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Oppdragsgiver:

Gjesdal Gard

Forfattere:

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Sammendrag

A large share of greenhouse gas emissions in agriculture in Norway is due to methane emissions resulting from the digestion process of animals. This project evaluates possibilities for methane capture and used in dairy farms and for meat production and benchmarks technologies.

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Summary

About 50% of the climate gas emissions from farming are methane emissions from the digestion process of cattle and other animals. These emissions might be reduced while animals are in the stables by capturing and/or converting the methane content in ventilation air. The project defined typical boundary conditions for a barn, using the Gjesdal farm as an example (e.g. ventilation flow, methane, heat, and CO_2 emission per animal) and supported by literature. Selection criteria including weight factors were defined by the involved users by describing aspects of the technology, including attributes that described the complexity and operational issues of the different technologies.

Different technologies that minimized the emission either by concentrating, converting or separating the methane were identified by a literature review. The technologies were evaluated and benchmarked based on literature sources and high-level estimations. The basic findings are:

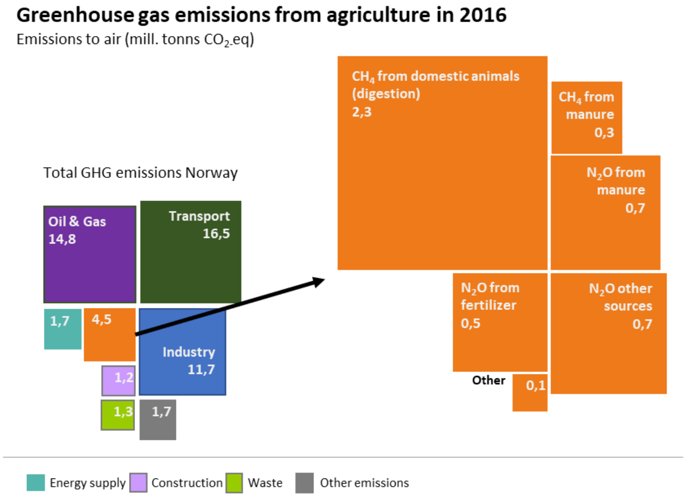
- Methane concentration in the ventilation air of stables is between 250 – 500 times lower than in other areas where technologies for methane capture have been used (e.g. mining ventilation). Large and complex installations, with some of them consuming a lot of energy, would be necessary to increase the concentration to a level which allows the use of existing technologies for methane conversion or utilisation.
- None of the technologies alone is well suited for being the only method applied in a barn given required dimensions, complexity of the technology, readiness of technology and / or investment costs.
- Some technologies have low technical readiness level; i.e. are in the status of early research and development, and will require a lot of effort to develop to a practical, usable technology for a barn, (e.g. absorption filters, Zeolites). It is difficult to estimate if and when they would be at the market.

However, if the technologies are combined with other ongoing activities, needs and requirements in the operation of a farm, some technologies might be more promising. One identified possibility is a combination of gravitation, using a high roof, and the guiding of the ventilation air to a local CHP and/or a biofilter, possibly in conjunction with biogas, might be a possible integrated systems approach. Such an integrated concept needs to be further evaluated in more depth. Measurements of gas composition should be a part of such a follow up project since detailed information on gas composition in the ventilation air of barns is missing.

Table of content

1. Introduction

A large share of greenhouse gas emissions in agriculture in Norway is due to methane emissions resulting from the digestion process of animals (Figure 1). It is therefore natural to evaluate possibilities for reducing these emissions. While activists want to reduce the number of livestock (i.e. reduction of meat consumption) several projects within agriculture targets the reduction via feed and feed composition for the animals (refs). Little attention is paid to possibilities and technologies for capturing the generated methane and its utilisation.



Source: Modified from Norwegian Environment Agency

Figure 1: Greenhouse gas emissions from agriculture

The aim of this project is to evaluate possibilities for methane capture and use in dairy farms and for farms for meat production. Gjesdal Gard (dairy) was used as case farm in combination with operational data representing modern state of the art agricultural activities.

2. Boundary conditions

To identify possible technologies to reduce methane emissions one need quantitative numbers of methane concentration in the air exiting a barn. The following paragraphs describes the selected boundary conditions used in the project to assess the different technologies and how the used criteria and referred values have been selected and calculated.

2.1. Livestock and operational issues

The boundary conditions used to evaluate various parameter influencing the operation of a ventilation system in a barn are listed in Table 1.

Table 1: Selected boundary conditions for the evaluation

Parameter	Value	Comment
Air flowrate	$42\,000\ m^3/hr$	Max. value of the ventilation system at Gjesdal gard. Eval. for 100%, 75% and 50% operation
Heat released per cow	$1{,}5\ kW/cow$	Maximum value from "Landwirtschaftskammer Niederösterreich"[1]
Methane emission per cow	$0{,}5\ kg/day$	Maximum value based on internet search, e.g. from[2]
Carbon dioxide emission	$9{,}78\ kg/day$	Based on the methane emission and result of measurements available in literature[3]
No. cows	50	Assuming 30 adult cows and 60 calves which account for 1/3 of an adult.
Ammonia concentration	$20\ ppm\ (volume)$	Maximum allowed concentration[4]
Air pressure	$1{,}0135\ bar$	ISO condition
Air temperature	$288{,}15\ K$	ISO condition
Relative Humidity	60 %	ISO condition
Other	Gases were assumed as being perfect gas; densities as function of temperature and specific heat capacities were approximated via 3rd grade polynomials where necessary covering the range from 250 K to 460 K. Examples for CH_4 are specific heat capacity and density: $cpCH4 := \left(-1{,}8585\cdot10^{-8}\cdot\left(\frac{Tref}{K}\right)^3 + 2{,}5443\cdot10^{-5}\cdot\left(\frac{Tref}{K}\right)^2 - 7{,}9527\cdot10^{-3}\cdot\frac{Tref}{K} + 2{,}8337\right)\frac{kJ}{kg\,K}$ $RhoCH4 := \left(-1{,}3750\cdot10^{-8}\cdot\left(\frac{Tref}{K}\right)^3 + 1{,}937\cdot10^{-5}\cdot\left(\frac{Tref}{K}\right)^2 - 1{,}0111\cdot10^{-2}\cdot\frac{Tref}{K} + 2{,}3146\right)\frac{kg}{m^3}$	

In most cases maximum values were used i.e. the heat generation produced per cow as well as methane and CO_2 emissions per cow. The motivation is that the max. values require the highest

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[1] Value from https://noe.lko.at/hitzestress-im-milchviehstall+2500+2464412 , accesses on 10.02.2020

[2] https://www.deutschlandfunk.de/rinderzucht-die-klimaschraube-im-magen-der-milchkuh.676.de.html?dram:article_id=453028

[3] N.M. Ngwabie e.a.: *Measurement of emission factors form a naturally ventilated commercial barn for dairy cows in a cold climate;* Biosystems Engineering 127 (2014) 103-114

[4] *Anonym, 2018. Indretning af stalde til kvæg – Danske anbefalinger. 5. rev. udgave. SEGES 184 pp.;*

ventilation rate. The high ventilation rate results in a worst case scenario for capture where large volume flows need to be handled, which in turn impact dimension of capture components.

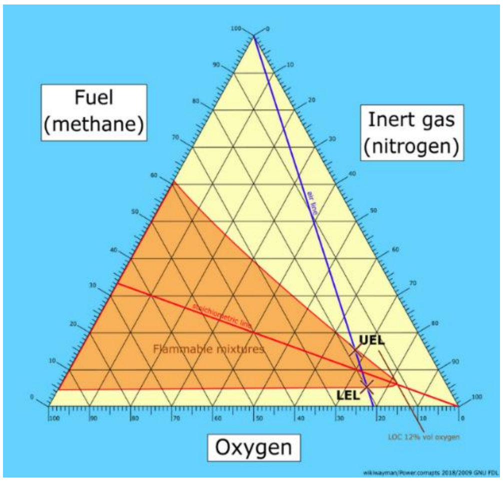
2.2. Estimations of emissions for various operating conditions

To evaluate the possible concentration levels of methane and carbon dioxide in the exit air of the barn and to evaluate possible temperature increase due to heat generated by the animals, three ventilation rates were used. Concentrations of the gases were estimated based on mass and volume. For climate gas concentration the volume-based values are commonly used while in energy estimations mass-based values are standard.

Table 2: Estimated concentration of gases in the exit air of a barn ventilation system

Parameter	**100%**	**75%**	**50%**
Methane (ppm volume based)	36,55	48,74	73,11
Methane (ppm mass based)	20,25	27,00	40,49
Methane all adult (ppm volume based)	*65,80*	*87,73*	*131,59*
Methane all adult (ppm mass based)	*36,45*	*48,59*	*72,89*
Carbon dioxide (ppm volume based)	658,8	745,1	917,5
Carbon dioxide (ppm mass based)	1007,6	1139,5	1403,2
Carbon dioxide all adult (ppm volume based)	*865,8*	*1020,9*	*1330,9*
Carbon dioxide all adult (ppm mass based)	*1325,1*	*1564,4*	*2034,5*
Ammonia (ppm volume based)	20	20	20
Ammonia (ppm mass based)	11,92	11,92	11,92

The maximum concentration of carbon dioxide (CO_2) in a barn to be below 3000 ppm with respect to the health of the animals, but it is recommended to keep it below 1000 ppm according to 4. Table 2 gives an estimation of concentration of gasses with 3 levels of ventilations. These values indicate that 50% of defined ventilation can be enough, estimated to 917,5 vol. ppm CO_2. Grown up calves, will have a higher CO_2 emission than calves (number in italic in Table 2). This needs to be considered as the CO_2 concentration is one of the parameters defining the ventilation rates in the barn.



wikiwayman/Power.corrupts 2018/2009 GNU FDL

Figure 2: Ignition limits for methane

The limit concentration for ammonia is given with 20 ppm as indicated above. There is no limit for methane set. However, given the limits for ignitable mixtures of air and methane (Figure 2) methane needs to be well below the lower limit of 4,4% (volume, source [5]). However, this value is more than 500 times larger than the estimated concentration of methane in the barn.

Another parameter influencing the ventilation rate in a barn is the air temperature and its increase due to the heat generated by the cows. In Table 1, a heat release of 1,5 kW per cow was selected as it seems to represent an upper value for heat release from cows. Temperature increase for a mix of cows and calves and for the worst case that all calves are grown up is summarized in Table 3 below.

Table 3: Correlation between temperature increase and % ventilation rate.

Parameter	**100%**	**75%**	**50%**
A) Temperature increase [K]	5,2	7,0	10,5
B) Temperature increase all adult [K]	9,4	12,6	18,8

Calculations are based on 1,5 kW heat release per cow, A) represents a mix of cows and calves and B) that all the calves are grown up, respectively.

Figure 3 indicates a mild stress condition on the animals when air temperature exceeds about 22 °C at 100 % humidity. When all calves are grown up a high level of ventilation might be required. The high ventilation rate will in turn reduce CH_4 and CO_2 concentration. However, this will depend on the season and the typical cycles of birth and growing of the calves.

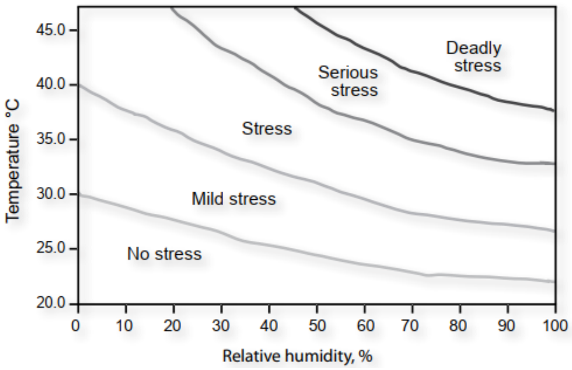


Figure 3: Heat stress for cows as function of temperature and humidity (4)

3. Existing technologies

There are two basic approaches to make use of the methane:

- Source of energy for e.g. power production
- Source for other products which might indirectly result in power generation or other production paths.

The energy content in methane is independent from the ventilation rate but will depend on the number of adult cows. The average power content in the methane is estimated of about 14,5 kW for the assumed mix of adult and calves, see Table 1 and about 26,0 kW when all are adult.

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[5] Source: https://www.engineeringtoolbox.com/explosive-concentration-limits-d_423.html

In addition to methane, ammonia contains energy. The ammonia concentration depends on the manure handling process in the stable and on a variety of parameters which cannot be evaluated within this study. Therefore, the max allowable concentration of 20 ppm is assumed for all flow rates of the ventilation system. These assumptions and a lower heating value of 18.8 MJ/kg lead to estimated 3,2 kW (at 100% vent.), 2,4 kW (at 75% vent.) and 1,6 kW (at 50% vent.). The energy content of methane is therefore at least about the factor of 8 higher than that of ammonia.

3.1. Increasing Methane Concentration / Separation

As per Table 2, the concentration of methane 0,0037 vol. % - 0,0073 vol. % in the exit air of the barn is more than two magnitudes lower than an ignitable mixture and concentrations which still are considered as being on the safe side towards any ignition. For comparison 3,5% methane concentrations in the ventilation air of coal mines is considered as being safe. The literature review indicated that available technologies for use and utilization of methane are often based on higher concentrations than those found in a barn. Evaluation of possibilities to increase the methane concentration in the barn would therefore be useful.

3.1.1. Natural gravity effects

A quick evaluation shows that the molecular weight of methane is lower that the molecular weight of other components of air (CH4: $16{,}04\ {}^{g}/_{mol}$, N2: $28{,}01\ {}^{g}/_{mol}$, O2: $32{,}00\ {}^{g}/_{mol}$, CO2: $44{,}01\ {}^{g}/_{mol}$). Therefore, the idea was that natural separation effects might occur resulting in an increased concentration of methane under the roof of the barn. However, it was suspected that with the high continuous ventilation in the barn the differences in molecular weight might not be great enough to overcome the mixing due to natural convection, diffusion ([6]), and

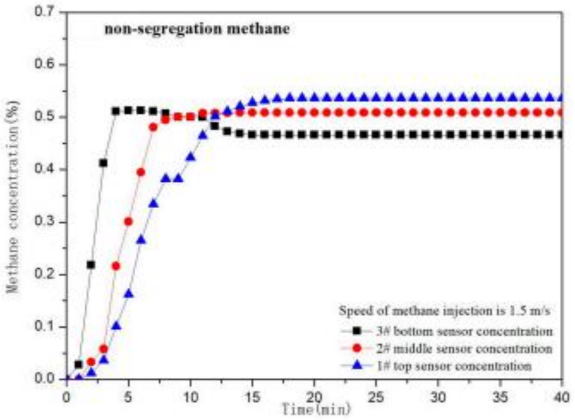

Figure 5: Test result of reference 7

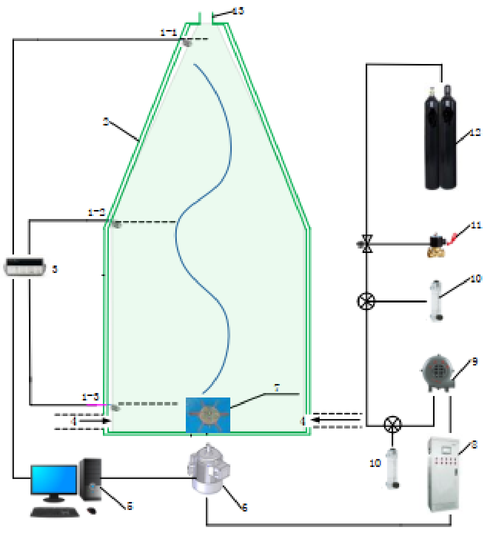

Figure 4: Test setup used in reference 7

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[6] T.R. Marrero, E.A. Mason: *Gaseous Diffusion Coefficients*, Journal of Physical and Chemical Reference Data, Vol 1, No 1, 1972

intermolecular collisions. This was confirmed by a reference which was experimentally evaluating the increase of methane concentration[7]. The tests performed in this study indicated that the concentration of methane at the top of the test unit (setup see Figure 4) was only about 10% higher compared to the bottom. This difference was stable after about 15 minutes without any turbulence generation inside the test unit. Due to turbulences being continuously generated in a barn (ventilation, movement of the animals etc.) this approach is not expected to result in a practical increase of the methane concentration. This assumption is aligned with the conclusion of the authors which state "Consequently, industrial applications of methane enrichment from buoyant forces are not feasible for low concentrations of methane".

3.1.2. Vortex tube

"A vortex tube is a simple mechanical device with no moving parts. A compressed fluid tangentially enters the tube via nozzles that are located at the periphery of the tube. The fluid is isentropically expanded through the nozzle, resulting in very high velocities and lower pressures. Vortices are generated such that the azimuthal velocity of the fluid far surpasses its axial velocity. The centrifugal force causes most of the fluid to flow very close to the periphery of the tube."[8] While early work with vortex technology focussed on the separation of gasses of different temperatures and using the difference in density of warm and cold molecules (Figure 6). Later work [8] evaluated the separation of gases using vortex tubes to increase methane concentration in air. Tests were performed at different pressures and the results indicated a possible increase of the concentration. The concentration was increased by about 80% (and more) at an inlet pressure into the vortex tube of 1,655 bar. To achieve such a result, it is necessary to increase the pressure of the ventilation air to 1,655 bar. This example applies to a vortex tube with two turns. Increasing the number of turns as well as the inlet pressure results in some further increase in concentration, but it needs to be questioned if the achieved improvement is worth the additional investment.

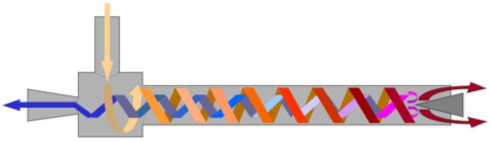

Figure 6: Schematics of a Vortex Tube (red warm streak, blue cold streak)

Estimating the required energy input (assuming a compressor efficiency of 85%) and the exit temperature of a compressor necessary to achieve the desired inlet pressure to the vortex tube is based on using the equation / correlations relevant for ideal gas:

$$P_{Compressor} = \dot{m}_{Air} \cdot R_{air} \cdot \left(\frac{k}{k-1}\right) \cdot T_{Inlet} \cdot \left(\left(\frac{p_{Exit}}{p_{Inlet}}\right)^{\frac{k-1}{k \cdot \eta_{Compressor}}} - 1\right) \tag{1}$$

$$\frac{T_{Exit}}{T_{Inlet}} = \left(\frac{p_{Exit}}{p_{Inlet}}\right)^{\frac{k-1}{k \cdot \eta_{Compressor}}} \tag{2}$$

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[7] W. Wang et.al.: *Experimental Enrichment of Low-Concentration Ventilation Air Methane in Free Diffusion Conditions;* Energies 2018, 11, 428; doi:10.3390/en11020428

[8] M.R. Kulkarni, C.R. Sardesai: *Enrichment of Methane Concentration via separation of Gases using Vortex Tubes;* Journal of Energy Engineering, April 2002

Where R_{air} and k are fluid properties, $\eta_{compressor}$ is the polytropic compressor efficiency p is the absolute pressure at inlet and exit of the compressor and T the temperature. $\dot{m}_{Air}$ represents the air inlet massflow into the compressor. Using this equation estimates the required power input to 747 kW (not including neither electric nor other losses). In case of lower massflow would the required power input be proportional reduced. The exit temperature of the compressor is expected to be in the range of 67°C which allow for heat recovery and use, again in the range of about 700kW.

For the case within this study it means that:

- The concentration could be increased from 36,55 ppm_V to 65,8 ppm_V (73.11 ppm_V -> 131,6 ppm_V)
- The concentration is still several magnitudes below e.g. 3.5%
- Therefore, about 11 vortex tubes would be needed in series as well as intercoolers, compressors etc. However, it needs to be noted that each additional stage (compressor, vortex tube and intercooler) would be smaller in terms of dimension as only a part of the flow enters the next stage.

In connection with a practical installation is it necessary to mention that compressors as well as the vortex tube itself is expected to operate at high noise level. This requires specific attention towards the design on silencers and enclosures / buildings around the equipment.

3.1.3. Scrubber

The technology of scrubbers to filter out various gas components and impurities is a widely used technology and are also used in connection with agricultural applications. Usually the contaminated gas is sent into a column in counterflow to a scrubbing liquid. The scrubbing liquid collects some of the contaminants. It is then sent to a regenerator where the contaminants are extracted from the scrubbing liquid, in case of captured gas often via the use of heat. The cleaned liquid is then sent back to the scrubber. While scrubbers are tested to work well for ammonia and nitrous oxides but with no positive impact on the extraction of methane[9]. The authors conclude “Methane could not be removed in any of the air scrubbers as methane is a hydrophobic component” but they see the possibility of “introducing methane oxidising bacteria in the biological air scrubber”. Downside of such an approach is, according to the authors

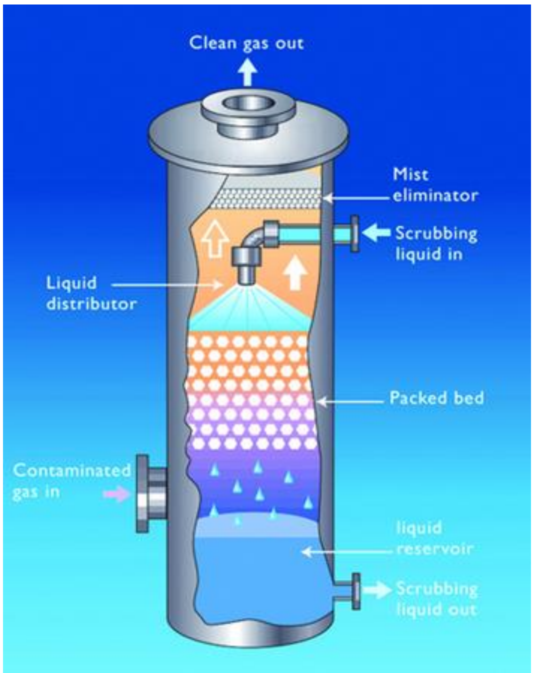

Figure 7: Schematics of a scrubber

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[9] C. Van der Heyden et.al: *Continuous measurements of ammonia, nitrous oxide and methane from air scrubbers at pig housing facilities;* Journal of Environmental Management 181 (2016) 163 - 171

to drastically increase the residence time from seconds to several minutes. This will in consequence result in significantly increased dimensions of the scrubber and therefore impact the costs. However, the technology of a similar technology, biological scrubbers/filters, biofilters will be evaluated in a different chapter of this report.

3.1.4. Cryogenic methane extraction

A cryogenic process might be used to extract methane from ventilation gas. The idea is to cool air down to a temperature at which methane condenses. The liquid methane can be then extracted for further use.

Dry air consists of 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide, and small amounts of other gases. Condensation temperatures of the main components are 77,15 K for nitrogen, 90,15 K for oxygen, 87,15 K for argon and the sublimation temperature of carbon dioxide is at 194,64 K. The one for methane is 111,15 K. Therefore, it is possible to also extract carbon dioxide during the process to achieve a temperature slightly below the condensation temperature of methane.

There are basically two possible paths to reach that temperature:

- Compression and expansion: in this process is the ventilation air compressed, cooled down to at least about 5 deg. above ambient temperature and then expended. During the expansion process is the temperature dropping following:

  $$\frac{T_{Exit}}{T_{Inlet}} = \left(\frac{p_{Exit}}{p_{Inlet}}\right)^{\frac{(k-1)\cdot\eta_{Turbine}}{k}}$$

  (3)

  with $Exit$ and $Inlet$ identifying the conditions at the inlet and outlet of the turbine for expanding the previously compressed and cooled gas. It needs to be expected that pressures of at least 50 bar need to be achieved, requiring multi-stage compressors and intercooling. Part of the energy required for compression can be recovered during the expansion process. However, a very simplified evaluation resulted in a required power input of about 6 MW at 100% ventilation. This value is of cause depending on efficiencies of compressor and turbine as well as pressure losses on coolers, tubes, valves and other components. The high power-input is a result of the large volume flow of ventilation air.

- Cooling the air down to the required temperature: this requires a series of coolers and ventilators which need to compensate for pressure losses. All components will be relatively large as they need to handle the volume flow. However, a slight reduction in the volume results from cooling. It can be expected that the cooled ventilation air has only 38% of the volume of the ventilation air flow before cooling. For cooling the ventilation air down to about 110 K to condense and extract methane need about 2,5 MW of heat to be extracted at 100% ventilation. This does not include energy to compensate for pressure losses, pump work etc.

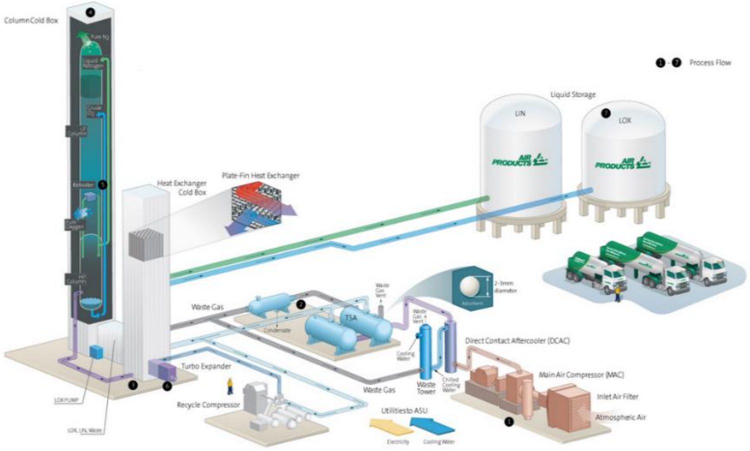

Figure 8: Example for a cryogenic air separation

In both cases, series of heat exchangers and turbo-machines including several auxiliaries are making the process relatively complex. However, cryogenic processes are standard in air separation plants, but not in small scale applications. An example sketch of a plant is shown in Figure 8[10].

3.2. Conversion and use of methane

In addition to / instead of the abovementioned technologies for increasing the concentration of methane (up to 100% methane with 3.1.4) this chapter covers the conversion/use of methane.

3.2.1. Combined Heat and Power (CHP)

Combined heat and power units are well suited to convert methane (and ammonia) into electricity and heat for local use. To utilize the energy content in a CHP are two scenarios evaluated:

- Use as fuel: This requires a significant increase of the concentration of the fuel, ideally up to 100%, or at least up to concentrations with a lower heating value equivalent to fuel with a low lower heating value (e.g. biogas). For both cases are CHP packages on the market. The lower heating value of methane was assumed with 50 $^{MJ}/_{kg}$ and of ammonia 18,8 $^{MJ}/_{kg}$. Methane concentration in exit air, see Table 2, varies with the "size" of the calves while ammonia concentration is subject to change in the ventilation massflow based on the assumptions used (see paragraph 2). Therefore, the energy content in methane varies between about 14.5 kW and 26 kW (all calves are adult/

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[10] Source & copy right: Air Products South Africa; http://airproductsafrica.co.za/wp-content/uploads/2017/04/ASU-Process-Flow.jpg

grown up) and the energy content in ammonia between 1,6 kW (50% ventilation) and 3,2 kW (100% ventilation). Capture of 100% of the fuel and a CHP with an electrical efficiency of 30% results in about 4.3 kW_{el} to 7,8 kW_{el} from methane and between 0,48 kW_{el} and 0,96 kW_{el} from ammonia. In total would be between 8,76 kW_{el} and 4,78 kW_{el} generated.

- CHP air intake uses ventilation air: In this approach is no increase of the methane concentration is necessary as the air intake of the CHP matches the ventilation air inflow. In case of using a CHP with variable speed it is possible to avoid an additional fan for ventilation. The CHP would operate in a draft mode relative to the barn, thus generating an under pressure in the barn. Given the low concentration for fuel in the ventilation / intake air it is necessary to add additional fuel. To evaluate the needed size of CHP that has a maximum air intake matching 100% ventilation, data of a known CHP was used assuming a similar efficiency and performance. Based on these assumptions it is expected that the CHP, with such an air intake, will have an output of about 2'000 kW_{el} with only 0,4% (for the best case scenario) of it covered via the methane content in the ventilation air. Therefore, a large amount of fuel from other sources needs to be added. The size of such a unit is also relatively large and a compact gas-turbine based unit is filling two 20-foot containers (Figure 8, source [11]). A CHP based on a gas turbine is used as an example as it has a significantly larger power density (e.g. 0,156 kW/kg) than for example an internal combustion engine (e.g. two stroke gas motor 0,065 kW/kg). An internal combustion engine is therefore expected to have an about 2,5 times higher weight than a gas turbine. The schematics below does not include the heat exchanger to recover the heat from the hot exhaust gas and the stack to release the exhaust gas.

Figure 9: Example of 2 MWel gas turbine based CHP

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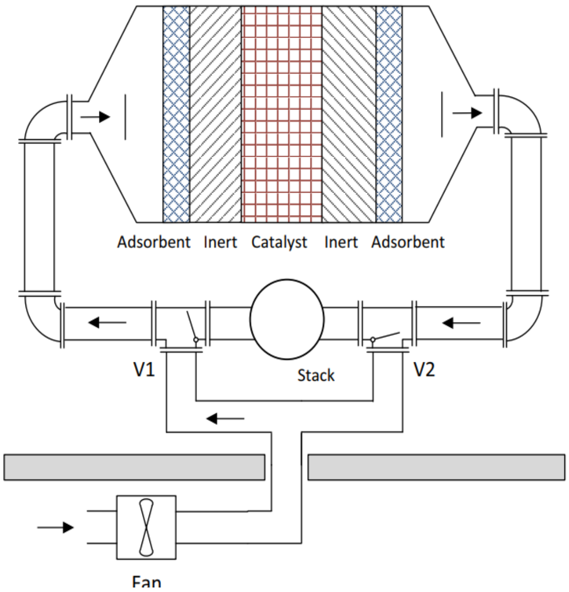
[11] Source Opra Gas Turbines at: https://www.opraturbines.com/package/

3.2.2. Catalytic reactor

Catalytic reactors convert the chemical energy in a fuel into heat at lower temperatures than a standard combustor in a boiler or gas turbine would do. An open flame does not exist as the reaction temperature is below the required min. flame temperature. The exothermal reaction is initiated in the presence of catalysts.



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Catalytic combustors are tested for ventilation air of coal mines and to convert the methane content into CO_2 while at the same time providing heat[12]. Figure 10 shows a sketch of the designed reactor, in which the flow is reversing after predefined period. The absorbent and heat regenerating bed will extract the water content in the ventilation air before it enters the catalyst. It consists of consist of γ-alumina pellets which are dried/regenerated when the flow is reversed. The design in 12 was done for a methane concentration of 0,3 $\%_{Volume}$ of methane, which is about 22 to 46 times higher than in the case considered within this study. The catalytic bed consists of palladium-based monolithic blocks with a cell density of 390 cpsi (cell per square inch). The size was adjusted for an average flow velocity of 1.13 m/sec and the flow was reversed after 4 minutes. If the same value is applied to the case of Gjesdal gard the throughflow area for the reactor needs to have an area of about 10 m^2. This would result in outer dimensions of at least 2m*5m or 3,2m*3,2m. Furthermore, insulation needs to be considered to reduce heat losses. It also necessary to consider heat exchanger for exhaust heat recovery etc. However, results of 12 indicate that temperature recovery and its utilisation is limited given the temperature profile in the reactor (Figure 11). The graph indicates the temperature in the reactor in flow direction at the beginning, in the middle and at the end of a period of 240 seconds. The dashed vertical lines indicate the location of the catalytic reactor zone. Temperature drop of the ventilation air after the reactor is due to the regeneration the absorber

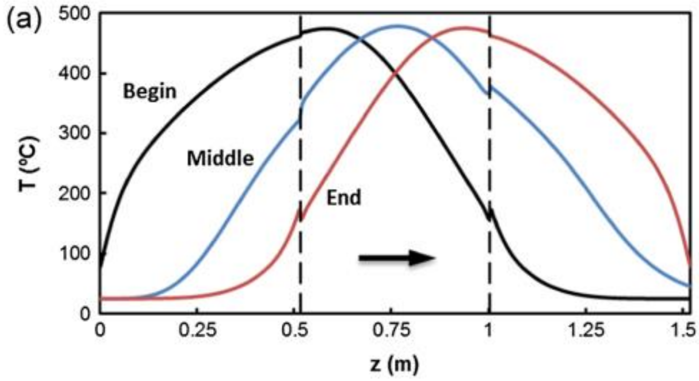

Figure 11: Gas temperature in the reactor for different points in time during one period (12)

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[12] J. Fernandez et.al.: *Combustion of coal mine ventilation air methane in a regenerative combustor with integrated adsorption: Reactor design and optimization*; Applied Thermal Engineering 102 (2016) 167–175

and therefore a result of evaporation of the absorbed water content. It also indicates the resulting low reactor exit temperature which limits possibilities for heat recovery.

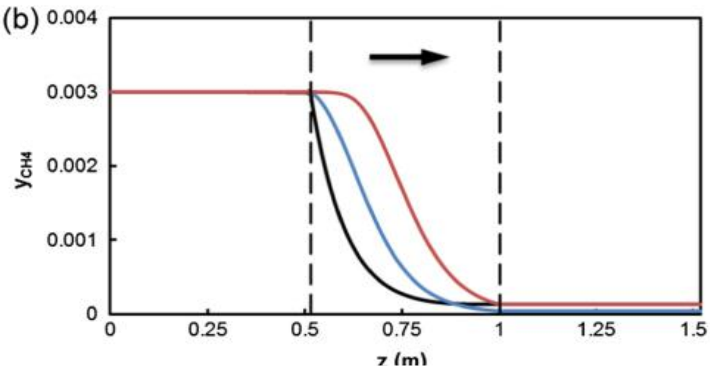

Figure 12: Change of methane concentration while the gas flows through the reactor (12)

Furthermore, it needs to be expected that the exist temperature for the Gjesdal case is even lower as the methane content is lower, resulting in less heat from the exothermal reaction. Given the significant lower methane concentration in Gjesdal will be -evaluation of the technology and design are necessary as results of 12 indicating that the conversion rate might flatten out with reducing concentration (Figure 12). This might result in extended length of the catalytic reactor part and thus impact costs. The catalyst is expected to be the main cost driver given the development of costs for 31,1g of it[13].

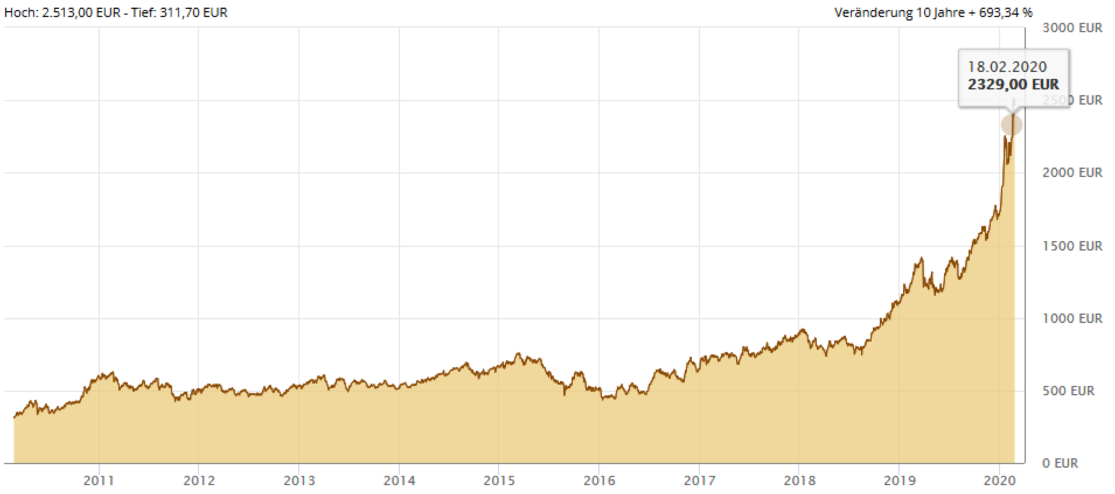

Figure 13: Market price development of Palladium for the last three years (13)

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[13] Development of the market price for Palladium; Source: https://www.gold.de/kurse/palladiumpreis/, Accessed on 24.02.2020

3.2.3. Biofilters

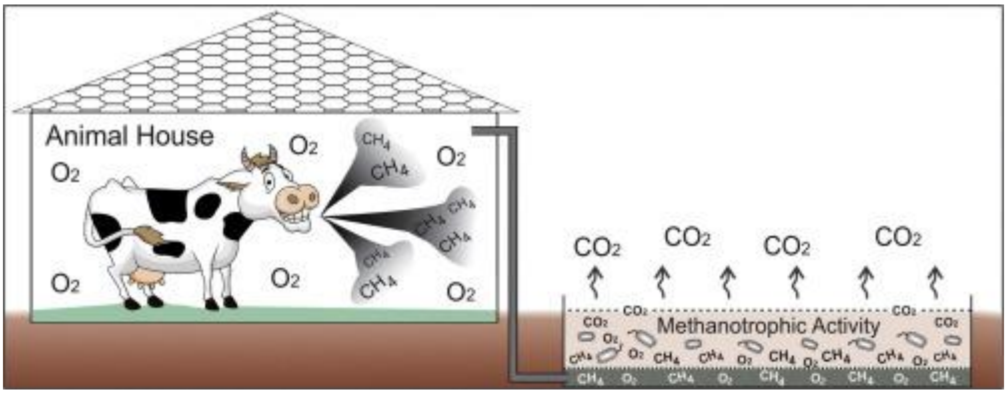

Figure 14: Schematic graphic of biofiltration from cow barns[14]

Biofiltration is a technique that has been commonly applied in agricultural and industrial sectors. Biofiltration is used to purify contaminated air evolved from volatile organic and inorganic compounds by involving microorganisms[15]. The microorganisms biologically degrade odours and other volatile air pollutants contained in waste air streams. The microorganisms exist on the surface and in a thin water film surrounding the surface of the biofilter material. The way methane oxidizing microorganisms oxidize CH_4 to CO_2 is similar for all methanotrophs. First, the MMO enzyme catalyzes the reaction between a single oxygen atom from O_2 and CH_4 to form methanol (CH_3OH). "There are two forms of the MMO: a particulate MMO (pMMO) located in the cytoplasmic membrane and found in most methanotrophs, and a soluble MMO (sMMO) which is located within the cytoplasm"[16].

During the biofiltration process the contaminated air is slowly pumped through the biofilter material. A biofilter has a filling material that support the development of the desired microbial methanotrophic consortia that oxidise CH_4. Packing materials such as compost, saw dust, straw, peat as well as mixtures of these materials have been tested. According to [17] the type of filter was not important for capacity if oxygen was supplied. Different types of biofilters and reactors have been suggested. It was found that methane removal using biotrickling filtration is not feasible if the global average atmospheric methane concentration, 1.7 ppmv, is assumed. This concentration is too low to support cell growth[18]. However, if the concentration is increased to 500-6000 ppmv, the same levels as above landfills, one type of methane oxidizing cells using the pMMO system could reach a steady state (stable process) within 2 months and a trickling bed could be a feasible type of reactor due to its smaller footprint.

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[14] Source: online version of 15 available at https://www.sciencedirect.com/science/article/pii/S0956053X1830391X?via%3Dihub

[15] F. Fedrizzi, H. Cabana; E.M. Ndanga, A.R. Cabral: *Biofiltration of methane from cow barns: Effects of climatic conditions and packing bed media acclimatization*; Waste Management 78 (2018) 669-676

[16] La, H., J. P. A. Hettiaratchi, G. Achari and P. F. Dunfield (2018). "Biofiltration of methane." Bioresour Technol **268**: 759-772

[17] Pawlowska, M., A. Rozej and W. Stepniewski (2011). "The effect of bed properties on methane removal in an aerated biofilter--model studies." Waste Manag **31**(5): 903-913

[18] Yoon S., J. N. Carey and J. D. Semrau (2009). "Feasibility of atmospheric methane removal using methanotrophic biotrickling filters." Appl Microbiol Biotechnol **83**(5): 949-956

In controlled conditions in the laboratory, in a fermenter, it has been shown a reduction from 50 ppmv to 2 ppmv methane and research is ongoing that possibly will identify more effective strains, but so far this is not a practical set up on a farm.

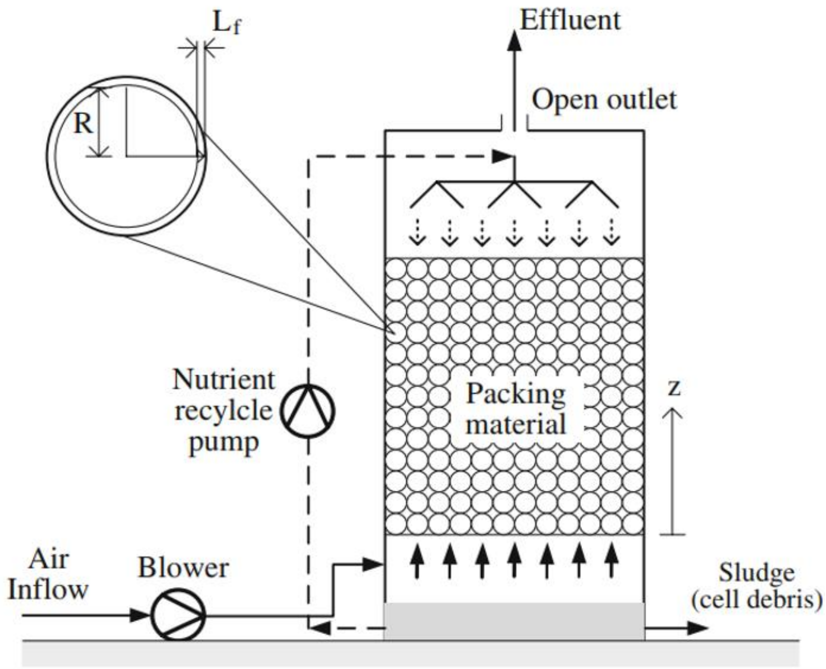

Figure 15: Schematics of a methane biotrickling filter [18]

"Typical CH_4 concentrations inside animal houses range between 5 and 100 $^{mg}/_{m^3}$ (milking cow). The average ventilation rate is 1000 $^{m^3}/_{hour}$ [19]. One important difficulty in using biofilters for CH_4 biotic oxidation is high air exhaust rates, that it will require very large biofilters. Inside the biofilter, microorganisms, methanotrophs, can oxidize the CH_4 under aerobic conditions, while generating oxidation by-products such as water (H_2O) and carbon dioxide (CO_2). Their activity depends on the presence of sufficient concentrations of both CH_4 and O_2 and is therefore limited in their distribution inside of the biofilter by diffusion of CH_4 and O_2. In paper 15 were the following results published:

The maximum oxidation rate (1.68 lg CH_4 gdw 1h1) was obtained with the commercial compost mixed with straw [15]. The performance of biofiltration to mitigate CH_4 emissions from cow barns was investigated in the laboratory using two flow-through columns constructed with an acclimatized packed bed media composed of inexpensive materials and readily available in an agricultural context. The biofilters were fed with artificial exhaust gas at a constant rate of 0.036 m3 h1 and low inlet CH_4 concentration (0.22 g m3 = 300 ppm). The empty-bed residence time (EBRT) was equal to 0.21 h.

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[19] Melse, R. W. v. d. W., Arjan W. (2005). "Biofiltration for Mitigation of Methane Emission from Animal Husbandry." Environ. Sci. Technol. **39**(14): 5460-5468

Using this information and the required EBRT are the following dimensions expected to be needed for the Gjesdal gard (assuming max. volume flow rate):

- Inlet area dimension 5 x 5 meter => 353 m length
- Inlet area dimension 5 x 10 meter => 176 m length
- Inlet area dimension 10 x 10 meter => 88 m length

In terms of operation: The efficiency and stability this type of technology will be affected by seasonal variations in temperature and summer season with most of the animals grassing. Since the filters are biological active these processes should be continuous. The reactor will need a period of acclimatization to be effective after a change in conditions. One also need to further assess a significant concern that biofilter operation may inadvertently increase other greenhouse gas emissions, in particular emissions of N_2O (which has a lifetime of over a century and a global warming potential 10 times greater than methane over 100 yr). Specifically, a review of bio-filters in the swine industry has shown that biofilters increase the amount of N_2O present of up to 400%[20] . This indicates that one need to consider bedding material especially in systems where nitrate is present at elevated concentrations.

3.2.4. Adsorption to filters

Methane is completely non-polar and interacts very weakly with most materials. Thus, methane capture poses a challenge that can only be addressed through extensive material screening and ingenious molecular-level designs, some of the most promising options are listed below.

Ideas of removing methane from air has been proposed as a complement to CO_2 removal. Methane and CO_2 removal from air share the requirement to expose large volumes of air to catalysts (for CH_4) or aqueous reactants typically for CO_2. Jackson et al [21] describes the use of electric fans can drive the forcing of large volumes of air to the catalysts that oxidize methane to CO_2. Catalysts in powdered, pelletized, or other forms could be exposed to air in tumbling bulk chambers or, instead, in parallel segmented chambers or packed reactors to optimize catalyst exposure while minimizing pressure drop through the system.

Zeolites have been identified for concentrating methane in industrial applications based on their favourable sorption capacities and CH_4/CO_2 and CH_4/N_2 selectivity. Coalmining ventilation air comprised of 1% CH_4, 1% CO_2 was used for zeolite screening resulted with a handful of candidates[22]. The goal of most previous zeolite research with methane has been to oxidize it partially to methanol (CH_3OH), a chemical feedstock, rather than fully to CO_2[23]. Methanol must be extracted from the zeolites.

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[20] Van der Heyden, C., Demeyer, P., & Volcke, E. I. P. (2015). Mitigating emissions from pig and poultry housing facilities through air scrubbers and biofilters: State-of-the-art and perspectives. Biosystems Engineering, 134, 74–93.

[21] Jackson, R. B., E. I. Solomon, J. G. Canadell, M. Cargnello and C. B. Field (2019). "Methane removal and atmospheric restoration." Nature Sustainability **2**(6): 436-438

[22] Kim, J., A. Maiti, L. C. Lin, J. K. Stolaroff, B. Smit and R. D. Aines (2013). "New materials for methane capture from dilute and medium-concentration sources." Nat Commun **4**: 1694

[23] Jackson, R. B., E. I. Solomon, J. G. Canadell, M. Cargnello and C. B. Field (2019). "Methane removal and atmospheric restoration." Nature Sustainability **2**(6): 436-438

Porous polymer networks[16] (PPNs), polymeric materials that contain small pores that can be used to capture, trap, and store compounds such as methane, and photocatalytic approaches for oxidizing methane. To be effective this though require high pressure (adsorption values up to 445 cm3 STP g−1 were measured 180 ba). Other families of materials, including carbon-based adsorbents, graphene-based materials, or metal–organic frameworks, appear to have poorer selectivity. Graphene, with proper doping and inter-layer spacing could potentially isolate CH_4 but more work needs to be done to optimize such a system for selective methane capture with high load capacity[22].

4. Benchmark

The described possible solutions are compared against criteria defined by the farmers involved into the project. A qualitative comparison shows the table below:

Criteria	**Methane concentration**			**Methane conversion**				**Methane separation**
	Scrubber	**Gravitation**	**Vortex tube**	**CHP**	**Catalytic combustion**	**Biofilter**	**Adsorption**	**Cryogenic separation**
Pre-requirements	fluid selection	minimized, no turbulences, long residence time	high gas pressure required	whenever possible increase CH_4 concentration	3 - 0,3 % CH_4 => increased concentration	Robust & simple, sensitive to variations and cold temperature preferably continuous use large volume	Need extensive screening/material design	energy for cooling
Energy demand	medium, heat input to release the gas	none, except for extracting CH_4	Compression energy: > critical pressure, high pressure, high volume flow	6.6. MW in fuel for full volume flow.	preheating to operational temp.	low for passive bed/some circulation - active types a bit more	Energy to force large volumes of air to the catalysts	cooling (only) demand down to CH temp about 2,5 MW
Condition for animals	no impact	Only in case of no airflow	High noise damping required (> 120 dBa)	OK, outside in a container	Low noise	Low noise	Separate unit outside of the barn	ok, needs anyway to be outside.
Climate impact	no positive impact	OK, if it would work	OK, if it would work	Conversion of CH_4 into CO_2	Conversion of CH_4 into CO_2	Conversion of CH_4 into CO_2; possible negative effect (N_2O) resulting from selected biofilter	Conversion of CH_4 into methanol or CO_2;	none
Cover own energy needs	no	yes	most likely not	Additional fuel needed; 5 kW out of 6.6 MW fuel covered	yes	no	no	5 kW only of more than 2,5 MW
Other energy aspects	heat required	no	High pressure requires energy	exhaust heat (600 °C) can be utilized	heat recovery (300 °C	no	no	cooling energy, compression energy, pressure losses etc

					operation temperature)			needed. Re-use of cooling energy
Usable as fuel	no	yes	yes	is used as fuel	no	no	Methanol?	yes
Usable for other products	no	yes	yes	no	no	Combine with compost or "jordforbedring" possible		yes
TRL level	3	1	1	3	3	2	1	8 (10 for air separation, methane less known/applied)
Technology expected to work	no, no scrubber liquid for CH_4 capture	yes, to increase concentration and in case of sufficient residence time	doubtful as not yet installed for CH_4 separation	yes, standard well-established technology	most likely, was tested in coal mines	yes, proven in small scale; impact on emissions depending on the selected biofilter	uncertain as research is ongoing (material research)	most likely, established technology in large scale
Practicality of installation	most likely	most likely	too complex	yes	most likely	yes, only a large storage and mor powerful ventilation needed	expected to take a few more years till being available	too complex
Complexity of plant	semi complex	low	medium	low	low	passive type is simple		quite high
Complexity of operation	well known	low	medium	low	intermediate	low to intermediate		automated, continuous operation

To quantify the evaluation were weight factors defined, which, together the value describing the criteria per technology result in the overall sum per technology (table below).

Criteria	Weight factor	Methane concentration			Methane conversion				Methane separation
		Scrubber	Gravitation	Vortex tube	CHP	Catalytic combustion	Biofilter	Adsorption	Cryogenic separation
Pre-requirements	1	2	3	1	1	2	2	2	1
Energy demand	3	2	3	1	1	2	3	2	1
Condition for animals	3	3	3	1	2	3	3	3	2
Climate impact	3	2	3	2	1	2	3	2	1
Cover own energy needs	1	2	3	1	1	3	1	unknown	1
Other energy aspects	1	2	3	1	2	3	2	unknown	1
Usable as fuel	1	3	3	2	2	1	1	unknown	3
Usable for other products	2	3	3	3	1	1	3	unknown	3
TRL level	2	3	1	1	3	3	2	1	3
Technology expected to work	6	0	3	1	3	2	3	2	2
Practicality of installation	6	2	2	0	3	2	3	1	1
Complexity of plant	3	2	3	1	2	2	2	unknown	1
Complexity of operation	3	2	3	2	3	2	1	unknown	3
Total Sum (with weight factor)		**63**	**94**	**38**	**77**	**72**	**80**	**42**	**36**

Note: The total sum results from multiplying the value per criteria with the weight factor and summing up all values in a column. The max possible value would be 99. For chapter 5 were the three technologies with the highest values chosen.

5. Discussion and further proceeding

The result of the technical evaluation and the benchmarking indicate that:

- None of the technologies alone is expected to be a realistic possibility to reduce the climate impact of the methane within the ventilation air of the barn at Gjesdal gard. This is due to:
    - Complex and therefore costly plants (cryogenic separation, vortex tube, CHP)
    - High additional energy consumption (cryogenic separation, vortex tube, CHP)
    - Large area requirement (gravitation, bio-filter, catalytic combustion)
    - Very low level of maturity (adsorption)

The option to use ventilation air alone as air entering e.g. a thermal heating unit (chip fired) will cover only a small amount of the ventilation air[24]. However, some of the technologies were evaluated as being promising even though maybe not as a stand-alone solution and maybe also in connection with other activities and infrastructures on a farm. This needs to be subject to an in-depth analysis. A combination of technologies utilizing the possibilities on a farm might be:

- **Ventilation:** Given that a main problem for developing a solution is the low concentration of the methane in the ventilation air, the first priority should be to reduce the rate as much as possible. The evaluation of temperature in the barn and CO_2 concentration (see 2.2 Estimations of emissions for various operating conditions) indicates the potential reduction of ventilation air. However, as available literature does not provide sufficient information on ventilation airflow as well as gas composition, measurements are needed to support the design and optimisation. The ventilation needs to be designed and optimised in connection with using gravitation and the design of the barn
- **Gravitation and design of the barn** to increase the methane concentration for better utilisation. A large barn (plus maybe specific design of it) and the timewise interruption of ventilation might be evaluated as a supporting approach to increase CH_4 concentration in some areas of the barn. The evaluation needs to be done in connection with the ventilation as mentioned in the previous bullet point. Ventilation air extracted from areas of accumulated CH_4 and therefore higher concentration and smaller volumes can be channelled to other technologies further reducing the climate impact. This will in turn have a positive impact on the size, cost and possibly energy consumption of subsequent processing steps. The extracted gas can be partly sent to a local CHP/boiler or biofiltration (see bullet points below).
- **CHP or boiler:** Parts of the CH_4 rich ventilation air can be used as inlet air to a local CHP plant (either a gas turbine or a motor). The CHP/boiler will require additional fuel which can be for example biogas from an anaerobic digester using manure or other biowaste with higher water content. As an alternative to biogas, syngas from a gasification / pyrolysis unit could be used which requires solid organic waste or biowaste with a lower water content (e.g. wood). The gasification/pyrolysis can also be used for hygienization of slaughterhouse wastes). It is also possible to use waste heat from the pyrolysis or from the CHP/boiler unit could be used for drying the feedstock.

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[24] The ventilation massflow of the barn , when being compared to the air intake of a 30 kW_{therm} pellet oven (to heat about $350m^2$ residential area), between about 362 and 725 tim larger.

- **Biofiltration:** might be used to filter CH_4 out of the part of the rich ventilation air which was not used for the CHP or boiler. Depending on used filter material it might be used for improving the quality of soil and replace industrially produced fertilizers. This replacement of industrial produced fertilizer further contributes to reducing climate gas emissions resulting from agricultural activities.

A possible schematic of a solution including several technologies and elements is shown in Figure 16. Such an approach is an integration of elements of the local energy system and the operation of the farm (ventilation, utilisation of organic waste) as well as different elements of it.

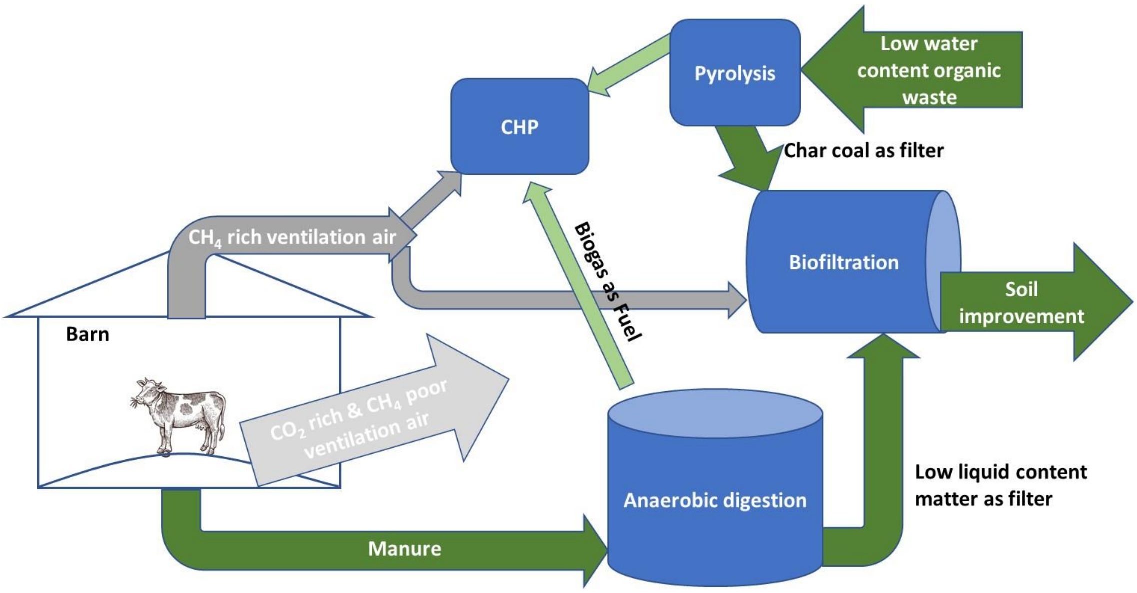

Figure 16: Schematics of an integrated concept for reducing methane emissions for a barn

However, a more thorough evaluation should be performed based on one or two reference farms to estimate the potential. The evaluation needs to be supported by measurements to estimate the impact of various parameters, especially in connection to the possible increase of methane concentration in ventilation air and its impact on reducing the climate impact. Key elements of such a follow up project is expected to be:

- Evaluation of the impact of the design of a barn and its ventilation on methane concentration in the ventilation air at different locations in the barn. This will include the potential impact of gravitation on the result. Different modes of ventilation control than continuous high level ventilation should be evaluated.
- The availability of feedstock for anaerobic digestion and/or pyrolysis can be evaluated in parallel to estimate the potential local fuel production. In case the amount is not sufficient, other sources could be considered such as power to gas options from fluctuating renewables.
- Results of this first step will form the input for an integrated concept, sizes of components etc. In an ideal case different options should be considered.
- The final step would be a pilot/prototype installation and the collection of real operational data.