SGC Rapport 2013:287

Evaluation of catalytic abatement technology for elimination of methane and odor emissions from biogas production plants

(Utvärdering av katalytisk reningsteknik för eliminering av metan och luktutsläpp från biogas anläggningar)

Tihamer Hargitai, Fredrik A. Silversand, Lars Gunnarsson

"Catalyzing energygas development for sustainable solutions"

SGC Svenskt Gastekniskt Center AB

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Denna studie har finansierats av:
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Malmö 2013

Martin Ragnar
Verkställande direktör

Swedish Gas Technology Centre, SGC

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Malmö, Sweden 2013

Martin Ragnar
Chief Executive Officer

Authors' foreword

This project was initiated June 2012 and was finalized one year later.

The following persons where active in the steering group, tied to the project.

Tobias Persson	SGC
Tihamer Hargitai	Catator
Magnus Dalemo	Absolent
Lars Gunnarsson	Conpura
Göran Liljedahl	Smidmek Gruppen
Daniel Ling	Purac
Marinette Hagman	NSVA
Johan Olsson	Lunds Energi

Absolent is a word-leading supplier of filter equipment for different emissions of oil mist, oil smoke and dust filters.

Catator is a catalyst- and system supplier and acts in a number of fields like emission technology, combustion technology and small-scale production of hydrogen for fuel-cell systems.

Conpura is focusing on the supply of mechanical equipment solutions for waste water treatment. Our products are used for physical separation and material handling within pre-treatment and sludge handling in both the municipal and the industrial markets.

Smidmekgruppen is focused on large-scale production of machined components and acts as a sub-supplier to many companies. Their special interest in this project is manufacture the developed emission abatement equipment.

Purac offers contracting for customers worldwide. We design and build treatment plants for wastewater, drinking water and process water, as well as plants for biogas production and gas treatment.

NSVA (Nordvästra Skåne Vatten och Avfall) is a water services company in the south of Sweden owned by six municipalities (Bjuv, Båstad, Helsingborg, Landskrona, Svalöv and Åstorp).

Lunds Energi Lunds Energi Group AB is owned by the holding company Kraftringen AB, of four local municipalities in Skåne. Activities include electricity production, heating, cooling, natural gas, communications, lighting and construction and maintenance services.

Summary

An innovative regenerative emission abatement unit (abbreviated MRO) has been evaluated in this project, financed by Catator AB, Smidmekgruppen AB, Absolent AB, Purac AB, Conpura AB, NSVA AB, Lunds Energy AB, and the Swedish Energy Agency through SGC AB.

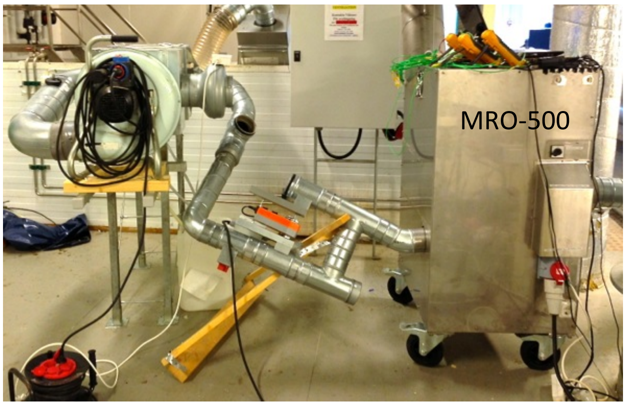
The purpose of the project is to evaluate the applicability, performance and robustness of catalytic purification technology with respect to greenhouse gases and odor substances from different biological processes. The main focus on specific compounds to reduce has been methane (CH_4), as a strong Greenhouse gas, and hydrogen sulfide (H_2S) as one of the main odor compounds.

Two separate, and different types of emission control systems has been constructed and demonstrated. The demonstration units are one regenerative unit MRO-500, with a capacity of 500 Nm^3/hr, and one recuperative unit DEO-100, with a capacity of 100 Nm^3/hr. Both demonstration units have been evaluated for an extended period of time (>1000 hr) at different test sites.

The results demonstrate that catalytic technology can be used for efficient and simultaneously reduction of both methane and strong odor in the same abatement unit (MRO-500 system). The efficiency for methane combustion depends on operation temperature. More than 95% conversion degree is obtained for methane at an operation temperature of about 700 – 800 °C. The energy consumption (running costs) very much depends on the energy content in the gas. The results shows that auto thermal conditions can be reached if the gas contains about 0,5 to 1,0 g VOC Nm^3 gas, corresponding to about 700 to about 1,400 ppm CH_4.

The deodorization efficiency was evaluated by using odor panel evaluation. The odor panel, usually 10 persons, evaluated and compared the odor from three undisclosed gas-bags. One sample was taken before the abatement unit. One sample after the abatement unit and finally one sample used as reference gas from an office. The results shows that the deodorization is very efficient even when very high emission levels of H_2S was analyzed (> 100 ppm H_2S).

An additional advantage with the developed MRO-500 system is the compactness of the unit, as shown below.



Sammanfattning

I detta projekt, som finansierats av Catator AB, Smidmekgruppen AB, Absolent AB, Purac AB, Conpura AB, NSVA AB, Lunds Energy AB samt SGC AB via Energimyndigheten, har en innovativ katalytisk regenerativ enhet för samtidig reduktion av växthusgaser och lukter utvärderats.

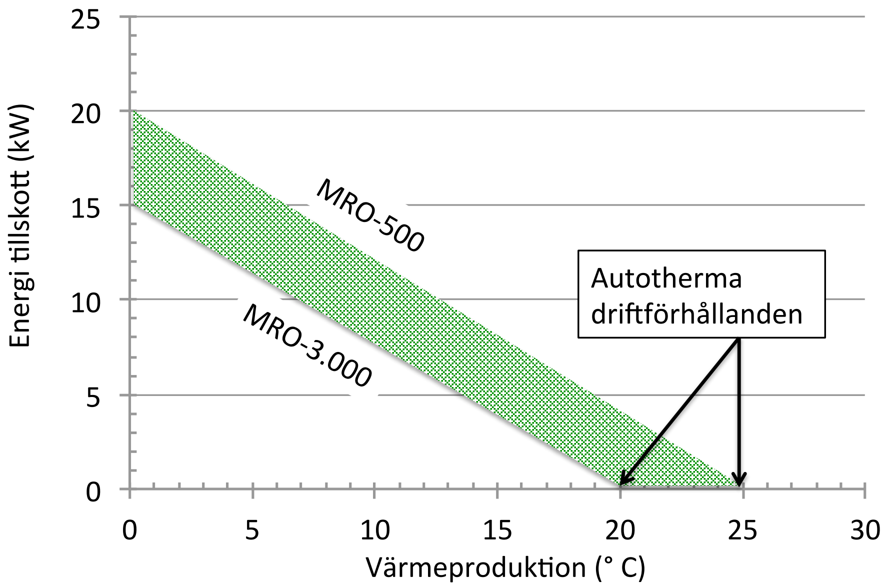
Catator har ett tidigare SGC-projekt (1) visat att katalysatorer kan användas för förbränning av olika växthusgaser såsom metan (CH4) men också för olika illaluktande organiska föreningar. Illaluktande föreningar består ofta av svavelföreningar (tex svavelväte, merkaptaner), olika typer av sura föreningar (smörsyra) och/eller olika kväveföreningar (aminer eller amider). De katalysatorer som är effektiva för metanförbränning (ofta palladium som aktiv substans) är inte effektiva för deodorisering (ofta platina baserad katalysator) och vice versa. Det är till och med så att metanförbränningskatalysatorn blir förgiftad av svavelföreningar varför det har varit svårt att i en och samma anläggning reducera både växthusgaser samt illaluktande gaser.

I föreliggande projekt har två stycken anläggningar konstruerats och utvärderats. Den ena anläggningen, kallad MRO-500 är en regenerativ anläggning medan den andra anläggningen, kallad DEO-100, är en rekuperativ anläggning. Den regenerativa anläggningen (MRO-500) har en kapacitet att behandla 500 Nm^3/t gas och kan reducera både växthusgaser och illaluktande gaser. Den rekuperativa anläggningen (DEO-100) har en kapacitet av 100 Nm^3/t gas och innehåller bara deodoriserings-katalysatorn. Den är tänkt att användas för att eliminera lukt från olika källor som finns i samband med biogas produktion, såsom lagringstankar, pumpstationer, slampressar, slamtransportörer, etc.

I MRO systemet har Catator arrangerat de olika katalysatorerna så att den aktiva katalysatorn för metan förbränning alltid skyddas mot förgiftning av svavelföreningar genom att dessa förbränns innan de träffar på metanförbränningskatalysatorn. Härigenom kan en effektiv förbränning erhållas av både växthusgaser samt illaluktande gaser i samma enhet.

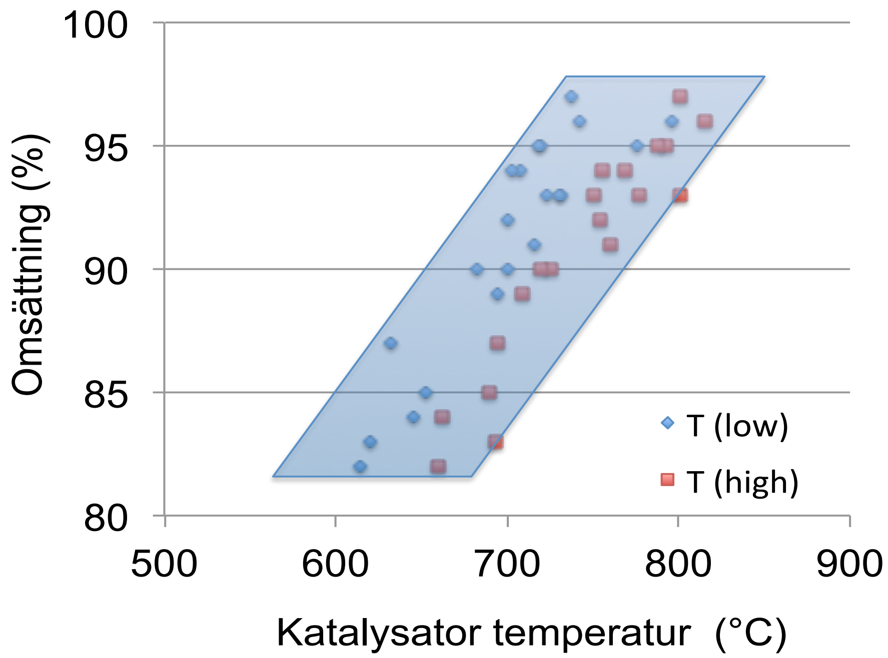
Målsättningen i projektet har varit att via långvariga fälttester (> 1000 t) demonstrera möjligheten med katalytisk reningsteknik inom främst olika processer som finns i samband med biogas produktion.

MRO systemet är baserat på en regenerativ teknik som resulterar ett system med mycket hög termisk verkningsgrad (> 95%). Driftkostnaden, definierad som tillskottenergi för att upprätthålla nödvändig process temperatur, beror helt på systemets termiska verkningsgrad och energiinnehållet i gasen. Den regenerativa designen, med hög termisk effektivitet, medför därmed att driftkostnaden domineras av energiinnehållet i gasen. Resultaten visar att auto-terma förhållanden, dvs förhållanden där ingen tillskottsenergi behöver tillföras processen, kan nås vid så pass låga energihalter i gasen som från 0,5 till 1,0 g VOC per m^3 gas, vilket motsvarar en temperaturökning om ca 20 till 25 °C, se nedanstående figur.

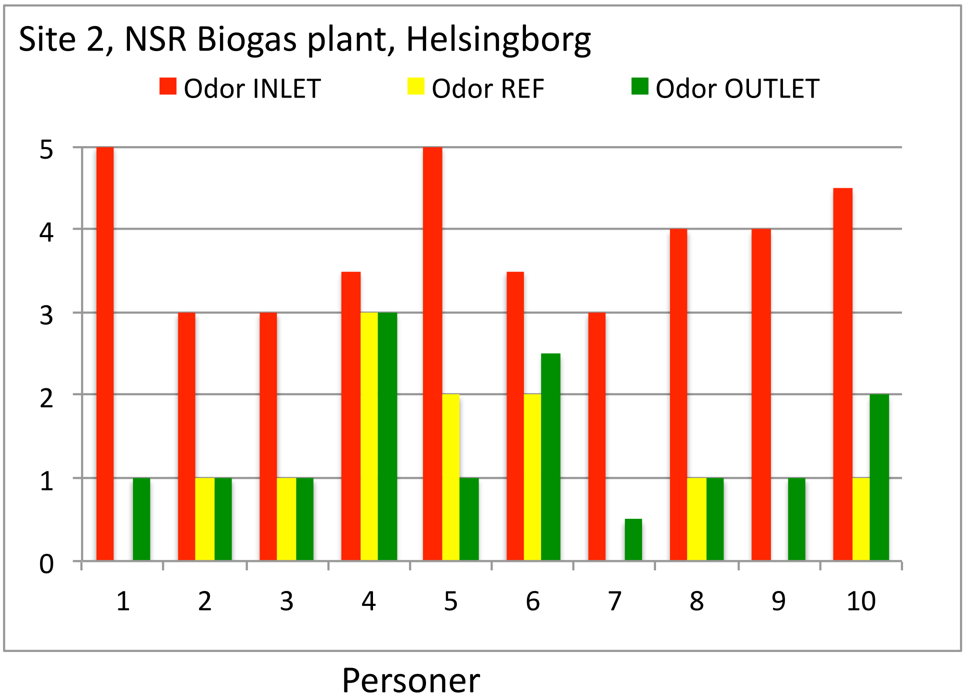


Ovanstående figur visar energibehov, som erhållen temperaturökning från förbränningen, för två MRO system med olika kapaciteter (500 respektive 3.000 Nm^3/h) för att upprätthålla konstanta driftförhållanden (autoterm process).

Omsättningen av växthusgaser beror dels på typ av växthusgas och dels på drifttemperaturen. Metan är en den svåraste föreningen att förbränna katalytiskt då den är en kemisk stabil förening. Den kräver relativt hög förbränningstemperatur, vilket resultaten visar. Det krävs en drifttemperatur på mellan 700 till 800 °C för att uppnå en omsättning på över 95%.



Utvärderingen angående eliminering av lukt har utvärderats genom att använda luktpaneler. Luktpanelerna har oftast bestått av ca. 10 st personer. Gasprover har samlats i oidentifierbara gaspåsar varefter personerna har fått utvärdera båda luktstyrkan och luktkaraktären på 3 olika gaspåsar. De tre gaspåsarna har bestått av gas taget före reningsanläggningen, efter reningsanläggningen samt ett gasprov som använts som referensgas. Referensgasen har tagits från kontorsmiljö. Resultaten visar tydligt katalysatorns förmåga att eliminera lukt, även om personliga variationer finns. Exempel på resultat baserat från en luktpanel visas i nedanstående figurer.



I ovanstående figur har luktpanelen (10 st) bedömt luktstyrkan för tre olika gasprover. Röd stapel visar ingående lukt före reningsanläggningen. Grön stapel visar på bedömningen av luktstyrkan efter reningsanläggningen medan gul stapel visar bedömningen av referensgas (kontorsluft). Skalan som använts är graderad mellan 0 till 5 och definieras enligt följande:

0	Ingen lukt
1	Mycket svag lukt
2	Svag lukt
3	Stark lukt
4	Mycket stark lukt
5	Outhärdlig lukt

Sammantaget visar projektet att det utvecklade MRO-systemet kan reducera både växthusgaser och illaluktande föreningar med hög effektivitet i små energieffektiva och kompakta anläggningar.

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1. Background

Catator has in a recently completed study, SGC report no. 248 [1] demonstrated the potential by catalytic methods to effectively reduce emissions of greenhouse gases and odorous compounds. The study was performed in connection to different biogas production plants and other processes related to biological systems such as composting and anaerobic digestion as well as wastewater processing. The results show that all organic emissions can be reduced with high efficiency.

The previous reported results [1] were conducted with small laboratory scale equipment's and over a relatively short test period. The study shows that the emissions often involve a relatively limited source strength (concentration) of odor substances. Depending on extremely low odor threshold (<1 ppb), this still can cause symptoms within a large radius of the release site. This means, in addition to health and safety problems for people working on the plants, also inconvenience for local residents.

Odor substances generally refer to linear, branched or heterocyclic hydrocarbons containing oxygen, sulfur or nitrogen. A particular problem is connected to hydrogen sulfide from certain process steps.

1.1 Objectives

The purpose of the project is to evaluate the applicability, performance and robustness of catalytic purification technology with respect to greenhouse gases and odor substances from different biological processes. The main focus on specific compounds to reduce in this study has been on methane (CH_4), as a strong Greenhouse gas and different odor compound, related to production of biogas from different waste material.

Methane is one of our most commonly used fuels, more commonly known as natural gas. One main advantage by using methane, compared to other fossil fuels (oil) is that it produces more heat per mass (ca 55.7 kJ/g) than other more complex hydrocarbons. This results in less emissions of Carbon dioxide (CO_2) for each unit of released heat. Another strong green house gas is Nitrous oxide (N_2O, laughing gas), which is produced at water treatment plants. The produced sludge from water treatment plants is often used for biogas production so both these compounds are of interest to reduce / eliminate at biogas production plants.

Both Methane and Nitrous oxide have a very large greenhouse effect compared to the general discussed Carbon dioxide. Methane is usually mentioned that it has a 20 times higher greenhouse effect than Carbon dioxide, while Nitrous oxide has more than 300 times higher greenhouse effect than Carbon dioxide. The greenhouse effect varies over each specific compounds lifetime, as shown in Table 1 [2].

Table 1. Atmospheric lifetime and global warming potential (GWP) relative to CO_2 at different time horizon for various greenhouse gases [2].

Chemical compound	Formula	Lifetime (years)	Global warming potential (GWP)		
			20-yr	100-yr	500-yr
Carbon dioxide	CO_2		1	1	1
Methane	CH_4	12	72	25	7.6
Nitrous oxide	N_2O	114	289	298	153

It is well established that catalysts can eliminate both Methane and Nitrous oxide very efficiently. The used abatement units in this study has the capability to eliminate the emissions of Nitrous oxide but no analyzes was performed at the field tests included in this study, even if some of the customers showed a large interest in the possibility.

Catator has demonstrated that the different developed catalysts for odor treatment and for total oxidation of methane and similar green house gases are very efficiency [1]. The aim of the present study is to demonstrate the possibility of simultaneous elimination of both greenhouse gases and odor from bio-upgrade processes, or similar processes, by the use of a combination of catalysts optimized for different types of emissions.

The odor experienced during processing of different wastes in order to produce biogas origins from a large number of different compounds (usually several hundreds of different organic compounds). All specific compounds have their own specific odor and odor strength. Many of them have a very low odor threshold and very sophisticated analyze equipment is needed to detect and quantify them. One of the well-known odor compounds is hydrogen sulfide (H_2S). The threshold is very low (< 1 ppm) and it's one of the compounds that usually are analyzed due to security reasons at biogas plants. Odor panels in combination with analysis on H_2S have been used for evaluation of the deodorization efficiency.

One of the challenges is that the active catalytic formulation for efficient methane oxidation (usually Palladium Pd/PdO) is deactivated very fast by Sulfur containing compounds, like hydrogen sulphide (H_2S). The usually used catalyst for total oxidation, for odor removal, is often based on Platinum (Pt) or different metal oxide formulations, which in turn are poor catalyst formulations for methane oxidation. The installed catalysts in one of the used abatement systems in this study contain a combination of two types of catalyst formulation. One catalyst formulation, with high efficiency towards methane oxidation, and one formulation with high efficiency for odor removal. The odor removal catalysts also prevent the methane combustion catalysts against deactivation by oxidation of harmful sulphur-containing compounds. The efficiency of the used catalyst is reported previously [1] but during rather short time of operation. The present study involves studies during > 1000 hours of field tests with pre-commercial demonstration units.

The studies are performed with two different demonstration units with larger capacities (full scale units within some applications) and during a longer operation time (> 1000 hr) compared to the previous reported study with laboratory scale units [1]. This increases confidence in the experimental data as well as enables a better technical and economic analysis of the tested systems. Furthermore, a technical comparison is mapped between the different alternative used technologies within the aimed application area.

1.2 Scope of work

Two separate, and different types of emission control systems have been constructed and demonstrated. The demonstration units are one regenerative unit MRO-500, with a capacity of 500 Nm^3/hr, and one recuperative unit DEO-100, with a capacity of 100 Nm^3/hr. The DEO-units are preferable to use for gas flows less than about 500 Nm^3/hr because of the technical simplicity of recuperative systems. The MRO units have excellent thermal efficiency, but somewhat more sophisticated technology than DEO systems, and hence more favorable to use on gas flows above 500 Nm^3/hr. Another advantage in this specific project is that the DEO-100 unit could easily be transported and thus evaluated at a number of different locations. The specific deodorization catalyst is the same in both demonstration units.

Both demonstration units (MRO-500 and DEO-100) have been evaluated in collaboration with different partners in the project and for an extended period of time (>1000 hr) at two different test sites. The performance was followed by total VOC analysis (FID equipment) and by odor tests on collected gasbags with an odor panel.

One general observation made visiting different plants and sources of emission are that large improvements can be performed regarding how to prevent diffuse emissions (mainly odor problem) as well as to optimize the operation conditions by increase of VOC concentration including methane emissions. Avoiding unnecessary VOC dilution reduces the running costs and installation costs substantially.

1.3 Available technologies

There are different types of commercially available technologies to treat green house gas and odor emissions, e.g. thermal combustion, UV & Ozone radiation together with different biological methods such as bio filters and adsorption (activated carbon). All mentioned technologies have both technical and economical advantages as well as disadvantages. A comparison between above-mentioned technologies is presented later in chapter 4.

There are companies that deliver thermal and catalytic systems based on regenerative heat recovery in pellet or monolith based heat sinks (Megtec, VOC technology and CTP). These actors have mainly focused on systems treating high gas flows (typically> 10,000 Nm^3/hr) even if such technologies are available also for flows around a few thousand cubic meters per hour.

Catator's emission technology, based on patented catalytically coated mesh structures or catalyzed heat exchangers, results in compact devices (see section 2.1.1), compared to conventionally used catalyst substrates. Catator has focused on small and medium size flows from about 10 Nm^3/h to ca. 5,000 Nm^3/hr. The appropriate technology has hitherto been difficult to find in this segment. Compared with thermal incineration, catalytic technologies offer increased compactness and reduced installation costs.

2. Experimental

2.1 Technical description of MRO technology

2.1.1 Wire-mesh technology

The major difference between conventional RCO systems and Catator's RCO systems (abbreviated MRO) is the use of the patented wire-mesh catalyst technology. It is commonly known that the mass-and heat transfer characteristics in a bed of pellets are superior to those in a honey-comb (monolithic) structure [3]. The pressure drop of a pellets bed is however significantly higher than the pressure drop of a honey-comb bed. Wire-mesh catalysts combine the excellent mass- and heat transfer characteristics of pellet catalysts with a relatively low-pressure drop of honey-comb structures. The wire-mesh technology is thus essential for novel design innovations in the MRO systems that have been made compared to conventional RCO systems based on monolith and/or pellet based technology.

Wire-mesh catalysts offer the following advantages [3]:

- High mass- and heat transfer numbers
- Moderate pressure drop
- Insignificant effects of pore diffusion and axial dispersion
- Thermal and mechanical strength
- Geometric flexibility
- Excellent thermal response

Previous studies [3] show that the reactor size can be reduced substantially by the use of wire-mesh technology compared to monolith and pellet based reactors, fig. 1. The figure compares the catalyst volume to reach same performance during combustion of CO. The distance between each channel in a monolith unit is described as channels or cell per square inch (cpsi) while the mesh number describes the distance between each wire in a mesh. A high mesh or scpi number indicate a short distance between channels or wires, and vice versa. Thus, a monolith with 400 cpsi corresponds to a mesh of 32. A 100 cpsi monolith should be compared with 20 mesh catalyst, etc. The three different sizes of catalyst substrates (cpsi and meshes) are comparable to each other, regarding distance for each molecule to react with the catalyst. The results clearly show that the catalyst volume is reduced radically for the mesh-based catalyst independently of used gas flow.

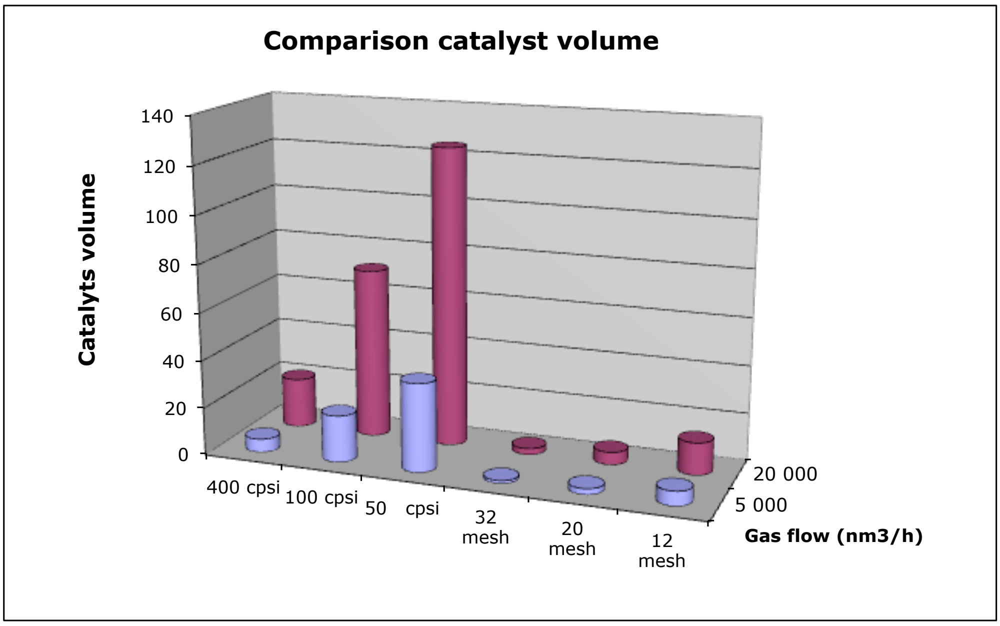

Figure 1. Comparison of wire-mesh and honey-comb based catalyst reactor volumes for CO-combustion at two different gas flows (blue 5.000 nm^3/h and red 20.000 nm^3/h), according to conditions presented in reference 7.

2.2 Principle design of MRO technology

The principal design of RCO systems is demonstrated in figure 2.

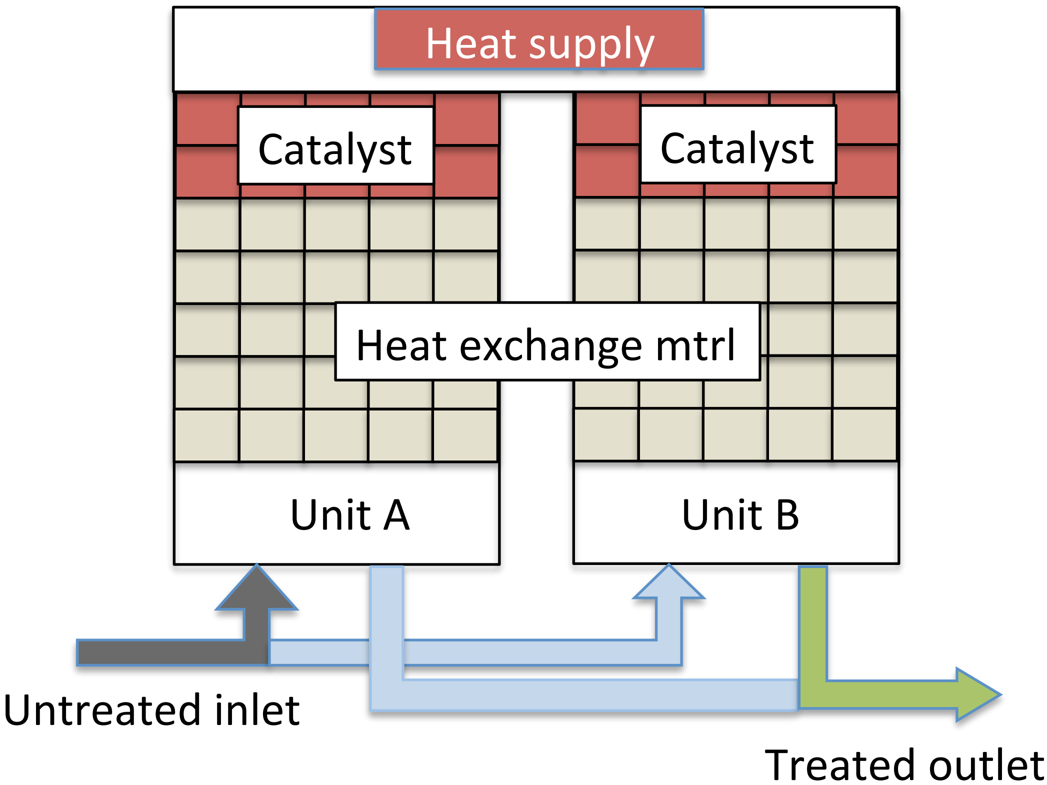

Figure 2. Principle design of a regenerative catalytic oxidation system (RCO).

The principle design of a regenerative system (both RTO and RCO systems), is that the incoming gas flow is switched between two separate heat exchange sinks (A and B in figure 2) before it enters the catalyst, or thermal combustion zone. The combustion reactions take place either during passing the catalysts or in a flame combustion zone. Additional heat to reach the desired operation temperature is added, if needed, to the system, either by electric heaters or by gas burners. The hot treated gas, leaving the combustion sections transfer the heat of combustion to the heat exchange sink and leaves the system with a low temperature, often only about 30 °C higher than the inlet temperature. The heat efficiency for these types of systems is very high (> 95%) compared to recuperative systems, which results in low running costs. The used heat sink materials in conventional systems are normally made of ceramic materials and in the shape of either pellets/granulates or honeycomb structures. This results in bulky and heavy systems.

Catator's system is based on the patented Mesh-technology. The principle design is presented in fig 3. The cold in-coming air is passing with a radial flow through several sections of meshes where the first one act as a heat exchange sink and the next two ones include the specific catalytic reactions. The first catalytic section is optimized for deodorization reactions and for protection of the second layer of catalyst used for methane combustion.

Electric heating in center of the unit is used to reach to the operation temperature as well as energy supply if the air to be treated has a too low content of energy to reach adiabatic operation conditions. The hot treated air is passing through same type of mesh sections and will through the final section transfer the heat to the heat exchange section.

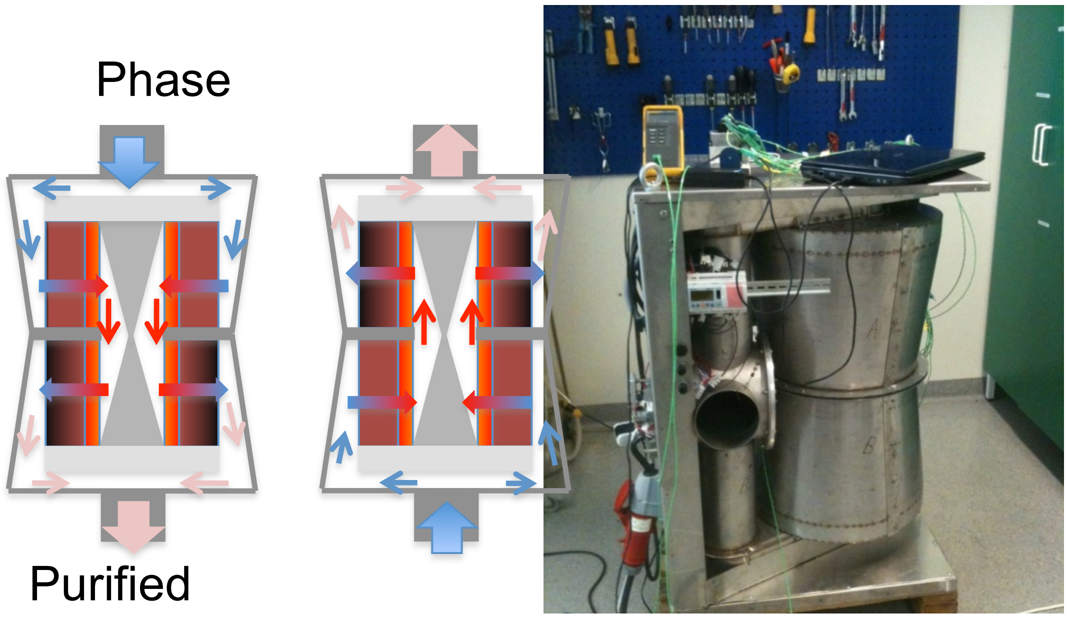

Figure 3. Schematic design of MR0-500 unit. Size 0,6 x 0,7 x 1,1 m (LxWxH).

The set point for the catalyst operation temperature is usually set between 250-400 °C for deodorization applications and about 650-750 °C for methane combustion. The reaction products are mainly carbon dioxide (CO_2) and water vapor (H_2O). The power demand of the unit depends on the energy content in treated air and the efficiency of the internal heat exchanger. The present demonstration unit, with a capacity of 500 Nm^3/h, has an installed capacity of the electrical heater of 10 kW and an efficiency of the heat exchanger of > 95%.

The design of the MRO system is scalable and estimations of different system sizes are presented in fig. 4.

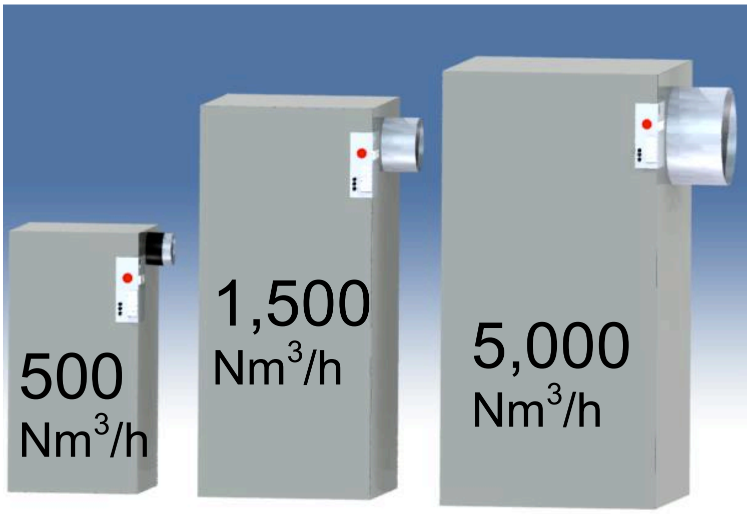

Figure 4. Estimated system sizes for different MRO systems. MRO - 500: 0,6 x 0,7 x 1,1 m (LxWxH), weight ≈ 250 kg, MRO - 1,500: 0,8 x 0,8 x 1,4 m (LxWxH), weight ≈ 600 kg, MRO - 5,000: 1,1 x 1,1 x 1,8 m(LxWxH), weight ≈ 1,500 kg

2.3 Principle design of DEO technology

The design of a recuperative unit is simpler compred to the regenerative system. The gas to be treated is pre-heated by passing through a heat exchanger. The actual operation temperature is reached by passing through an electric heater. The set point for the catalyst operation temperature is usually between 250-400 °C for most deodorization and VOC applications. The VOC compounds are combusted in contact with the catalyst and the resulting reaction products are carbon dioxide (CO_2) and water vapor (H_2O). The power demand of the unit depends on the energy content in treated gas and the efficiency of the installed heat exchanger. The present demonstration unit, with a capacity of 100 Nm^3/h, has an installed capacity of the electrical heater of 3 kW and an efficiency of the heat exchanger of about 60%.

A schematic drawing of the internal design of DEO-100, and a picture during assembling of the unit is presented in Figure 5.

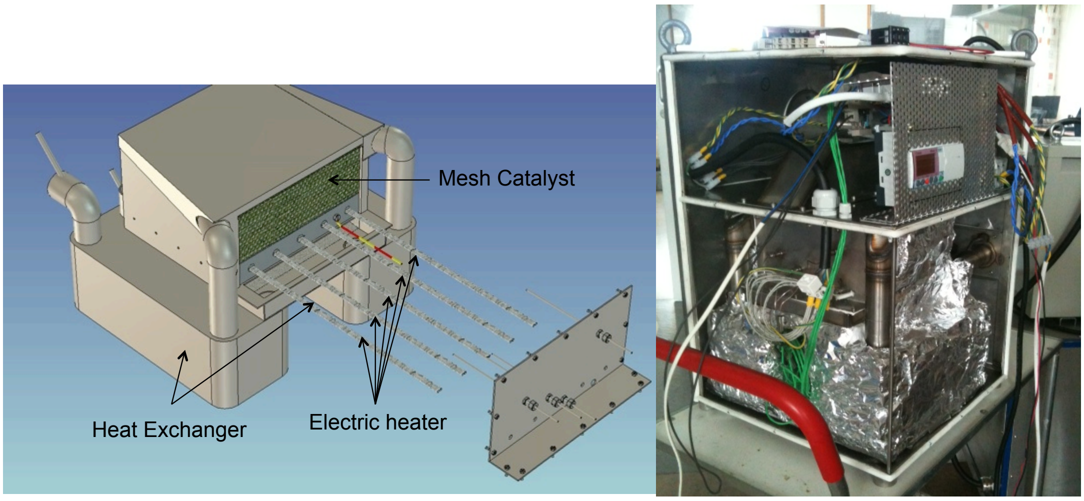

Figure 5. Principal design of DEO-100. Size of unit 0,4 x 0,4 x 0,6 m (LxWxH).

The DEO-systems are also scalable from very small compact units (about 1 Nm^3/h) up to about 500 Nm^3/h. The MRO technology, with much higher thermal efficiency, and as a result, lower running cost is preferred technology at capacities over about 500 Nm^3/h.

2.4 Analyses of odor and methane

Odor is one of the most common of all air pollution complains in a community. Odors from wastewater treatment, biogas production plants, compost units and similar industrial processes can affect the community and lead to nuisance complaints.

Our sense of smell (olfactory system) is one of our five senses and the most complex and unique in structure and organization. The olfactory system is important, not only for flavor sensations during eating but also plays the major role as a defense mechanism by creating an aversion response to malodors and irritants.

Greenhouse gases (like methane) are typically difficult to detect as an odor, due to a high odor threshold for our sense. On the other hand, these emissions are rather high (> hundreds of ppm) so they are, on contrary to ill smelling compounds, rather easy to analyze and quantify by different technologies (FID, GC, IR, etc.).

Odor emitted from biogas production and wastewater treatment processes consist of a large number of different compounds, each with a specific character, response factor, threshold limit and they also effects each other and our perception when mixed. Odor can be detected at very low concentrations (threshold level on ppb levels) and the perception of odor may change with increasing concentration, intensity, time, frequency and previous experience with a specific odor. It is therefore often difficult to perform quantitative and qualitative analyzes and in detail pinpoint which specific compound/s that cause the odor. The most accepted and used methodology to determine if a certain odor reduction technology has an efficient removal of odor is to use human odor panels, even if the ability to identify odors varies among people (and gender) and decreases with age (women usually outperforms males). There is an ongoing research and development of advanced technologies, like artificial or electronic nose, but still with rather limited use.

The total hydrocarbon (HC) emissions were analyzed with FID equipment (Flame Ionization Detector, which presents the results as total amount of hydrocarbons (HC) given as ppm propane equivalents. Portable H_2S/CO-alarm equipment (Gas Alert Quattro or Multitec 540) was used for “on-site” –analysis of H_2S emissions. In addition, gas samples were collected in gas tight bags (Tedlar bags) and odor assessment was performed by a number of persons in an odor panel (usually about 10 persons).

We have from the previous studies experienced that it is very difficult to analyze odor by conventional equipment since the odor threshold is very low for a large number of odor compounds (thresh hold in the range of few ppb units). Odor is measurable and quantifiable using standard practices as published by the American Society of Testing and Materials (ASTM E679 and E544) and by the European Union. In 2000 the proposed European Normalization Standard, prEN 13725, was implemented and become the de facto "International Standard" for odor testing [4].

The project budget did not include the possibility to include “professional” evaluation by different olfactory methods and odor panels. We have used a simplified olfactory standard form on a randomly selected test panel, usually constituted by 10 persons. The test panel had to determine the odor from three different unidentified gasbags. One bag with a gas sample upfront the deodorization unit, one bag contained gas from the exhaust of the unit and finally one bag that was used as reference gas, containing air from an office. The odor evaluation form is presented in figure 6 [5]. The character of an odor can be described using “standard odor descriptors”, as shown in the left side of the form. Odor characterization is also known as “odor quality”. The other part of the form evaluates the odor intensity. Odor intensity is a measure of the experienced relative strength of an odor above the threshold. Odor intensity can be assigned a word descriptor or a number on a “5” or “10” scale. We have used a 5-scale descriptor. The persons attending the odor panel received an explanation of the form together with some examples of compounds defined in the different odor characterization groups. Most of the people involved in the odor panel thought it were difficult to evaluate the character of the odor, while the intensity scale was easier to understand and use. The results from both odor characterization and odor intensity tests are a very powerful and rather easy (and cheap) way to evaluate the performance of deodorization equipment.

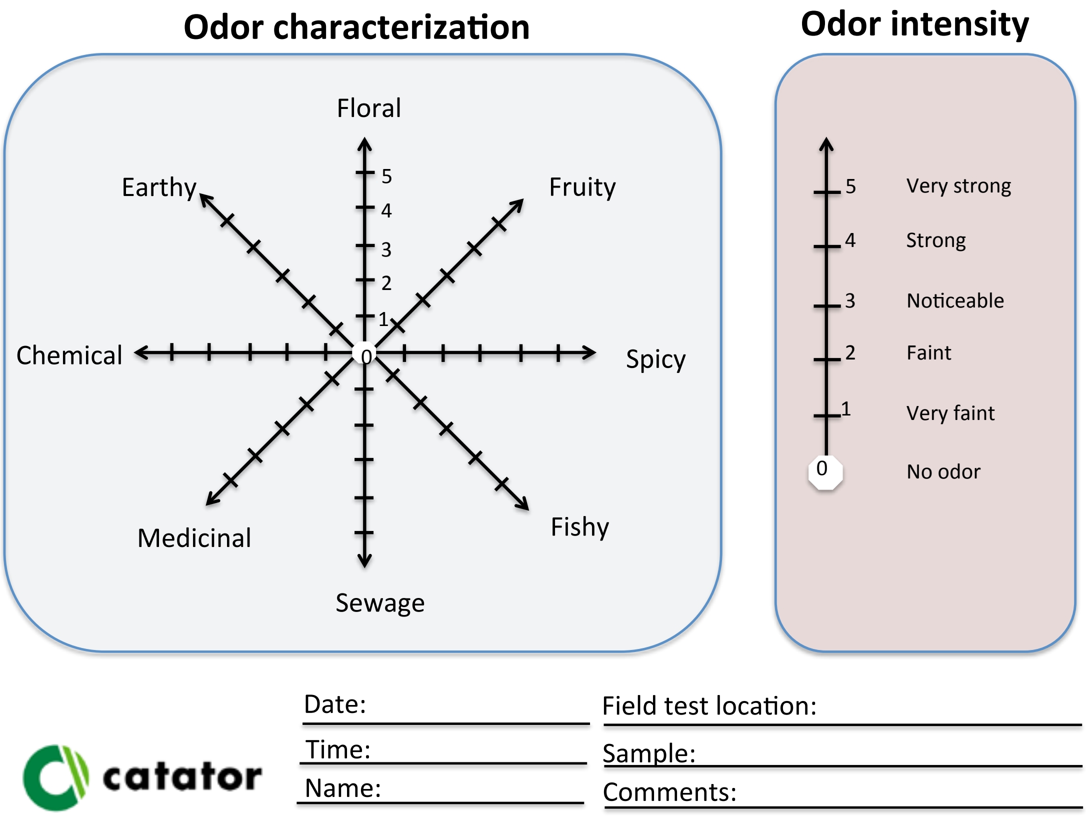

Figure 6. Odor characterization and odor intensity form used to evaluate the performance of DEO and MRO systems at different field tests.

3. Results and discussions

3.1 Conversion and energy efficiency, MRO-500

Technical validation of MRO-500 was performed before installation at field test. The four different test compounds used where Toluene (C_7H_8), Ethanol (C_2H_5OH), LPG (mix between propane (C_3H_8) and butane (C_4H_{10})) and NG (mainly methane (CH_4)). The result is presented in Fig. 7. Methane is the most difficult substance to combust catalytically due to the high stability of the molecule (one carbon atom in the center of 4 surrounding hydrogen atoms results in an energy stable molecule).

A suitable catalytic active phase for combustion of methane is Pd/PdO [6]. The activity is high at operation temperatures > 600 °C but there are effects that results in the need of higher operation temperatures to reach high activity. Sulphur compounds have a strong inhibition on Pd activity due to formation of palladium sulphates [7]. Palladium sulphate is decomposed to in PdO and SO_x at temperatures above 550 °C and the activity for methane combustion is restored but shifted to higher operation temperature. Water vapor also reduces the performance of the combustion reaction due to adsorption to active sites on the catalyst [7]. This results in that the observed conversion degree in field tests will be shifted to higher temperatures, with about 100 °C, compared to results from laboratory tests. The results of methane combustion from field tests confirm these inhibition effects (fig 19, section 3.6).

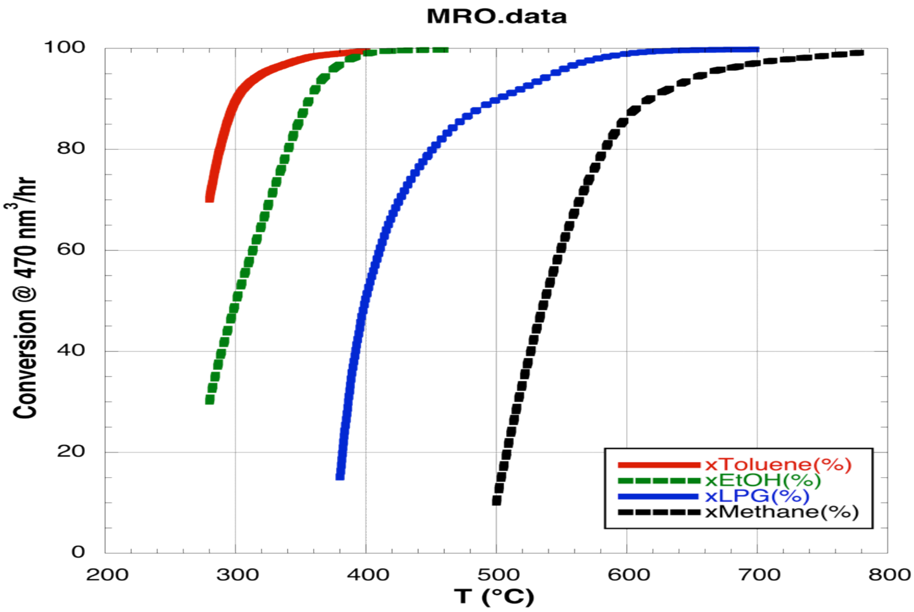

Figure 7. Evaluation tests with MRO-500 unit. Conversion degree of different compounds, as a function of catalyst temperature at 470 Nm^3/h.

Efficiency calculations show that the limit for auto-thermal operation condition corresponds to about 1 g/m^3 of methane (about 1,400 ppm CH_4) for small units (< 1.000 Nm^3/h) and down to about 0,5 g/m^3 for larger units (3-5.000 Nm^3/h). Auto-thermal conditions can thus be reached if the heat of combustion – temperature increase - is higher than about 20-25 °C (independent of treated compounds), as presented in fig 8. Lower heat production results in need of additional energy supply.

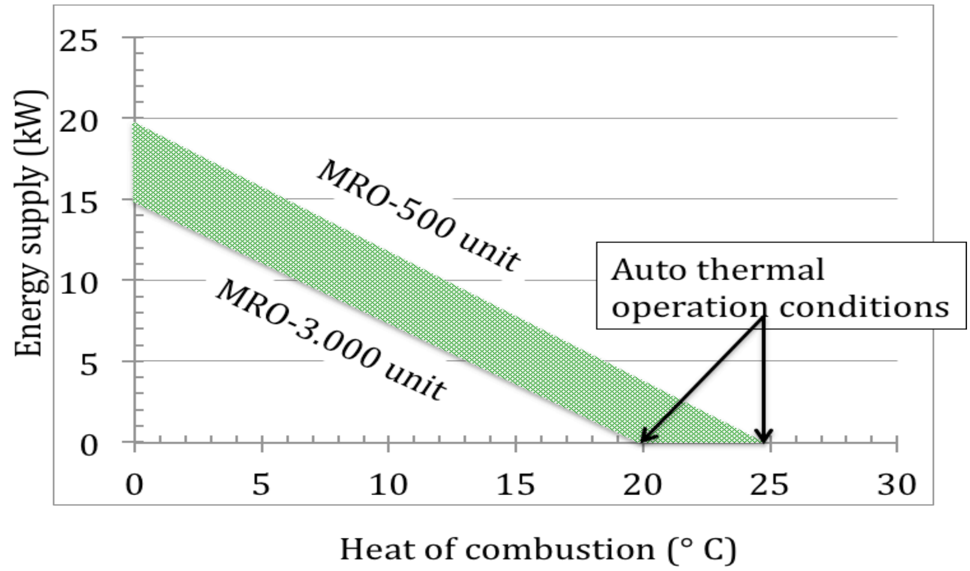

Figure 8. Heat of combustion needed to obtain auto-thermal operation conditions, as a function of unit capacity of MRO systems.

It is possible to increase the thermal efficiency in the MRO-systems even more by increasing the available heat exchange capacity but it is always a trade off between increased system size, weight and cost.

Another parameter that influences the energy efficiency of the system is insulation of the system. The heat losses from the unit are kept very low due to the design of the unit. Figure 9 shows a thermo photo during operation but without any installed insulation. The flange connection between the two reactor sections is the dominated area for heat losses. The other parts of the reactor have a low surface temperature, which leads to low heat losses.

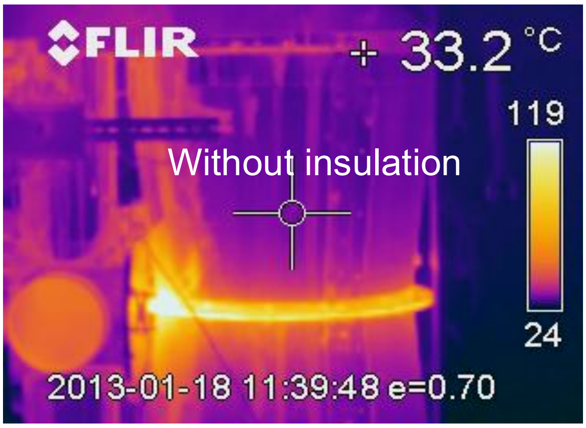

Figure 9. Thermo photo showing heat losses from the reactor unit during NG combustion. The unit is without insulation at the occasion.

The estimated total needed yearly energy supply for a MRO-3000 unit, as a function of the hydro carbon (HC) content, is presented in Table 1.

Table 1. Additional energy supply to obtain auto-thermal operation conditions, as a function of total hydrocarbon (HC) content. The figures are estimations based on a MRO-3.000 unit (3.000 Nm^3/h).

HC content (g/Nm^3)	Energy supply (kW)	Energy supply/year (MWh)
0.5	0.0	0
0.25	8	70
0.1	12	105
0.0	15	132

The major running costs are thus completely determined by the energy content in the treated gas. Once again, the importance of optimizing the VOC concentration is vital for the running costs.

It is not necessary to use electricity as additional support of energy. Any low cost fuel (waste HC compounds) can be added to the gas to supply the amount of additional energy needed to reach to auto-thermal operation conditions.

3.2 Valve shift temperatures and valve shift times

The valve shift temperature and valve shift time controls the operation temperature of the catalyst and must be regulated in order to keep the catalytic reaction at suitable operation conditions. High heat production results in shorter valve shift times and/or increased valve shift temperature. The excess of produced heat must be able to leave the system. Additional energy is supplied to the system if the heat of combustion is too low to operate the unit under auto-thermal conditions. The control system is programmed to always be as close to optimal operation conditions as possible.

An example showing the temperature profile during laboratory tests is presented in fig. 10. The curve shows the temperature profiles during combustion of simple hydrocarbons (simulation of odor), LPG and NG. The white line shows the temperature of the electric heater and the dark and bright blue lines, at the bottom area in the diagram, shows the valve shift temperatures and shift times. The other colorful lines represents temperatures in the different sections through out the installed meshes (heat exchange meshes and the two different catalysts). The valve shift time is between 1 – 3 minutes, depending on operation conditions. The actual speed of valve shift is less than a second and can be reduced to tenth of a second.

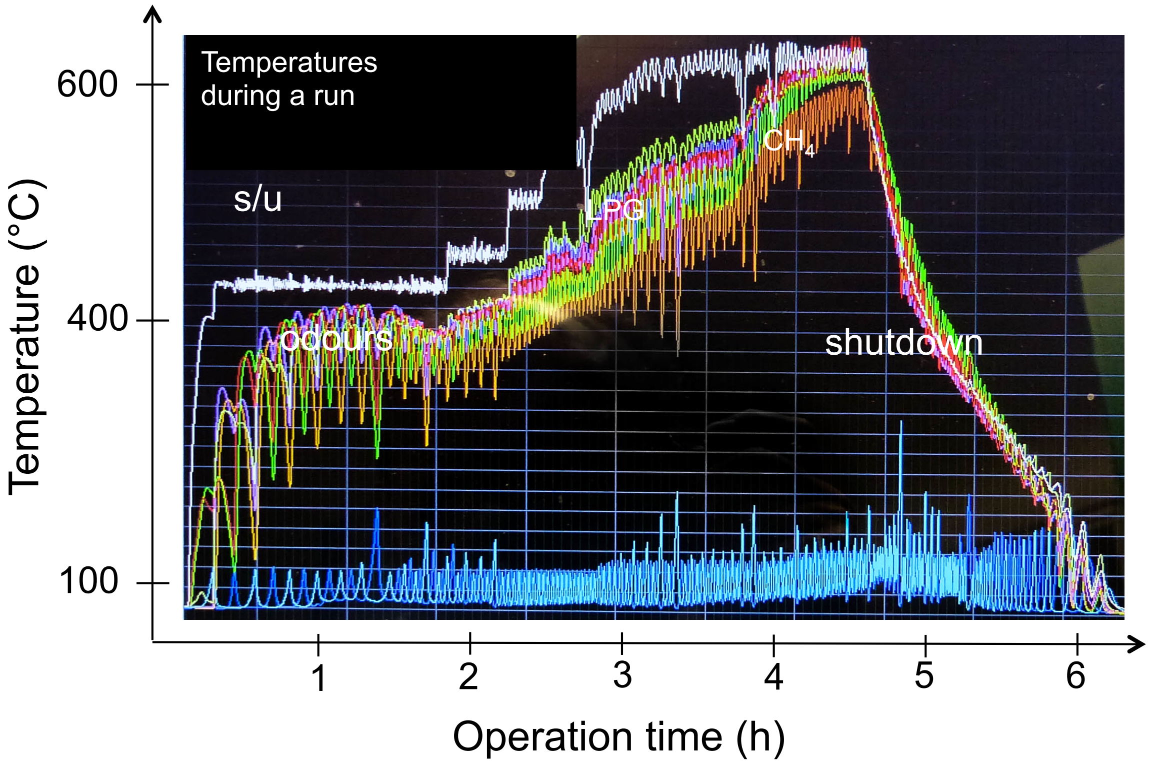

Figure 10. Temperature profile during combustion of different hydrocarbons.

Small amounts of untreated compounds will inevitable leave the unit as emissions during the valve shifts. It is important to minimize these losses. The design of the MRO shows very small losses from the system since the dead-volume of untreated gas is very small and since the actual shift time for the valve is very short (less than a second). The calculated losses are between 0,5 to 2 %. Figure 11 shows the emission concentration (ppm) at inlet (the big peak far left) and outlet. The 5 small peaks show the emission level due to valve shifts.

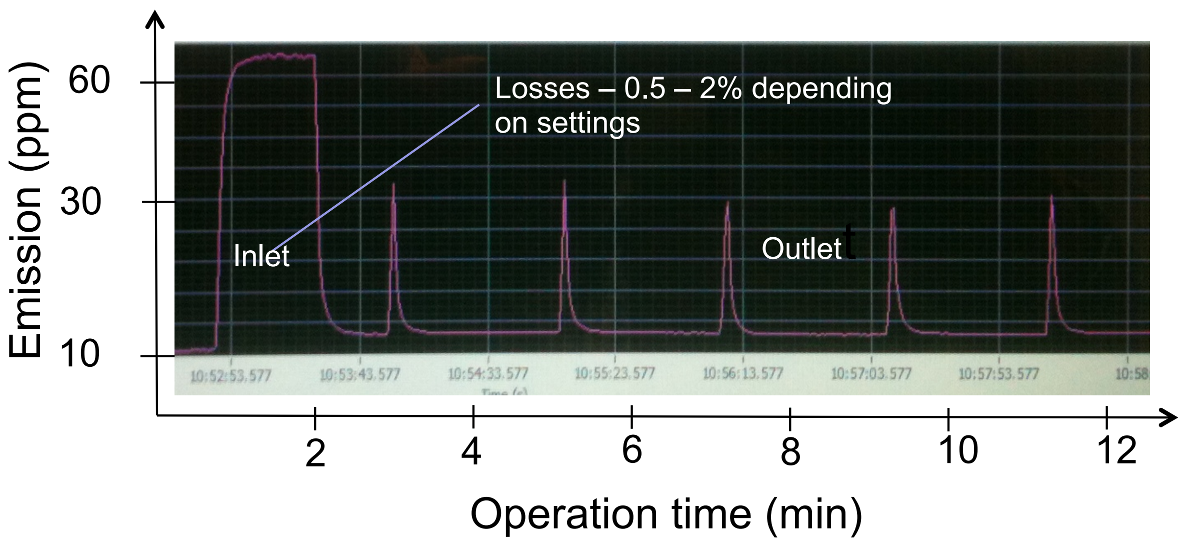

Figure 11. Untreated emissions of VOC due to valve shift in MRO-500 unit.

3.3 Start-up and shut down time

The start-up time of the system depends on the capacity of installed heating elements. Normal start-up time for operation at 650 °C is about 40 minutes. Steady state conditions are reached within a 5-10 minutes after a change in set point temperature. An example of steady state condition during NG combustion is presented in fig 12.

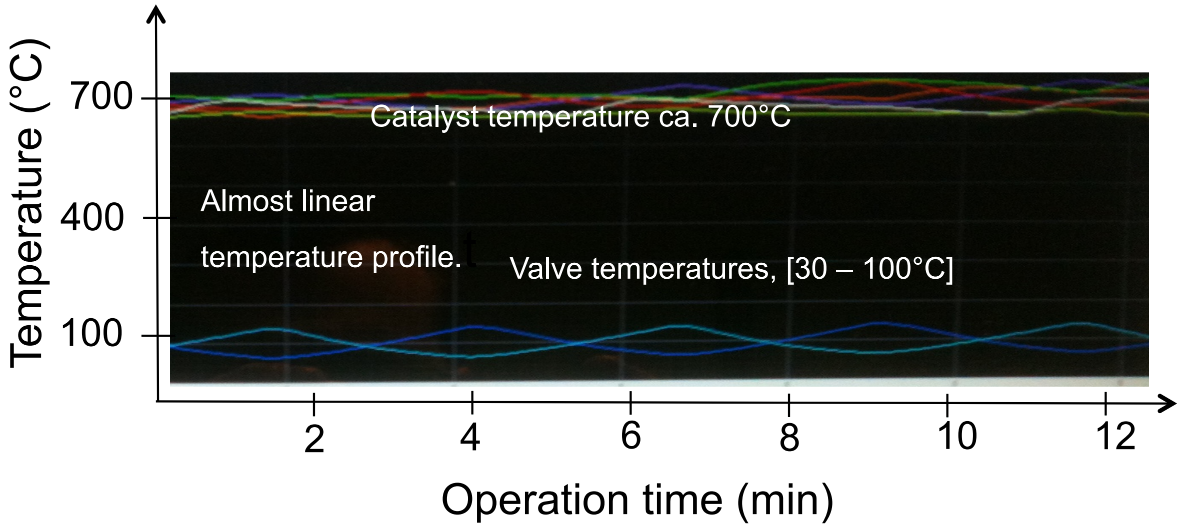

Figure 12. Steady state conditions during natural gas combustion. The dark and bright blue lines shows valve shift temperatures (heat sink temperature) while the colorful temperatures shows catalyst temperatures.

The shut down time is normally a couple of hours (from 700 °C to below 100 °C), due to the amount of energy stored in the heat sinks and due to that ambient air is used as cooling agent.

3.4 Verification tests DEO-100

Technical validation of DEO-100 was performed before installation at different sites. The installed deodorization catalyst is the same type of catalyst formulation that is installed in the MRO-500 unit. The aim of the catalyst is two-fold: to protect the methane combustion catalyst towards catalyst poisons present in the odor (mainly sulpfhur compounds like H_2S) and efficient odor elimination.

The verification tests were performed with a number of different test compounds such as Toluene (C_7H_8), Ethanol (C_2H_5OH), n-Butyl acetate ($C_6H_{12}O_2$), 1-Butanol (C_4H_9OH), Thiophene (C_4H_4S) and Butyric acid ($C_4H_8O_2$). All compounds showed a conversion degree larger than 98% at temperatures above 350 °C and without any noticeable odor in the emissions.

3.5 Field tests locations

The aim of the MRO-500 unit is to demonstrate simultaneous emission reduction of both greenhouse gases and odor, especially connected to biogas production and /or wastewater treatment. The aim of the DEO-100 unit is to demonstrate the possibility for efficient odor reduction, which usually also are found in connection to biogas production plants as well as wastewater treatment plants.

3.5.1 Källby Biogas production plant, Lund

Lunds Energy company, has a municipal water treatment plant, in co-operation with VA-Syd, and a biogas production plant in Källby, Lund. The produced biogas is upgraded to vehicle fuel by a water scrubber unit installed by Malmbergs AB. The off-gases from the upgrading plant contains small concentrations of methane as well as some odor. The odor is adsorbed in a carbon filter unit. The methane is emitted to the atmosphere without any further treatment. The total off gases from the upgrading unit is about 200-250 Nm^3/h.

The MRO-500 unit was installed and connected up-front of the active carbon unit as shown in fig 13. Field tests were performed during more than 1000 hours of continuous operation.

Figure 13. Installation of MRO-500 unit at Källby biogas upgrading plant. The unit is connected to the exhaust tube up-front the activated carbon tank.

3.5.2 NSR biogas production plant, Helsingborg

Nordvästra Skånes Renhållningsverk AB (NSR) has a biogas production plant in Helsingborg. They use different type of waste material (municipal material, food waste, etc.) to produce biogas. The DEO-100 unit was evaluated for about 1000 h on gas from a storage tank for waste. Very high levels of H_2S, (up to 200 ppm) and other odor compounds, are emitted from the tanks. This site is an excellent site to observe the performance of the deodorization catalyst. The DEO-100 unit was installed above the storage tank, as showed in fig 14.

Figure 14. Installation of DEO-100 unit on top of waste material tank, at NSR bio-gas production plant, Helsingborg.

3.5.3 FAMAX biogas production plant,Kalmar

A very similar test site to the above described test site at NSR is at FAMAX biogas production plant in Kalmar. They use the same type of waste material for biogas production. The DEO-100 unit was installed on top of one of the buffer tanks, as shown in fig 15. The unit was only tested during a couple of hours due to stormy wetaher.

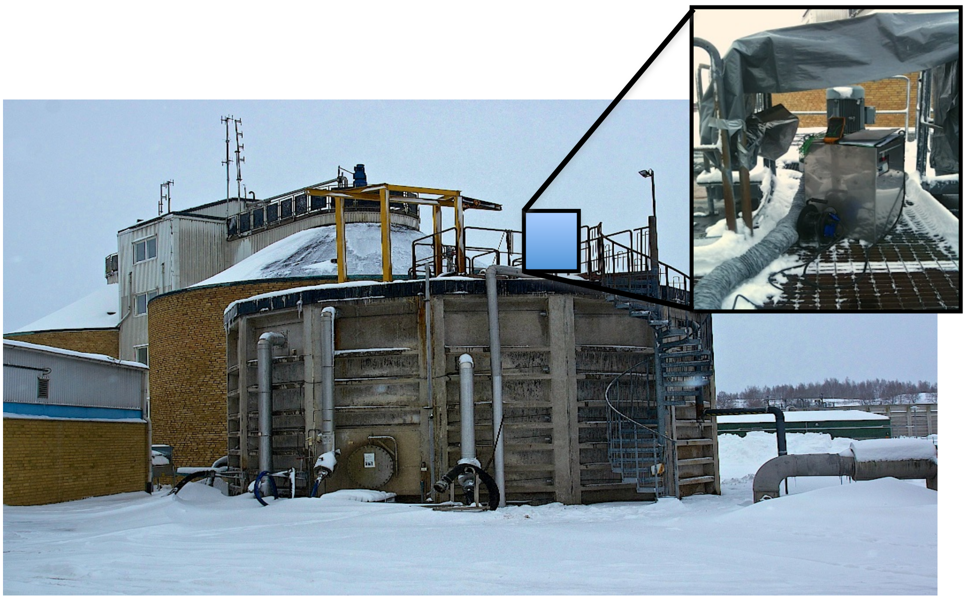

Figure 15. Installation of DEO-100 unit on top of waste material tank, at FAMAX biogas production plant, Kalmar.

3.5.4 NSVA pumpstation, Hilleshög, Landskrona

All municipal wastewater from a small island, named Ven, is pumped under the sea to the mainland of southern Sweden and further to the local wastewater treatment plant in Landskrona. The local company responsible for the water treatment is NSVA (NordVästra Skånes Vatten och Avlopp).

The pump station is located very close to residents (within 100 m), which results in complaints. The DEO-100 unit was installed in the control room (under ground room) just beside the pump station, see fig 16. The DEO-100 unit has an internal fan that draw the gas above the wastewater tank to the unit and emits the deodorized air through a chimney above the ground level. The unit was evaluated for 1000 hours.

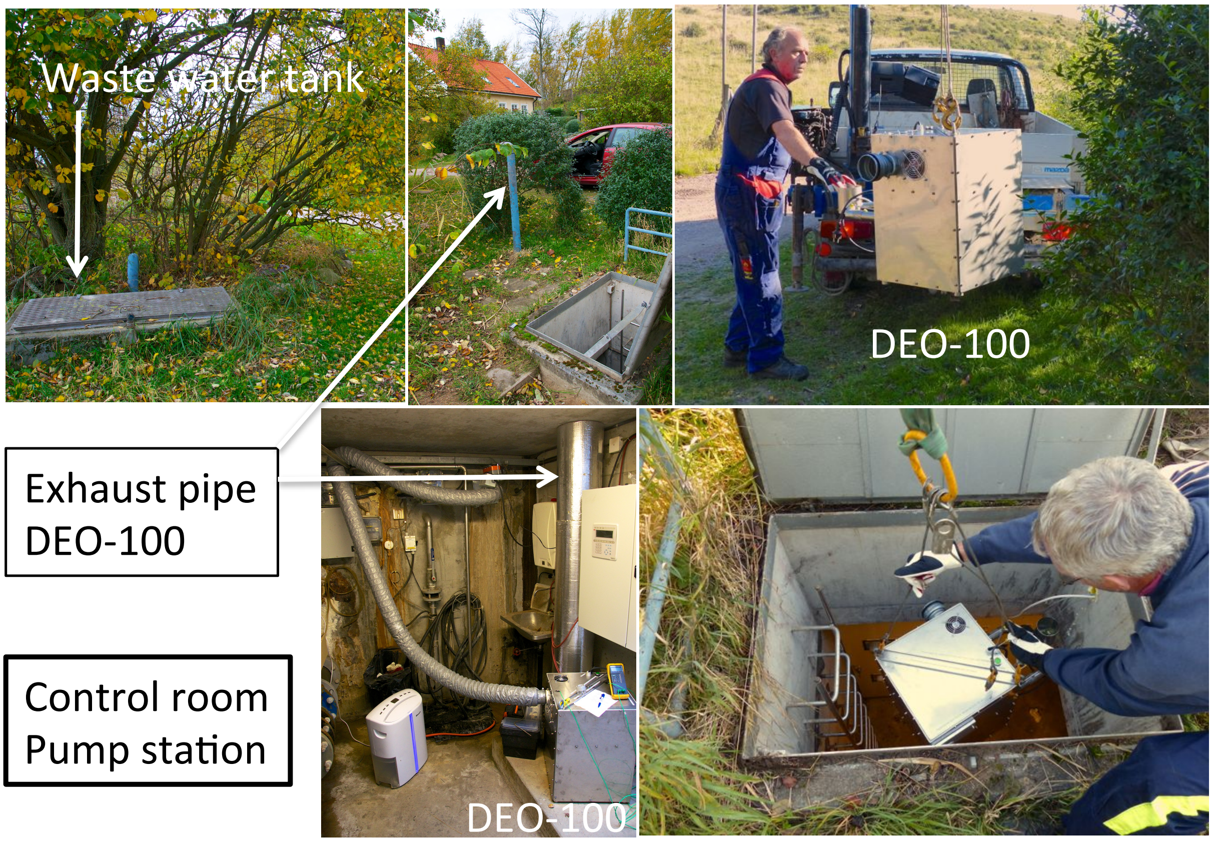

Figure 16.Installation of DEO-100 unit at Hilleshög pump station for waste water.

3.5.5 Sludge press at NSVA, Landskrona

High emissions of H_2S are observed at the municipal water treatment plant at NSVA, Landskrona, at the process of dewatering of sludge. Most of the emissions are captured in a “closed” ventilation system, which finally emits the gases outside the building. The tests with the DEO-100 unit were performed during one day (fig 17).

Figure 17.Evaluation of DEO-100 unit at dewatering press for sludge at NSVA municipal water treatment plant in Landskrona.

3.5.6 Dafgård food production plant, Lidköping

One project partner (Absolent AB) has products for removal of oil mist (aerosols). The products have high efficiency but still, to some extent, emit odor if the odor compounds are released as a gas that can pass the filters. The MRO-500 unit was installed at one of Dafgårds meatball production lines in Lidköping for reduction of odor, fig 18. The unit was evaluated during one day.

Figure 18. Evaluation of MRO-500 unit at a production line for meatballs at Dafgård, Lidköping

3.6 Results MRO-500

The MRO unit has been tested at two different locations of which the long time test (> 1000 hr) was performed at Källby Biogas production plant. A short time field test for odor reduction was performed at Dafgårds meatball production plant.

The aim of the evaluation at Källby was to simultaneously reduce both slip of methane and odor. The concentration of HC (methane and odor) varies frequently during the day and depends on the production conditions at the biogas plant. The inlet emissions were analyzed by FID and usually varied between 150 to 600 ppm. Previous gas analyzes (1) presents methane concentrations of between 0,1 -0,7 vol%. The FID results indicate a rather low concentration of methane slip, probably more close to 0,1 – 0,2 vol%. The concentration of H_2S was measured during different occasions and varied between 0 and 4 ppm.

The conversion degree for methane strongly depends on the catalysts operation temperature as presented in fig 19. The catalyst operation temperature fluctuates about 100 °C during one valve shift as the direction of the gas flow changes. The observed conversion degree is stable during the valve shift but the actual measured catalyst temperature change between a low and a high value, as presented in fig 19. High conversion degrees (above 95%) could only be reached when the temperature of the catalysts was fluctuating between 700 to 800 °C. One section of the catalyst is always close to 800 °C which results in a stable conversion degree. The data presented in fig 19 is compiled from test data during the whole test period (> 1000 hr).

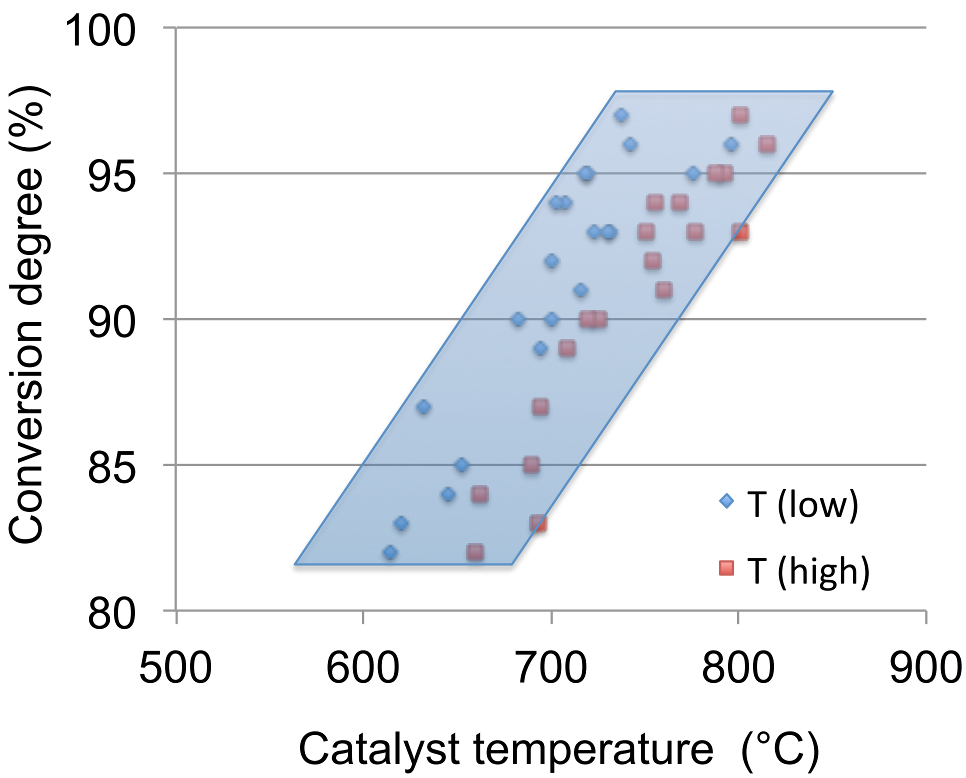

Figure 19.Conversion degree of methane as a function of catalyst operation temperature. Gas flow 200 Nm^3/h.

The operation condition for the upgrading plant is presently set to avoid high levels of methane slip from the process. This results in a “low” methane concentration in the upgraded methane gas. This is compensated by addition of propane since the energy content in the gas must reach a certain energy content to be certified.

It is however possible, and an advantage for the MRO-system, to optimize the upgrading process so higher concentration of methane is obtained in the produced gas. This is an advantage for the MRO-system! The increased concentration of methane in the slip gas results in that the abatement system is operated under auto thermal conditions. This will reduce the running costs dramatically (see energy demands in fig. 8 and Table 1).

The MRO unit has also been evaluated for odor removal at Källby biogas plant and at Dafgårds meatball production plant. Both test plants have a rather low odor level, compared of some of the other test sites used for evaluation of the DEO-100 unit (results presented in Table 2). The inlet VOC concentration (FID result) at Dafgård was about 16-21 ppm and the conversion degree was about 78-82 %.The FID results from Källby bio-gas plant represents the total inlet of VOC, both methane slip and odor. The odor is eliminated at much lower temperatures than methane combustion (300-400 °C), which explains why we still detect VOC by FID (due to methane slip) but no odor.

The results from odor tests from the MRO-500 and DEO-100 units, by an odor panel, are based on “blind-tests” on three different un-marked gas-bags containing untreated gas, treated gas and reference gas (office gas). The results show that the installed deodorization catalyst is very efficient for elimination of odor and that the emissions measured with FID don’t correlate with the results from odor tests. Some test results from FID show high emissions but still with very low odor intensity. This depends on that some VOC compounds, like methane, is detected by the FID but do not have a very high odor threshold (almost “odorless”). This was especially observed during evaluation tests with DEO-100 unit. The odor results from test with MRO-500 unit will be presented together with the results from the DEO-100 unit, see the next section 3.7.

3.7 Results DEO-100

The DEO-100 unit has been evaluated on two different sites for about 1000 hr at each site and on two other additional sites for short period. The measured H_2S values differ very much between the sites but the perception, and results from the odor panel, shows that it is very difficult to distinguish between the actual measured values of H_2S as a correlation to strong or very strong odor.

One part of the results from the odor test is presented as the odor intensity, without any reference to the odor character (fruit, chemical, spicy, sewage, etc.). The other part of the results describes how the odor is characterized before and after the used abatement unit. Both type of results are interesting and demonstrate that the results from the odor panel probably describes the performance better than only analyzed results from “conventional” used devices (FID, portable gas analyzers).

3.7.1 Results odor intensity

The odor intensity results, from all test sites, are presented in Table 2. It is interesting to observe the difference in experienced odor intensity between the two sites with high concentration of H_2S (site 1 and 2) with sites with rather low concentration of H_2S (site 3,4 and 6). The experienced intensity is almost the same for all sites. There are obviously a number of other compounds that affects the odor intensity which not are analyzed even if H_2S is one common compound often referred to in different studies.

Table 2. Results from odor intensity test on sex different test sites. The test is performed by an odor panel as a "blind-test" on three different uNmarked gas-bags containing untreated gas (IN), treated gas (OUT) and reference gas (REF, office air).

	Odor Intensity Test location	**Operation Temp (°C)**	**H2S IN (ppm)**	**In Intensity**	**Out Intensity**	**Ref (air)**
1	Kalmar, sludge tank, Biogas (DEO)	300	>200	4,3	3,1	1,4
2	NSR sludge tank, Biogas (DEO)	400	≈ 100-200	3,8	1,4	1,1
3	NSVA , pumpstation wastewater, (DEO)	350	≈ 2	3,9	1,6	1,7
4	Lunds Energi, Upgrading of Biogas (MRO)	>600	≈ 2	3,2	1,3	1,5
5	Dafgårds, Food industry, (MRO)	500	NA	2,6	1,5	1,5
6	NSVA, sludge press, (DEO)	350	≈ 8	3,9	1,4	1,5

A conclusion from the field tests is that the operation temperature for efficient odor removal has to be about 350 °C, especially for high concentrations of H_2S (which probably also correlates to high concentration of similar compounds). An example of this can be observed comparing the results between test site 1 (operation temperature 300 ° C) and test site 2 (operation temperature 400 °C). Both test sites are very similar applications. The test at site 1 was stopped before the operation temperature was increased further due to practical reasons (heavy snow storm stopped the tests).

The variation between each individual person in the odor panel shows how the odor intensity is perceived. There is a large individual difference which shows how important it is to have a reasonable large number of "certified" persons in the panel and that the tests are performed according to the suggested standards. The individual results regarding observed odor intensity from 3 different test sites, are presented Appendix 1.

3.7.2 Results odor characterization

All persons involved in the different odor panels had difficult to characterize the odor. The individual results from test sites 1,2 and 3 are presented in appendix 2. One general observation is that there is a shift in the character from sewage&fishy smell to chemical/earth/medicinal smell as the sulfur containing compounds is oxidized to sulfur-oxides (SO_x), which in high concentration is perceived as "acidic".

3.7.3 Results lifetime tests

The DEO-100 unit has been operated for more than 1000 hours at two different sites. The variation of in and outlet concentration of H_2S was analyzed frequently during about the first 600 hours operation at NSR Biogas production plant. The variation of inlet concentration of H_2S is presented in fig 20. The concentration could vary between several hundred ppms during a day, all depending on type of waste material that was pumped into the sludge tank. The average concentration during the first 600 hours of operation is slightly above 100 ppm of H_2S. No regular analysis were performed after 600 h of test until the unit was stopped (after more than 1100 h).

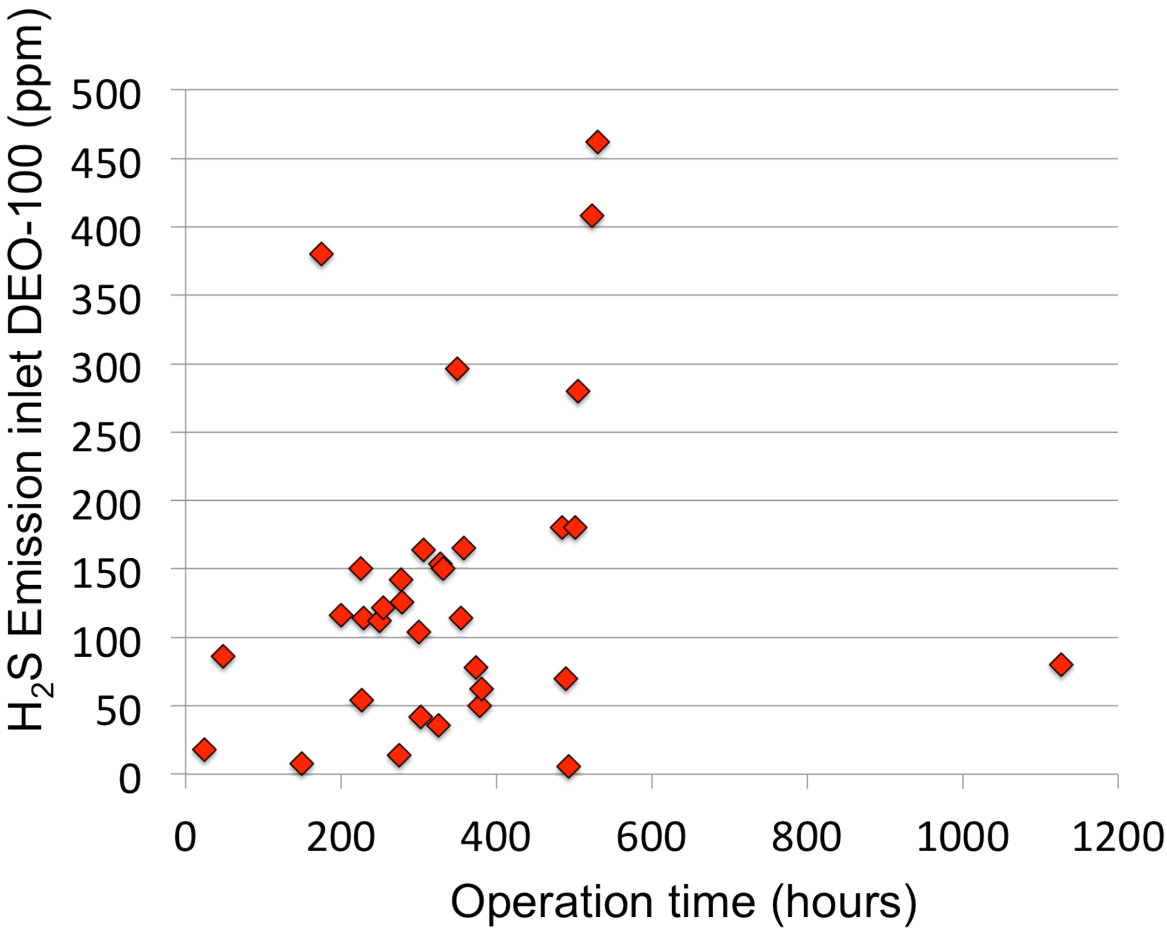

Figure 20. Variation of emission level of H_2S (inlet values) during operation of DEO-100 unit at site 2 (NSR Biogas plant Helsingborg).

The conversion of H_2S varied from time to time. The outlet emissions were sometimes rather high (> 10 ppm of H_2S) but without any observed odor! This indicates that some other compounds in the emissions sometimes interfere with the used analyzer (Multitec 540, Sewerin). The H_2S detector is based on infrared sensor technology and the supplier confirmed that SO_x interfere to some extent with the detector. The interference was not consistence over time and not investigated in detail. The best evidence for satisfactory deodorization is that the experienced odor was very low each time analyzes were performed. The variation of the conversion degree of H_2S is presented in fig 21. The analyzed in and out-let emissions for each presented conversion degree is presented in fig 22.

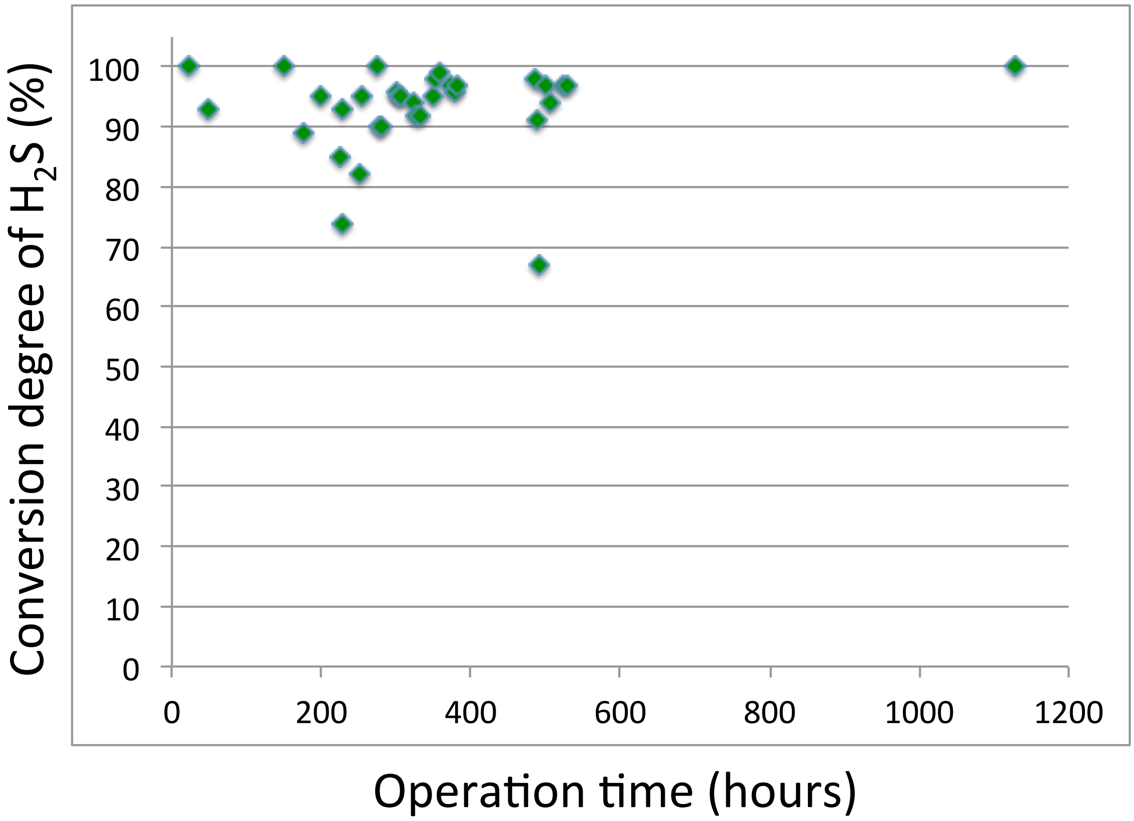

Figure 21. Variation of conversion degree of H_2S during operation of DEO-100 unit at site 2 (NSR Biogas plant, Helsingborg).

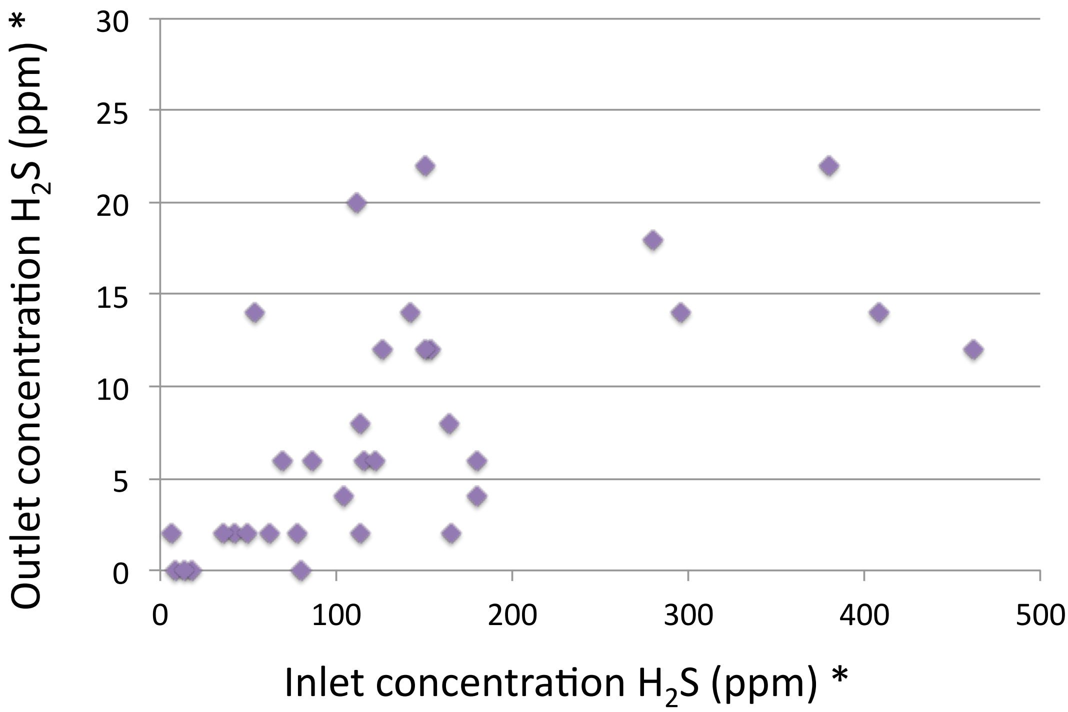

*Figure 22. Variation of inlet and outlet values of H_2S during operation of DEO-100 unit at site 2 (NSR Biogas plant, Helsingborg). * No odor is detected at outlet even if the analyzed out let emissions of H_2S is high. This indicate interference of other compounds for the analyze device.*

3.8 Discussion

The deodorization catalyst has been used for about 15 years in different deodorization applications, mainly in Japan. The catalyst has also successfully been used for selective combustion of ammonia within semiconductor and blue laser production plants. The increasing market for biogas production also increases the need for efficient odor treatment, especially since most urban areas are growing and moving closer to the biogas production plants.

The produced biogas (methane) is in most cases upgraded to fuel quality and some slip of methane is emitted. The awareness of the green house gases on the enviroNment forces the goverNments to restrict the emissions more and more. Catalytic combustion of methane, and other types of greenhouse gases like laughing gas (N_2O) is one suitable solution to reduce the emissions of methane.

The results from the project demonstrate that the observed problems with simultaneous odor and methane emissions can be solved efficiently in one abatement unit by combining two different catalysts.

Visiting different test sites revealed the importance of optimizing both the diffuse sources of emission, as well as the ventilation system for the concentrated odor. Optimizing results in decreased running costs.

One open question regarding the lifetime of a system is how the corrosive gases effect the equipment. The present tests were performed during 1000 hours without any observed problems. The lifetime of the equipment is expected to be more than 50.000 hours with a catalyst life time of about 20.000 h. Proper choice of construction material for the equipment is vital for the life time since the unit is handling corrosive gases.

4. Market survey and application fields

There are a number of different available technologies to reduce the emissions of climate gases and odors. The most common used ones include different oxidation technologies like the use of thermal and catalytic oxidation, UV radiation and addition of ozone. There are also a number of scrubbers and adsorption technologies including activated carbon, zeolitic or porous polymeric adsorption material as well as biological processes (bio-filter). The number of available technologies is large and it is not easy to choose among them since most of them have both advantages and disadvantages. The applications also vary a lot and a number of parameters influence the choice of equipment. Some of the parameters that should be considered are:

- Volumetric gas flow (Nm^3/h)
- Gas composition (type of compounds, energy content, particles, sticky compounds, acidity, humidity, poisons (catalyst), temperature, etc.)
- Availability (plant size, ground conditions, accessibility for maintenance, proximity to residents, etc.)
- Internal personal resources (control and maintenance)
- Financial aspects (investment and running costs)

One of the most important parameters to optimize is the volumetric gas flow and thus the energy content in the gas. The investment and running cost very much depends on these two parameters. A low gas flow in combination with a high energy content generally results in low investment and running costs. There are certain limits (legislation) regarding the maximum energy content in the gas that must be observed and not all available technologies can be operated with high concentration of emissions. The overall conclusion is that there is no obvious choice of emission technology that is superior to all different available applications. One publication, where different odor control technologies are compared, with respect to effectiveness and cost [8], conclude that all 5 compared technologies (wet scrubber, biofilter, engineered media, granulated activated carbon, and catalytic/regenerative carbon) have applications in which they have inherent advantages and cost benefits.

It's difficult to obtain and compare investment and running costs for different available technologies since each specific application also includes additional supplies and/or custom specific demands. We have compared a number of different available technologies, presented in table 3, on a number of specific parameters such as their overall performance, capital expenses (CAPEX) and operation expenses (OPEX), etc. There are not so many available technologies that can combine efficient destruction of both greenhouse gases and odor. Catalytic and thermal oxidation is the most efficient and commonly used technologies if both types of emissions shall be eliminated in same equipment.

The market in the following comparison, Table 3, is defined as climate gases being Methane (CH_4), Nitrous oxide (N_2O) and odor from wastewater treatment plants and sewage pumping stations. The flow to be treated is < 5 000 Nm3/h.

Table 3. Relative comparison of the overall performance and the ability to eliminate greenhouse gases and odors. Green top, yellow in between, and red worst rankings. White field (0) represents no data found. CAPEX – Capital Expenses. OPEX – Operation Expenses

Technology	CAPEX	OPEX	Installation	Footprint volume	Stable operation	Emission Odor	Emission CH_4	Emission H_2S	Emission N_2O	References
Catalytic oxidation	Yellow	Yellow	Green	Green	Yellow	Green	Green	Green	Green	White
Water-scrubber	Red	Yellow	Red	Red	Green	White	Yellow	Red	Red	Yellow
Carbon filter	Yellow	Red	Red	Red	Green	White	Yellow	Red	Red	Yellow
Chemical perfume	Green	Red	Green	Green	Red	White	Red	Yellow	Red	Red
Ionization	Green	Green	Green	Green	Yellow	Red	Red	White	White	Red
Combustion	Yellow	Red	Red	Green	Green	Yellow	Green	Red	Green	Red
Ozone	Yellow	Yellow	Red	Yellow	Green	Yellow	Green	Green	Green	Yellow
UV	Red	Green	Yellow	Green	Yellow	Red	Yellow	Red	Red	Red
Bio-scrubber	Red	Red	Red	Red	Yellow	Red	Green	Red	Red	Yellow
Bio-filter	Yellow	Yellow	Yellow	Red	Red	Red	Green	Red	Red	Yellow
Chemical-scrubber	Yellow	Red	Red	Green	Green	Red	Yellow	Red	White	Red

The total number of installations to reduce odor is very high. Installations can be found in wastewater treatment plants, composting plants, biogas plants, solid waste processing, food industry, chemical industry, pulp and paper, kitchen in restaurants etc. These installation range from very large volumes of air to be treated, several 10 000 m3/h, to low flows < 100 Nm3/h. It ranges from highly concentrated streams to very dilute emissions.

Installations to reduce climate gas emission are fewer but expected to increase as regulations will become harder and suitable techniques are made available. The exact number of installations today cannot easily be calculated because statistics do not exist, suppliers reference list is often not reliable and hard do obtain. Odor control is often part of a contractor's scope of supply and therefore difficult to separate from the total contract. Furthermore, one site, one industry, can have several installations with different technologies for odor control in different part of their process and odor control techniques combined in series to be able to address the problem. In Sweden it is safe to predict the number of installations to be several hundred. Even harder is to estimate the annual sales to address odor and climate gas emissions. Based on the number of installation, turn over of specialized companies and interviews the sale per year is estimated to be in the region of 100 – 200 million SEK annually in Sweden alone.

5. Conclusions

- There exist a large, and growing, interesting market potential for deodorization technologies
- DEO systems are suitable for small-scale deodorization and VOC-abatement
- MRO systems are suitable for medium scale VOC-abatement and for simultaneous combustion of greenhouse gases and odor
- The conversion efficiency and thermal efficiency depends on customer's demands in combination with acceptable investment and running costs (depends on amount of catalyst and system design).
- The running costs are mainly determined by the VOC concentration. Important to optimize the VOC concentration as much as possible!
- Major issues (yet to be found…) like corrosive environment, demanding conditions (transients?) must be proven during a number of full-scale installations and during several years of operation.

6. Acknowledgements

There have been a large number of persons involved in the project that all contributed in different ways and made it possible to perform the evaluations tests.

Lars Gunnarsson, Conpura AB, is author of chapter 4, regarding the market survey and field of applications.

The process engineers at NSR Biogas plant who kindly performed daily analysis during more than 600 hours.

Marinette Hagman and Peter Ågren at NSVA that made it possible to perform evaluations tests at different sites within Landskrona.

Magnus Dalemo at Absolent that made it possible for us to evaluate the MRO-500 unit at a food production plant for deodorization purpose.

Daniel Ling and Olof Petterson for all help with the tests at FAMAX Biogas production plant in Kalmar (bad luck that we were hit by a snow storm!)

Johan Olsson and Jonas Olsson at Lunds Energi who supported us with the installation at Källby upgrade process for biogas.

7. Literature

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Appendix 1. Individual results from odor strength test at different test sites.

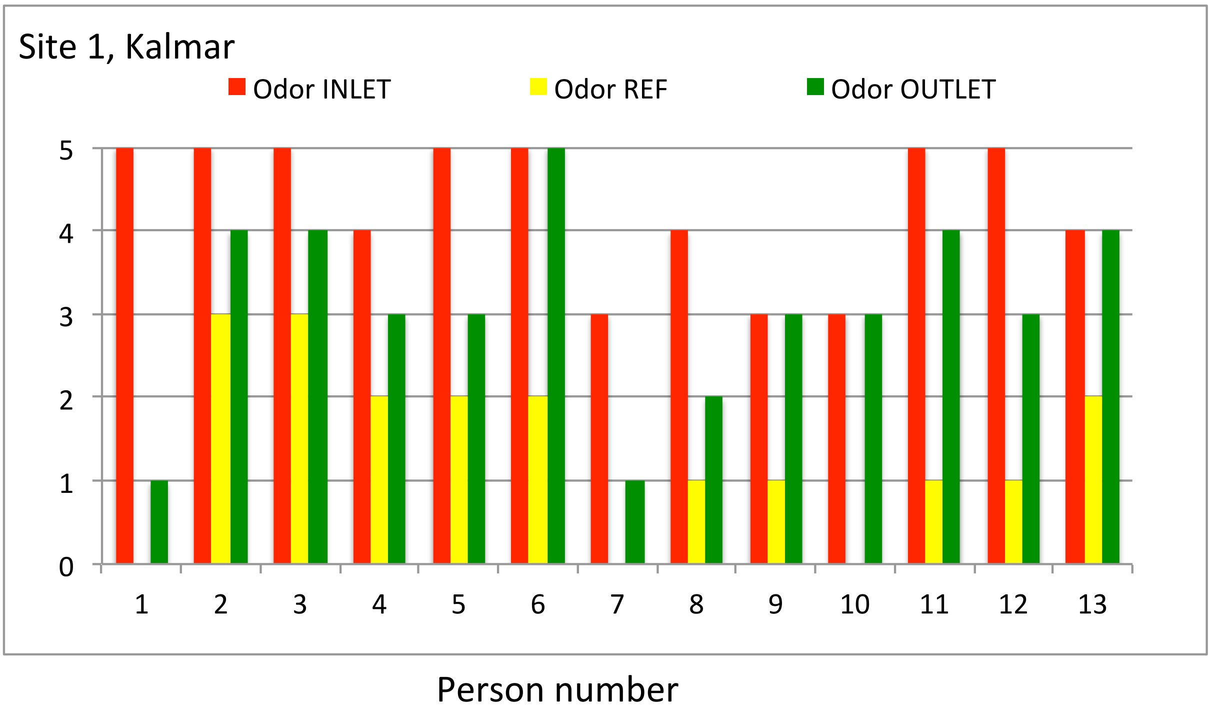


Figure 1. Individual results regarding odor intensity at site 1 (FAMAX Biogas plant)

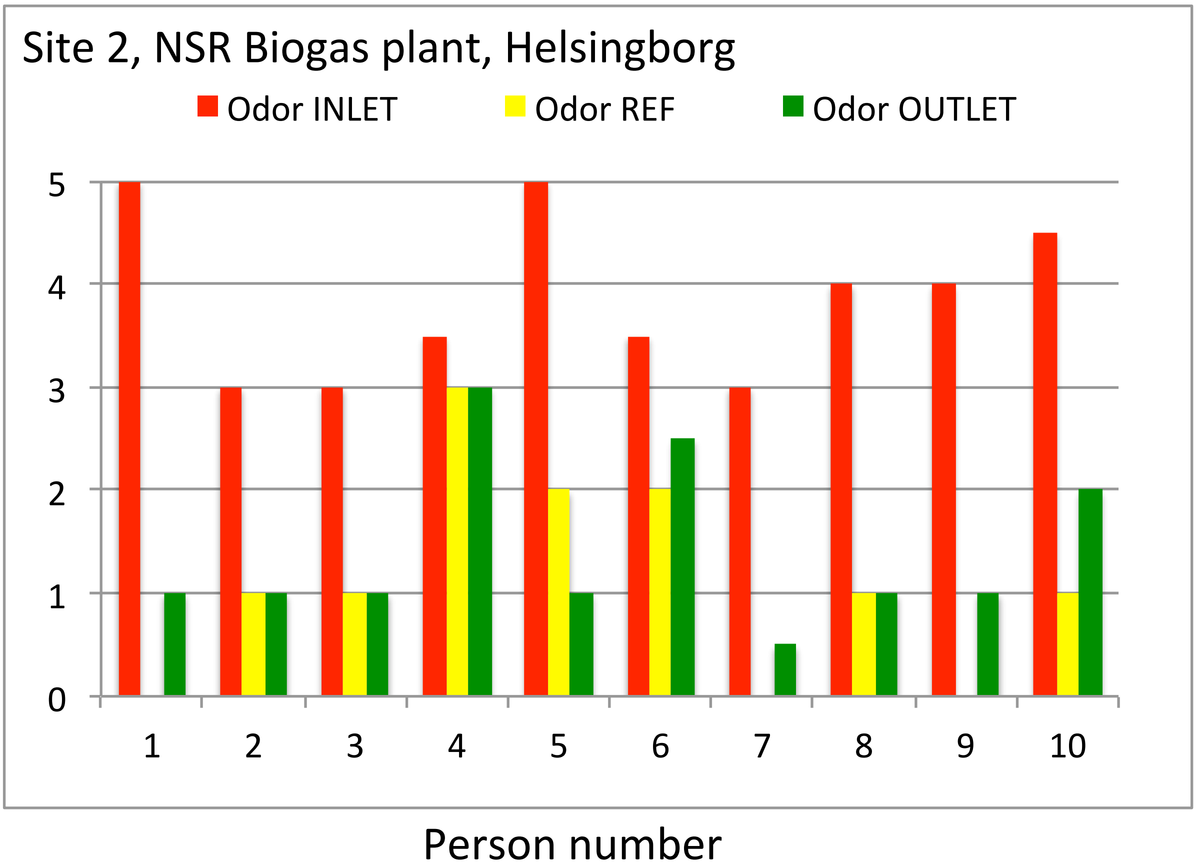


Figure 2. Individual results regarding odor intensity at site 2 (NSR Biogas plant)

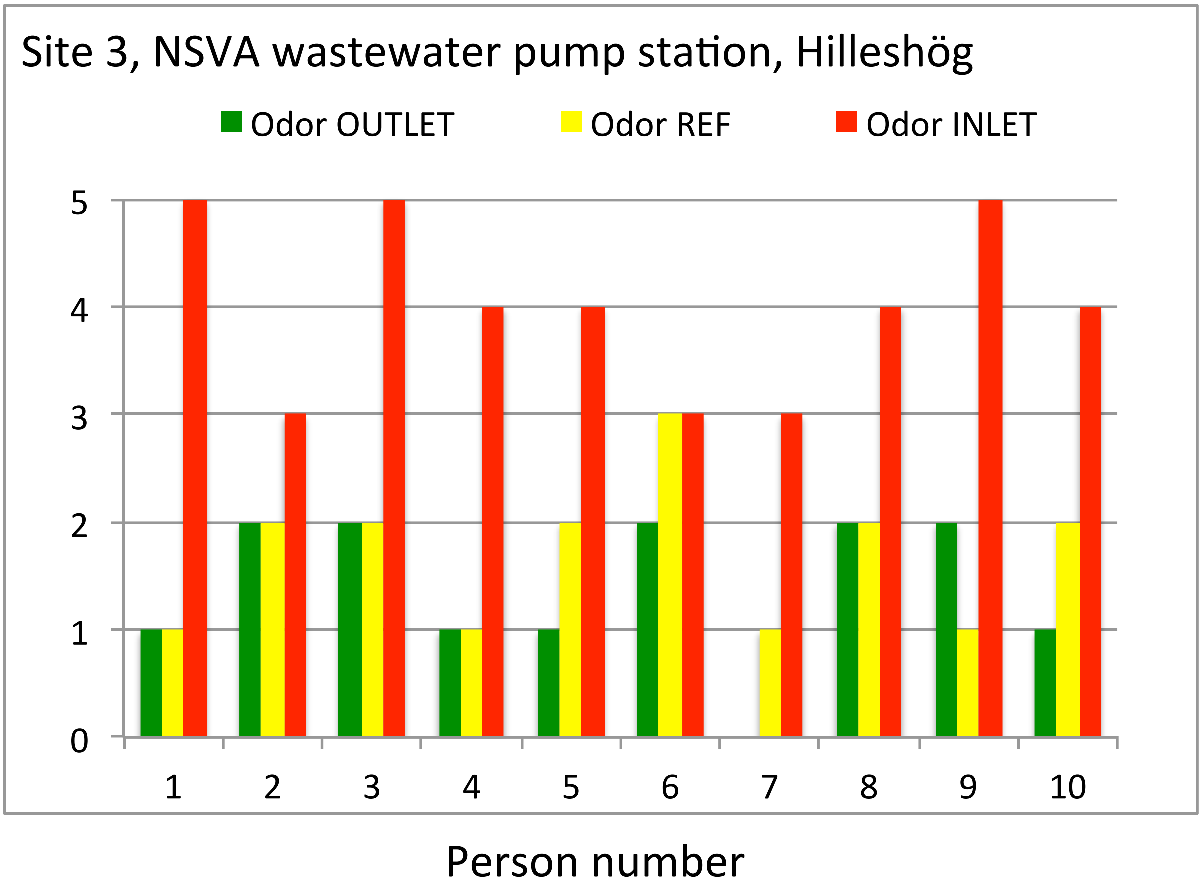
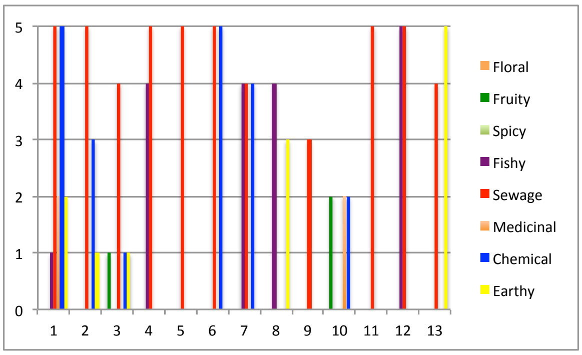
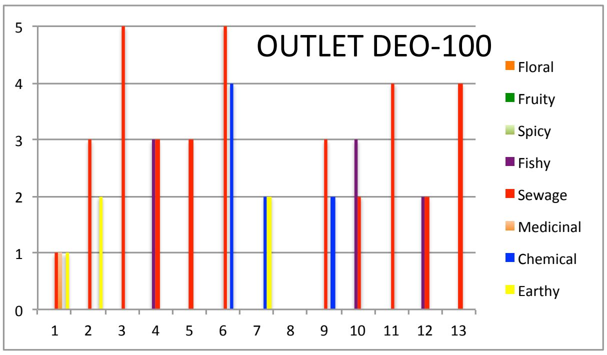


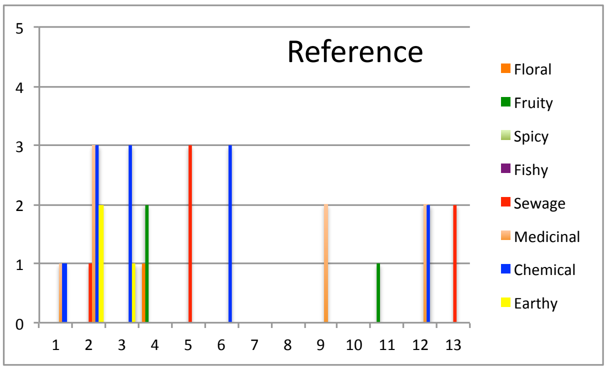
Figure 3. Individual results regarding odor intensity at site 3 (NSVA wastewater pump station, Hilleshög)

Appendix 2. Individual results from odor characterization test at different test sites.



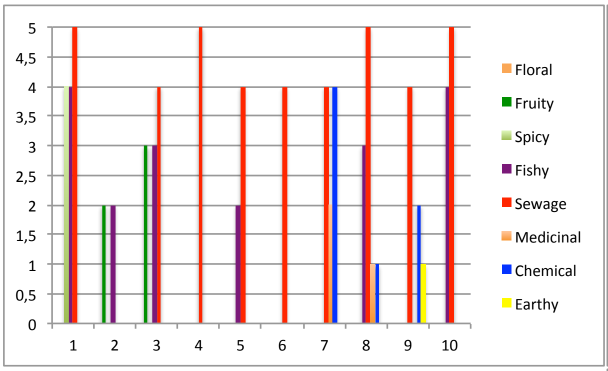
INLET DEO-100



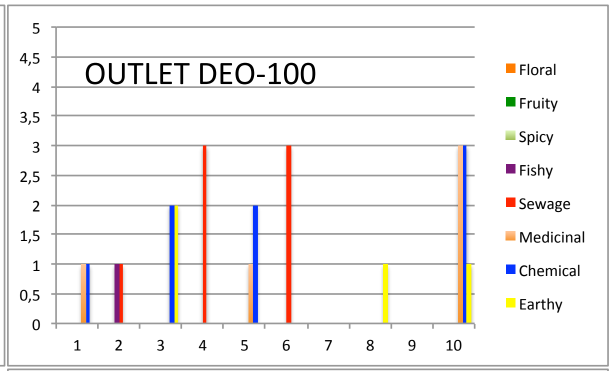


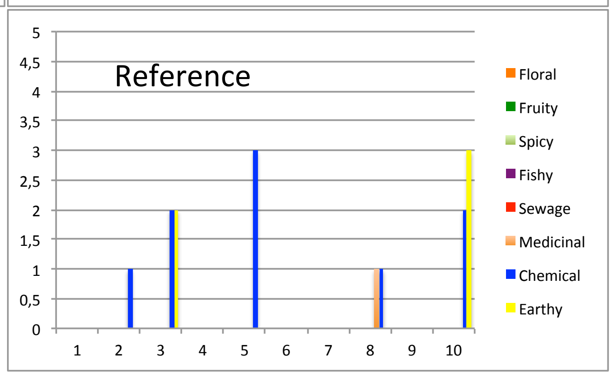
Site 1
Results odor characterization
FAMAX, Bio-gas plant, Kalmar
(13 persons)

Figure 1. Individual results regarding odor characterization at site 1 (FAMAX Bio-gas plant)



INLET DEO-100





Site 2
Results odor characterization
NSR, Bio-gas plant, Helsingborg
(10 persons)

Figure 2. Individual results regarding odor characterization at site 2 (NSR Biogas plant)

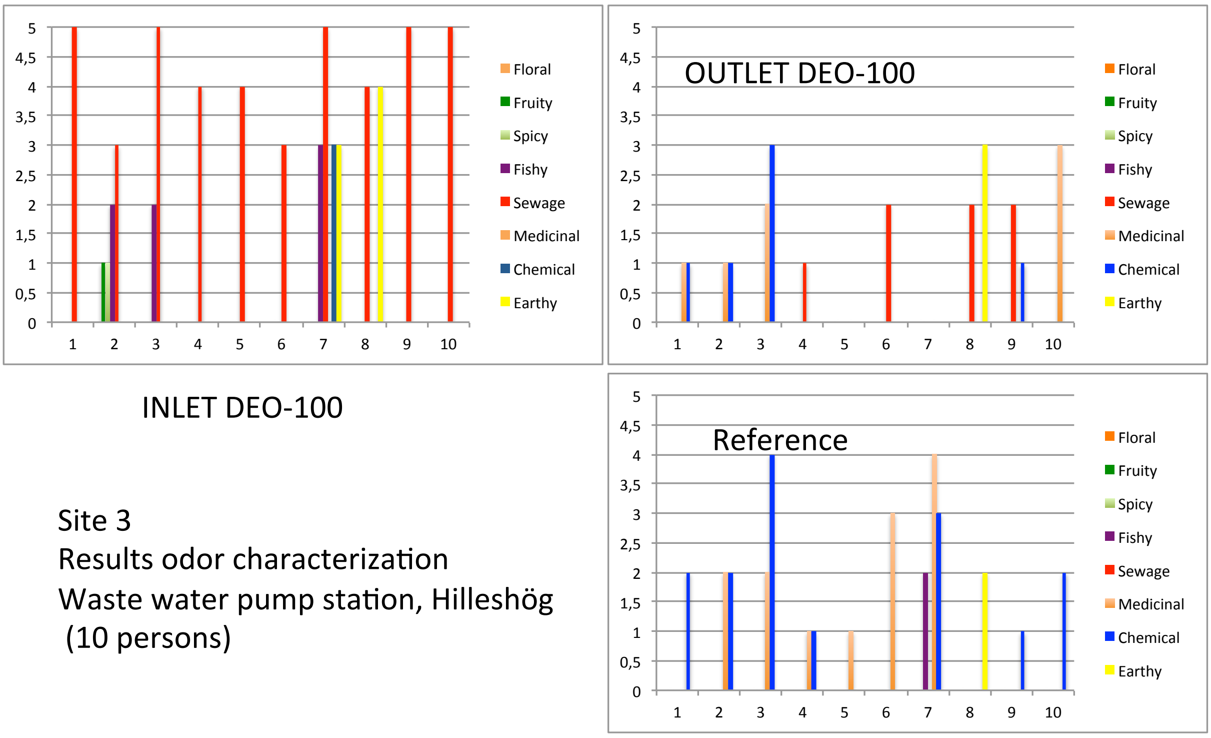


Figure 3. Individual results regarding odor characterization at site 3 (NSVA waste water pump station)