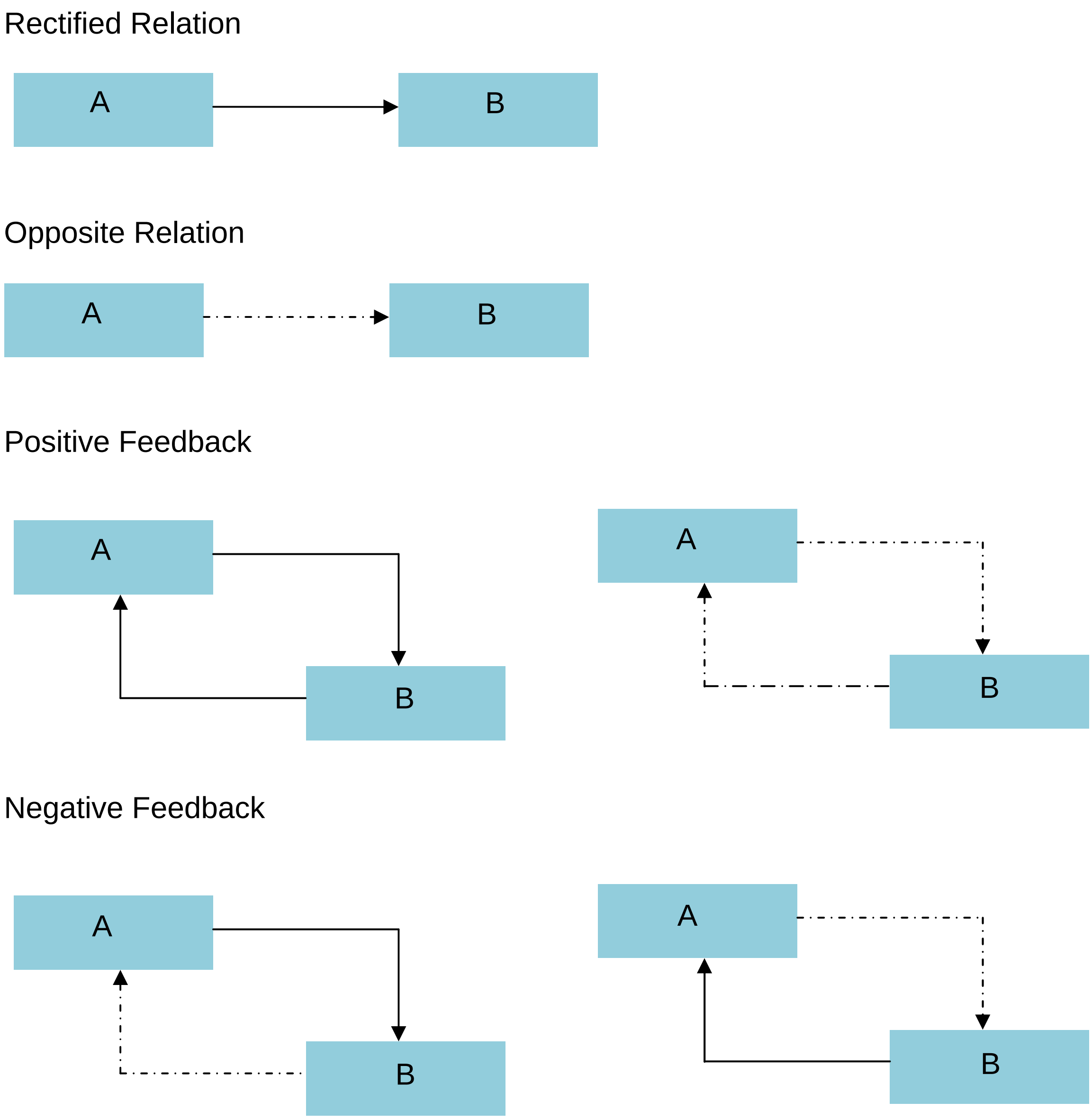


Figure 27: Visualization of effect structures according to F. Vester

Within this master's thesis the analysis of effect structure was done in a simplified way for the "inner dimension" of the market for biogas gas permeation technology itself. Relevant variables from the influence matrix were chosen and aggregated to the following variables:

- Market share gas permeation
- Market share competitor technologies
- Extension area for biogas upgrading technologies
- Investment and upgrading costs for gas permeation
- Niche products for gas permeation

- Qualified man power and service for gas permeation
- Political support for upgraded biogas
- Availability of natural gas (low availability means high costs and vice versa)
- Confidence in gas permeation technology

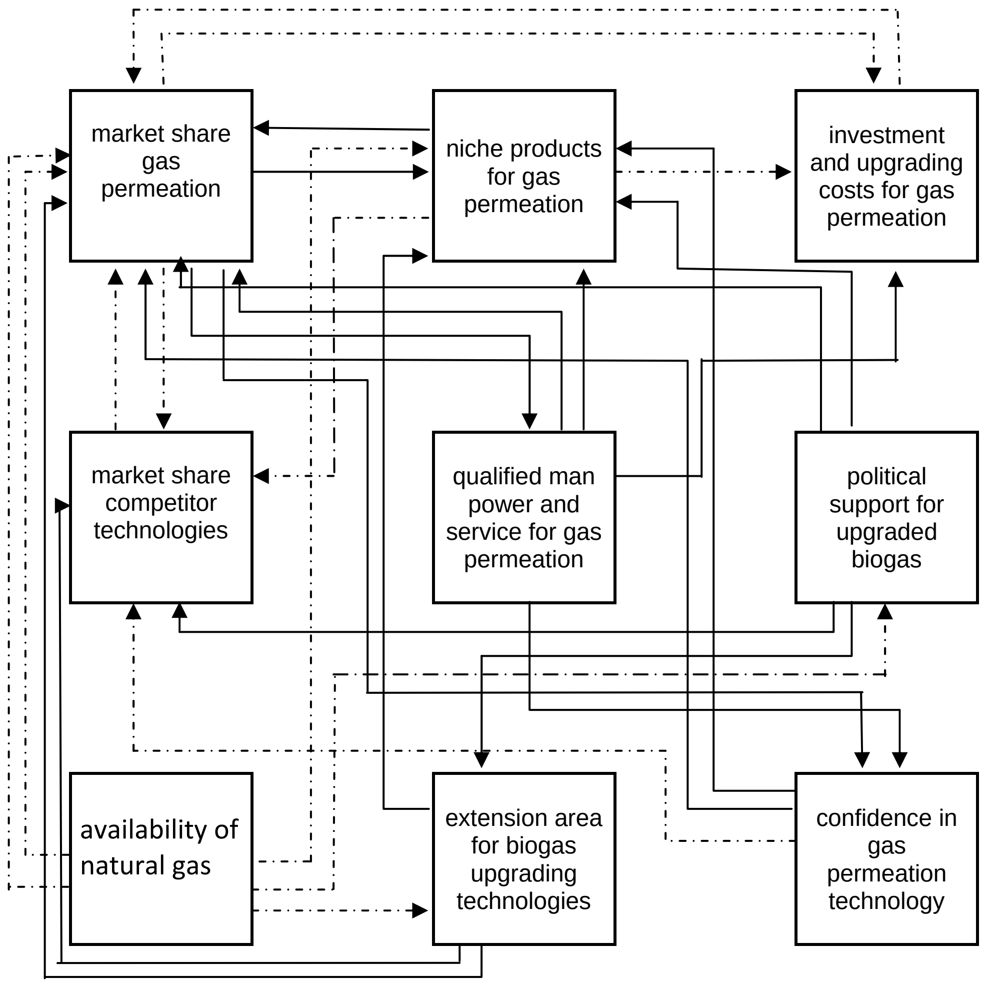


Figure 28: Effect structure – market for biogas gas permeation technology

The effect structure analysis of the system illustrates the actual situation. Evident is the prevalence of positive feedback. This can be interpreted as a high risk for instability of the system due to its self-energising character. In the initiating phase, these positive feedbacks are important, but afterwards negative feedback reactions should be implemented in the system to reach stability. These negative feedbacks are in actual fact completely absent in the system. Most feedback reactions are linked to the market share of the gas permeation itself. Once a certain level has been reached, for example, by those with investment and upgrading costs for gas permeation, niche products for gas permeation, qualified man power and service for gas permeation and confidence in gas permeation technology can decrease. These parameters need to be expanded in the market introduction phase. The market share for gas permeation technology and competitor technologies are also influenced by a number of other factors. They can be identified as the crucial elements within the system. The same can be confirmed by parameters that are directly linked to the marked share of the biogas gas permeation technology, such as, niche products for gas permeation, investment and upgrading costs for gas permeation. The availability of natural gas is the only parameter that is not influenced by any other factor but influences others. It needs to be continuously observed, however, one cannot actively act on it. The political support for upgraded biogas has a high impact on the other parameters. It can be influenced externally by lobbying measures. It is indirectly influenced by the availability of natural gas. Qualified manpower and services for gas permeation and confidence in gas permeation technology illustrates a prevalence of influencing effects. They are drivers for successful positioning of the new technology in the market.

5. Forecast of biogas market development

Today, there are more than 4500 biogas plants in Europe, including a large number of landfill sites. The total European biogas production in 2004 was estimated at 50 TWh. This showed a 43% increase compared with production results from 2002. More than 55% of the biogas production comes from landfills and sewage sludge treatment. This is expected to change since the deposition of organic material in landfills must be reduced. In some European countries it is even banned now! Emerging in its place is the steady increase of biological treatment or the incineration of organic material. (Persson et. al IEA task 37 2006)

A study performed by Solagro (from biogas to energy: a European overview, 2001) predicts a production of 210 TWh by the year 2020. This can be compared with the European (EU 25) primary natural gas consumption of 4.960 TWh in 2004. The natural gas demand of the EU25 is foreseen at 5.675 TWh. Compared with the previously mentioned biogas potential, this would mean a possible substitution of the natural gas demand of approximately 3.7 %. (Eurogas) (Persson et. al IEA task 37 2006)

The working group for the injection of biogas, of the “Deutscher Fachverband Biogas”**,** is more optimistic and estimates a technical potential in European countries between 10 **-** 30% of the CNG consumption of these countries (Tentscher 2002a). Most of this potential is agriculturally based.

The countries with the highest production of biogas per capita are the UK, Sweden, Denmark, Switzerland and the Netherlands. In the short term, the main potential for biogas production is in the treatment of wet wastes, such as, sewage water sludge, manure and waste from different food industries. In the long-term, the main sources for biogas production will come from the different kinds of agricultural products. (Jönsson 2003)

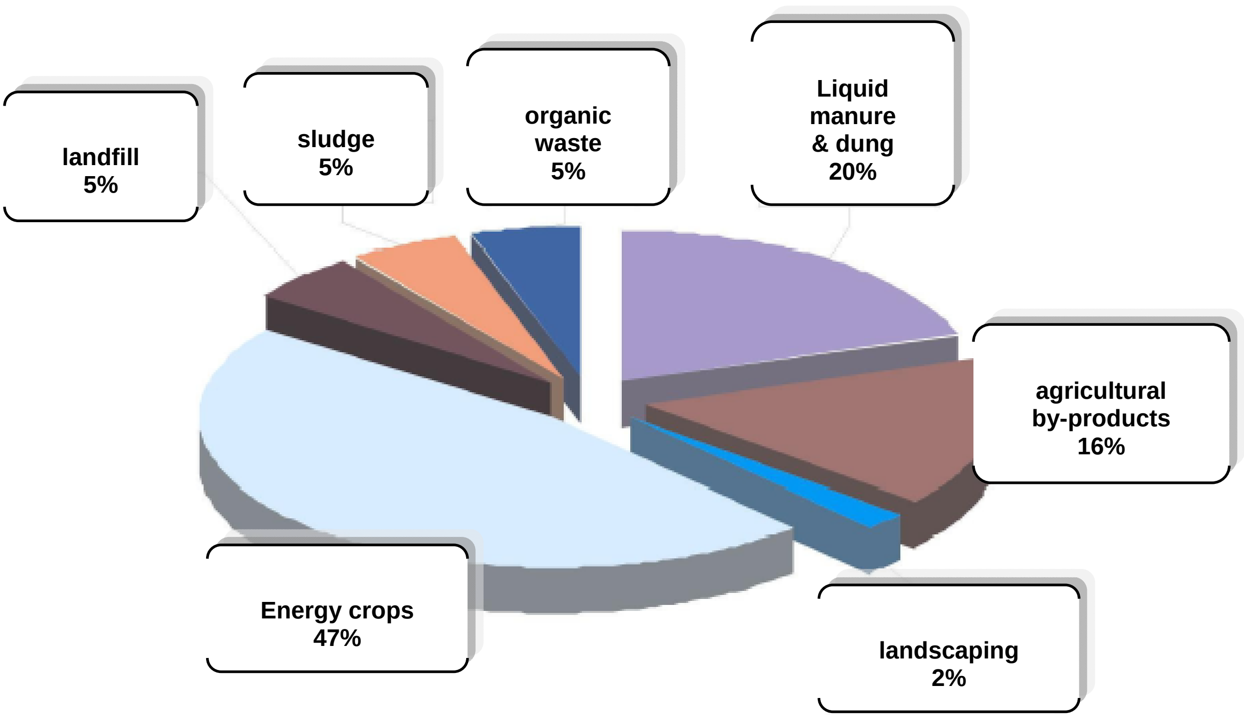


Figure 29: Technically available biogas potential – example Germany

6. Conclusion

A new biogas upgrading technology based on gas permeation has been under development over the past few years. The leader of this new technological development process is the Vienna University of Technology together in association with a small Austrian engineering enterprise. Successful test operation phases in a bench-scale unit and in a pilot plant have already taken place. The results obtained were very promising and have attracted a great deal of interest in this new technology from both experts and the biogas market itself. The next steps relating to a commercial launch of the new technology need to be prepared quickly.

Within this master's thesis, the market surrounding this commercial launch of the gas permeation technology was analysed and some conclusions derived.

Climate change together with a continuous growth of energy consumption requires new concepts for a sustainable energy system.
One component is biogas. Biogas is considered to be CO_2-neutral. Several applications are technically possible for biogas. The decoupling of the biogas conversion and utilisation processes by feeding biogas into gas grids and transporting it over notable distances leads to a more efficient usage of the biogas energy content and increases the utilisation possibilities beyond just electricity, for example, transport fuels or other substitutions of natural gas that could be used for several purposes.
The technical potential for biogas in European countries was estimated by experts in the range of 3.7 - 30% of the natural gas consumption.

Several European and national economic and legal frameworks influence the net integration of biogas. The frameworks with the strongest influencing capabilities are the guidelines concerning net access and gas quality standards.
The reference market for upgraded biogas is the same as for natural gas. Therefore, the availability of natural gas is a crucial component for the market development of biogas upgrading facilities. Biogas production could decrease the dependency on natural gas imports. If through the treatment process, the required quality standards

are obtained, the existing infrastructure for natural gas can also be used for the distribution of biogas.

For the upgrading of biogas several technologies are available and some have been recently applied, such as, PSA, water scrubbing and amine scrubbing. These can be considered the main competitors for the new biogas upgrading technology. All of the available technologies have advantages and disadvantages. According to the specific local conditions, the benchmarking and evaluation of various technologies can lead to different results being obtained. Major interest is in the reliability and availability of the technology, maintenance costs of maintenance resources and energy consumption within the process, the reachable gas quality by the technology and the overall upgrading costs.

The gas permeation technology applied in the pilot plant Bruck/Leitha resulted in a very stable, high quality and a high availability of the gas produced at the plant. The main advantage of gas permeation technology compared with other upgrading technologies is its low maintenance costs due to a reduction in the requirement of maintenance resources. A definitive prediction for the lifetime of the technology cannot be given as the wear of membranes in contact with the biogas has not yet been established.

Sensitivity analysis of the system “market for biogas gas permeation technology” according to F. Vester highlighted the main dynamics within this system and provided some insight into successful market introduction for the new technology.

Several variables responsible for influencing the system were identified and analysed by an influence matrix. This first step analysis illustrates the potential influences of several variables.

The most active variables in the system were found to be the costs and the availability of natural gas, the available gas net infrastructure, the agricultural innovation power, costs of biogas and qualified manpower for gas permeation technology. Changes to these variables result in having a substantial influence on others and are potentially those able to control the system, particularly if they are extremely active in the system.

The most reactive variables are CO_2-emissions, consumption maintenance resources, such as, process water, process energy and other process resources, the confidence in gas permeation technology, the market share of the competitor technologies and the financial potential of the shareholders. All of these variables are highly influenced by other variables of the analysed system. As a result these are not influential enough to control the system dynamics. However, under certain circumstances, they may be able to intercept the system in critical periods.

A high involvement in the system attitude was identified for the market share of the gas permeation technology itself, the extension area of biogas upgrading facilities, the political support for upgraded biogas, the market share of the competitor technologies, costs of biogas upgrading and niche products for gas permeation; Their effect on the system is very clear, whether active or reactive.

A low involvement in the system attitude was identified for the consumption of maintenance resources and process water, the availability of biogas raw material, qualified man power for gas permeation technology, costs of natural gas, agricultural innovation power and financial potential of the shareholders; Their influence on the system is considered to be relatively low.

The combination of these results leads to a better understanding of the role of the variables within the system.

Changes to the cost of natural gas, the qualified manpower for gas permeation and the agricultural innovative power result in a stabilising effect on the system.

The market shares of the competitor technologies are quite critical to the entire dynamics of the system. Changes to them can accelerate or slow the market for biogas gas permeation technology.

The recent situation was identified with the use of effect structure analysis. A prevalence for positive feedback reactions within the system “market for biogas gas permeation technology” was identified. This can be interpreted as high risk and instable due to its self-energising character. In the initiating phase, these positive feedbacks are important, however, negative feedback reactions need to be implemented in the system to ensure its stability.

Most feedback reactions are linked to the market share of the gas permeation itself. Once a certain level has been reached, such as, those with investment and upgrading costs for gas permeation, niche products for gas permeation, qualified man power and service for gas permeation and confidence in gas permeation technology can drop out. These parameters need to be further investigated in the market introduction phase.

The market share for gas permeation technology and the competitor technologies are also those influenced by most other factors. They can be identified as the crucial elements within the system. The same can be affirmed by the parameters directly linked to the marked share of biogas gas permeation technology, such as, niche products, investment and upgrading costs for gas permeation.

The availability of natural gas is the parameter that is not influenced by any other. It has an influential effect on others. It needs to be observed continuously, however, there is no potential to act on it actively.

The political support for upgraded biogas has a relatively high influence on other parameters. It can be influenced externally or by lobbying measures. It is indirectly influenced by the availability of natural gas.

Influencing effects are also qualified manpower and services for gas permeation and confidence in the gas permeation technology. These are the key drivers for successful market positioning of the new technology.

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