Cost-efficient handling of oxygen from bio-methane in the European gas grid

REPORT

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Foreword

This report and the calculations done for it are based on extensive knowledge of the Danish biomethane plants combined with more limited knowledge of biomethane plants in other European countries. The latter has been attained through GERG and CEN groups working with biomethane problems and especially the oxygen issues [1][2]. Due to this, many assumptions will be based on knowledge from the Danish system, which is believed to sufficiently apply to other European countries as well. This will be discussed during the sections describing such assumptions.

Throughout this report, some background knowledge of biogas upgrading technologies and sulphur removal techniques is assumed. For more information on these technologies, reference is made to [3] and [4].

In the report, biomethane is often referred to as being “oxygen-free” if certain sulphur cleaning or upgrading techniques are used. In reality, small amounts of oxygen could be present due to accidental air from leaks, air pockets in biomass etc. The term “oxygen-free” in this report refers to biomethane production that can produce sufficiently oxygen-free biomethane if the necessary precautions are made at the biomethane plant.

Revision 1 of the report was updated to include additional calculations, graphs and considerations based on external feedback on and questions to the report. Revision 2 includes a minor update to Table 11, which does not influence the report’s conclusions.

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1. Background

Biomethane is an important tool to ensure a greener and more independent energy sector in Europe. The war in Ukraine has emphasised biomethane as a commercially and readily available part of the solution to both the climate and the energy crisis. While the biomethane production varies greatly among the EU countries, the newly launched REPowerEU ambition has set a course for significant increases in biomethane production across EU in the coming few years.

However, this development has also emphasised some of the technical and political challenges that increased biomethane shares still pose for the European gas infrastructure. One of these is the increased oxygen content from biomethane. While fossil natural gas is oxygen-free, a traditional, European biomethane plant produces biomethane with around 0.5% oxygen [2][5]. This means that increasing biomethane production will also mean increasing oxygen levels in the gas grid.

Gas storage facilities have no experience with oxygen in the gas and fear that increasing oxygen levels can cause e.g. increased corrosion, bacterial growth with pore blockage and sulphur depositions [6]. Some types of chemical industry also require low oxygen levels.

Some countries have low national limits for oxygen in the gas grid (e.g. Germany, France and The Netherlands [6]), meaning biomethane injection must be considered carefully to keep oxygen levels in the grid below the limit, potentially limiting biomethane growth. Other countries have high limits for oxygen (e.g. Denmark, Italy and Belgium [6]), meaning storage facilities and chemical industry have to handle the increasing oxygen content in their feed somehow. It also means TSOs might need to invest in oxygen removal at border crossing to countries with low oxygen limits.

Up until now, oxygen from biomethane has not posed a significant issue to national growth in biomethane. The biomethane share in most EU countries has been so low that the oxygen concentration has been diluted to insignificant levels after local use and/or mixing with the fossil natural gas[1]. However, if biomethane share is to increase as planned with REPowerEU, this dilution will not be a sufficient solution anymore.

In order to ensure the desired growth in biomethane in REPowerEU, national states (or possibly EU) need to decide on how best to handle the oxygen issue. This could be done by reducing the oxygen level in the biomethane or by removing it somewhere in the gas system. Ideally, it should be done in the cheapest possible way for the gas sector – not just now, but also in the long term in a

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[1] The Danish biomethane share is more than 25%, but as the national limit for oxygen in biomethane is 0,5%, increased oxygen content in the gas grid has not been a hindrance for the growth in new biomethane plants.

near future with significantly higher biomethane shares in the grid. And even more ideally, a common solution for EU should be found, so different oxygen limits do not hinder free trade of gas across borders.

However, quantitative data has been lacking for making such a decision. This project and report attempt to supply quantitative estimates for making such an informed decision through the development of an advanced analysis tool.

2. Conclusion

Using the developed analysis tool, estimated expenses were calculated for handling oxygen either at the biomethane plants or at the gas storage facilities for four countries: Denmark, Germany, France and Italy. The analysis tool was used to evaluate whether it is more cost-efficient to handle oxygen at each biomethane plant (by avoiding oxygen addition or by catalytic removal of oxygen) or to handle/remove oxygen catalytically at the gas storage facilities. In addition, the influence of size and technology choice for upgrading plants on these conclusions was investigated.

The following observations and conclusion were made based on the results from the analysis tool:

- For Denmark, Germany and France, it was found that when the biomethane share surpassed a certain value (65%, 35% and 15%, respectively for the three countries), oxygen removal at gas storages was cheaper than avoiding/removing oxygen at each biomethane plant. For Italy, it was cheaper to avoid/remove oxygen at the biomethane plants for all biomethane shares. These observations are based on the assumption that future biomethane plants resemble the existing ones in technology and size. The difference in biomethane share is due to e.g. differences in upgrading technology and size, and amount of storages.

- Catalytic cleaning is expensive – especially for small scale at biomethane plants. If future biomethane plants are built similarly to existing plants but avoiding technologies that would require catalytic cleaning at the biomethane plant, this would have an immense effect on the results. If this change is made, avoiding oxygen at the biomethane plant is the cheapest for all biomethane shares for both Denmark, Germany and Italy. For France, catalytic cleaning will still be cheaper for 10% biomethane share and up. This is due to the very small biomethane plants in France making oxygen-free production more expensive. If plant sizes in France are increased with 100-200%, oxygen-free biomethane production will become much cheaper due to economy of scale. For biomethane plants 200% bigger than existing plants (similar in size to Germany), avoiding oxygen at the biomethane plants will be the cheaper solution for all biomethane shares.

- In order to produce oxygen-free biomethane with as low extra cost as possible, investments are required at existing and future biomethane plants – especially for biological sulphur cleaning. If this is to be possible, some sort of support for financing might be necessary, as small biomethane plants might have difficulties raising money for investments [7]. The alternative would be a significantly more expensive sulphur cleaning method (with lower investment cost) to ensure oxygen-free biomethane production. Even if support is given to finance the necessary investments, small biomethane plants might find the biological sulphur cleaning process too technically complicated. This will make oxygen-free biomethane production at small biomethane plants significantly more expensive.

- Upgrading technology and size has a large influence on expenses for handling oxygen at the biomethane plants. Water scrubbers add oxygen to the biomethane, necessitating expensive, catalytic cleaning at the biomethane plant for oxygen-free production. Economy of size means that larger upgrading plants can produce oxygen-free biomethane cheaper than smaller plants. Small upgrading plants (average size of 400 Nm^3/h biomethane) with 35% of plants being water scrubber plants could have extra expenses of around 1.6 €¢/Nm^3 biomethane. This corresponds to an extra expense of 2% relative to total cost of biomethane production (Danish 2019 values) [8]. For large upgrading plants (average size of 2000 Nm^3/h biomethane) without any water scrubber plants, the extra expense will only be around 0.01 €¢/Nm^3 biomethane. However, due to differences in national subsidy schemes (some favouring smaller or bigger plants), as well as the rush throughout Europe to build more biomethane plants (limiting available technology suppliers), the choice of size and upgrading technology will be influenced by more than price alone.

- The content of H_2S in the biogas (before any reduction/cleaning) has a relatively large influence on the results and conclusions in the report. Low H_2S concentrations will make converting to oxygen-free production more expensive, as it will make the price difference between existing sulphur cleaning solution (typically iron chloride, in-situ oxygen and activated carbon, where price is proportional to H_2S concentration) and the oxygen-free alternative (typically external biological cleaning, where price is almost independent of H_2S concentration) larger. Conclusions here are based on average H_2S concentrations of 2000 ppm.

- If research finds that gas injected into gas storage facilities can contain more than 10 ppm oxygen without damaging the facility, fewer storage facilities will need to install catalytic removal units. The consequence will be that the overall cost of handling oxygen at the gas storage facilities will decrease, influencing the conclusions made above.

- If two neighbouring countries choose different approaches to handling oxygen (i.e. have different oxygen limits in their gas grids), oxygen removal will be required at the border. The expenses for this are currently being paid only by the country with high oxygen limits (i.e. handling oxygen at the gas storage facilities). This could potentially influence biomethane growth and/or free trade of gas across borders. A good solution from an overall gas sector perspective to avoid such extra expenses would be common EU oxygen limits and approach to handling the oxygen issue. Alternatively, some consideration regarding how best to handle border issues might be given.

Based on the observations above, thought should be given to the size and especially upgrading technology of future biomethane plants. Avoiding upgrading plants adding oxygen to the biomethane and building not-too-small biomethane plants would allow relatively cheap avoidance of oxygen in the biomethane. If this is done, handling oxygen by avoiding it at the biomethane plants has the potential to be the most cost-efficient solution. If current trends for biomethane plants continue, handling oxygen by catalytic removal at the gas storage facilities would be the most cost-efficient solution for biomethane shares above a certain limit (generally around 10-40%) for most countries – depending on existing plants and gas storage facilities.

It should be noted that results, observations, conclusions and recommendations in this report are made on the basis of assumptions and estimates and mathematical modelling. Results should be seen as estimates – not as a solid price for expenses of handling oxygen.

3. How to avoid or remove oxygen

Danish Gas Technology Centre has made a separate report (currently in Danish) on why oxygen is present in the biomethane and how it can be produced oxygen-free or with a very low oxygen content [9]. In short, oxygen enters the biomethane:

- Accidentally, through leaks or unintended air from vacuum-valves or air pockets in biomass. These can all be handled by various process adjustments and fixes.
- From sulphur cleaning – typically in-situ oxygen injection in the digester, air-injection for activated carbon filters or upstream, conventional biological cleaning. Changes in sulphur cleaning methods (see Section 5.3) can avoid oxygen addition but will often have extra expenses and/or require an investment in new equipment.
- From the biogas upgrading process where air is added as part of the upgrading process. The only upgrading process (to the author's knowledge) with air addition is the water scrubber process. To upgrade without oxygen addition, an oxygen-free upgrading method should be chosen, or a catalytic plant should be installed for removing oxygen from the produced biomethane.

If oxygen is not avoided in the biomethane, the alternative is to remove it somewhere else in the system – probably by removing it catalytically.

The calculations and conclusions in this report are based on these approaches to handling the oxygen.

4. Method

In order to estimate the best and most cost-efficient way to handle the oxygen, an analysis tool was developed using Excel. This tool is designed to look at two possible ways to handle the oxygen:

Option 1: Avoid oxygen injection by either reducing or removing it sufficiently at each biomethane plant.
Option 2: Remove the oxygen at gas storage facilities to avoid oxygen injection.

Ideally, option 2 would have included chemical production (if sensitive to oxygen content) and export across borders too, but this has been left out due to lack of input data.

For both option 1 and 2, the analysis tool must calculate expenses not only for the current biomethane share, but especially for increasing biomethane share, so countries can decide on the best and most cost-efficient solution with a longer time frame in mind.

The subsections below will describe the principles behind the calculations for option 1 and 2, while necessary assumptions will be described in Section 5, and collection of required input data will be described in Section 6.

4.1. Estimating oxygen concentration in the grid

When calculating the expenses for option 2 above, the important factor is the concentration of oxygen in the *transmission* grid, where the gas storage facilities are connected. Often, the majority of the biomethane plants are connected to the *distribution* grid. Here, a lot of the biomethane will be used by local consumers, and only if the biomethane production in that area is higher than the consumption, the surplus will be re-injected into the transmission grid. Thus, the biomethane share (and oxygen content) in the transmission grid will normally be significantly lower than in the distribution grid.

To illustrate this, the national biomethane share in Denmark in July 2021 was around 50%, while the local share in Northern Jutland was 116% (see Figure 3 on page 15 below). Despite this, the oxygen content in the gas injected from the transmission grid into the gas storage in Northern Jutland during July was only around 50 ppm, corresponding to a biomethane share of around 5% in the transmission grid[2] [10][11][12].

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[2] Based on an average content of 0.1% oxygen in Danish biomethane plants, calculated by the analysis tool.

When calculating the oxygen content in the distribution grid, it will be a direct function of the biomethane injected into it. When calculating the oxygen content in the transmission grid, it is more complicated. The oxygen concentration here will be calculated based on biomethane plants with injection directly into the transmission grid with the addition of re-injection from the distribution grid through reverse flow stations, *if* local biomethane share is higher than local consumption. Whether local biomethane production exceeds local consumption (thus leading to re-injection into the transmission grid) will depend on a series of factors described in the subsections below.

4.2. Estimating monthly variations

While biomethane production is relatively constant throughout the year, gas consumption is not. More gas is used during the winter for e.g. district or local heating, while summer consumption is generally low, as gas is only used for chemical industry (as fuel or substrate) and hot water. This means that the same biomethane production will lead to significantly higher biomethane shares (and thus oxygen concentration) during summer than during winter. At the same time, summer is also the time when gas storage providers fill their storage facilities before the coming winter, making the storage facilities more exposed to the oxygen content in the gas grid.

To take this variation in biomethane share and oxygen content into account, it is assumed that the variation in the monthly consumption follows a normal distribution. The analysis tool calculates the monthly consumption by fitting a normal distribution based on two parameters:

- The sum of monthly consumptions calculated from the normal distribution should be equal to the total gas consumption in that country.
- The lowest monthly consumption calculated from the normal distribution should be equal to the lowest monthly consumption in that country.

The figure below shows a comparison of the actual and modelled Danish gas consumption from 2014 to 2021 [11]:

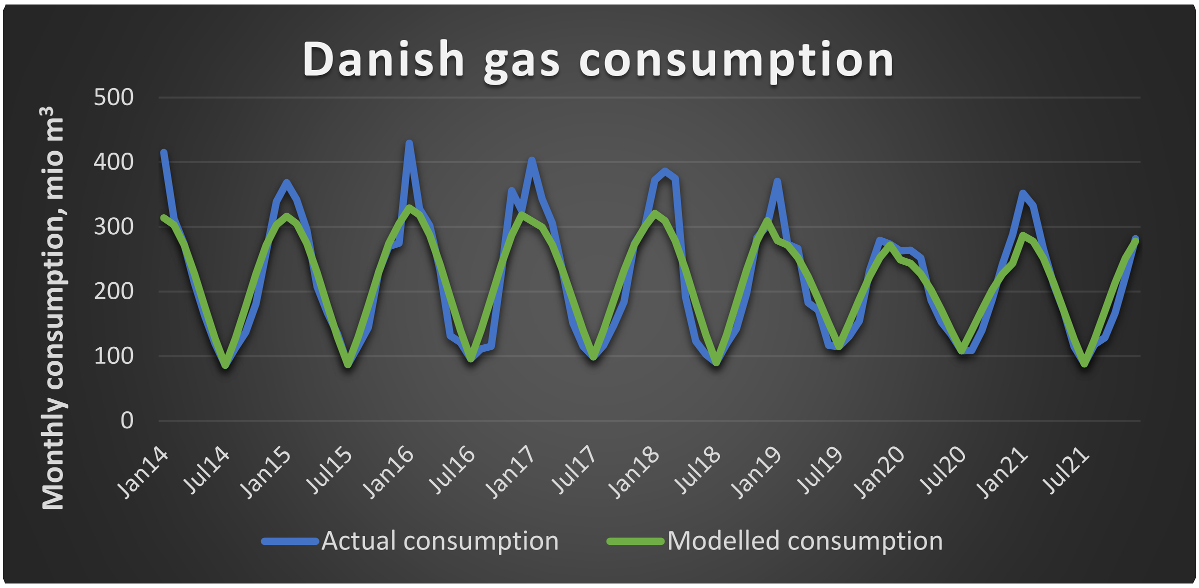

Figure 1: Comparison of actual gas consumption in Denmark [11] and the modelled consumption assuming normal distribution for the period 2014-2021. The modelled data has been fitted for each year to the total consumption and minimum monthly consumption of the given year.

As can be seen from Figure 1, the modelled consumption does not completely fit the actual consumption, but it resembles it relatively well – especially at months with low consumption, which is the most important time for this purpose, as oxygen levels will be the highest.

4.3. Estimating local variations for biomethane share

While biomethane production is relatively stable and continuous throughout the year, it is rarely evenly distributed throughout the country. Some areas of a country will have more farming (i.e. high availability of manure and/or energy crops) or otherwise be more attractive for placing biomethane plants in. In addition, some areas will have lower gas consumption than others. These factors combined will lead to higher-than-average biomethane share (and thus higher oxygen content) in some areas and lower in others.

In addition to this, the development of the distribution grid (that many of the biomethane plants are connected to) is also an important factor. Small, local distribution grids will be more likely to have local overproduction of biomethane and require re-injection, while larger, interconnected distribution grids will enable operators to distribute the gas to a wider range of customers without having to re-inject into the transmission grid.

In combination, the factors above lead to variations in local biomethane share across the country. As data is not available on how this local share may vary, a kind of finite-element-approach has been used instead. Using this approach, the country is split into 25 hypothetical pieces with unknown locations. Some of these areas will have higher biomethane shares, some will have lower.

To model the variation in biomethane share, it is assumed that the variation in biomethane production among these 25 hypothetical areas follows a normal distribution. This is expected to be a reasonable assumption: that the majority of the areas will have biomethane shares close to the national average, while some, but fewer, areas will have significantly higher or lower biomethane share. The normal distribution is fitted to the total biomethane production (with distribution grid injection) and a user input of how well distributed the biomethane plants are across the country and how developed the distribution grid is (see further explanation of the latter after Figure 3).

Based on this normally distributed biomethane production in each of the 25 hypothetical areas, the biomethane share in each area for each month (based on monthly consumption, see Section 4.2) is calculated. Variations in local consumption is assumed to be sufficiently covered through the variation in biomethane share calculated this way.

As an illustration, the variation in July for Denmark for the 25 hypothetical areas is shown below together with actual biomethane share for five different regions in Denmark from 2021 [12]:

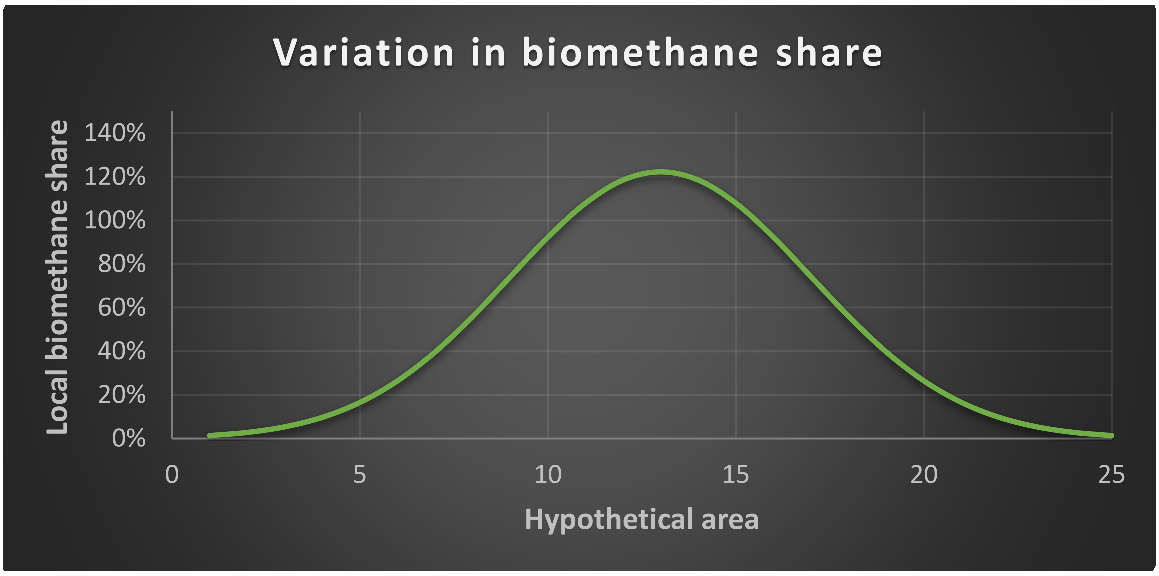

Figure 2 Estimated variation in biomethane share in Denmark in July (lowest monthly consumption) for each of the assumed 25 hypothetical areas.

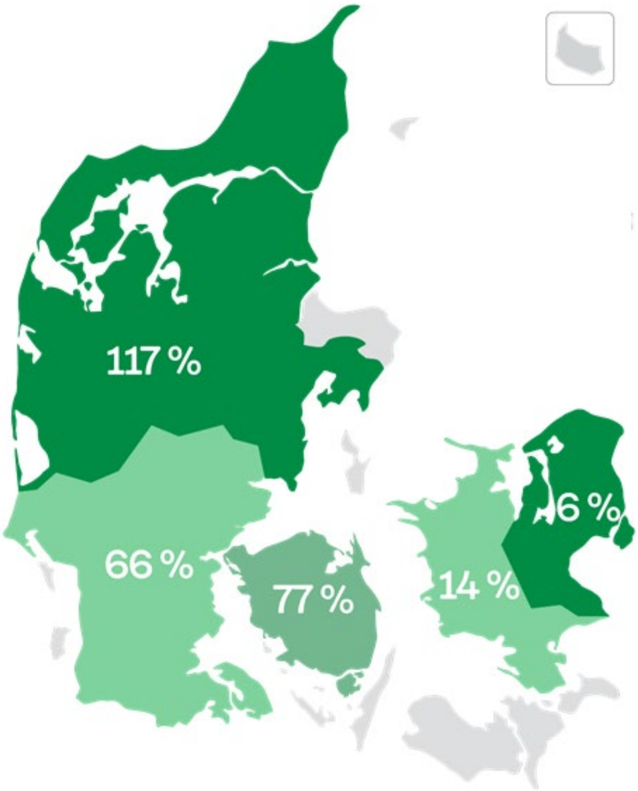

Figure 3 Biomethane share in 5 different regions in Denmark for July 2021 [12].

In order to create the normal distribution of the biomethane production, a user input is given of how well distributed the biomethane plants are across the country and how developed the distribution grid is. Here, the analysis tool has the option of setting a value from 1-3 for how well distributed the biomethane plants are, and a value from 1-3 for how developed the distribution grid is. Based on this, the analysis tool uses different standard deviations for the normal distribution. In this way, a country with very evenly distributed biomethane production and/or very well-developed/connected distribution grid will have a lower local variation in biomethane share. Similarly, a country with very localised biomethane production and/or very small/limited distribution grid will have greater variation in biomethane share. The resulting difference in local biomethane share is shown for Danish biomethane production (assuming the biomethane plants were located differently than they are or that the distribution grid was more/less developed than it is):

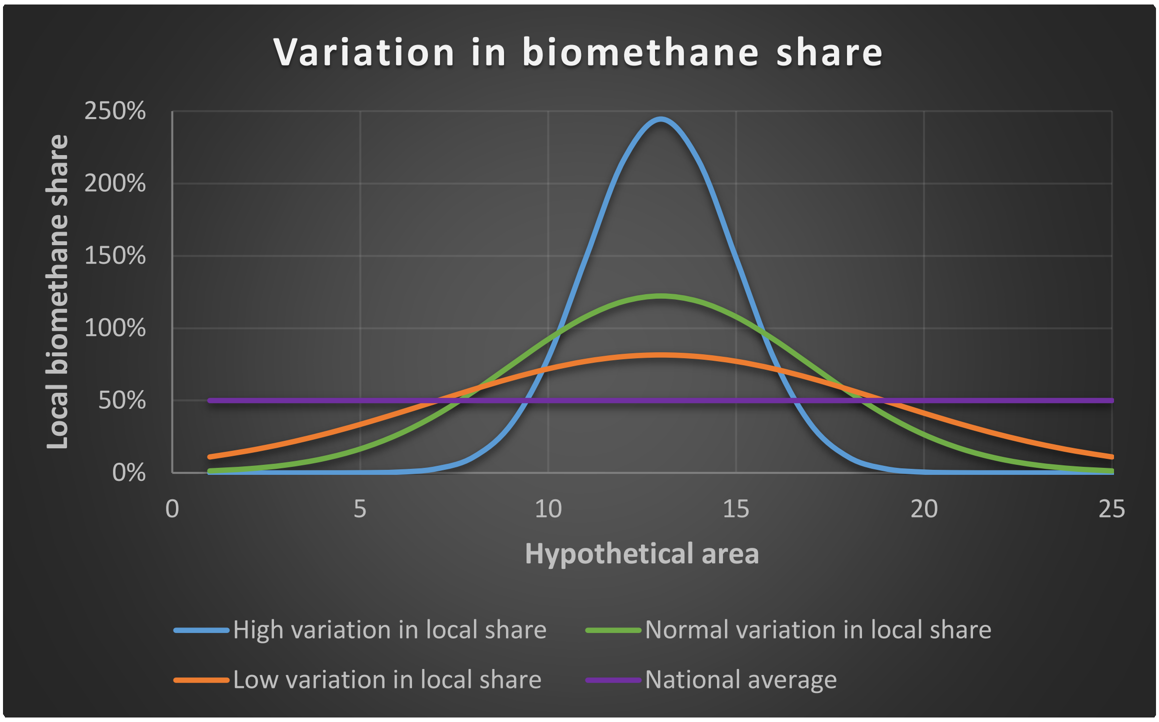

Figure 4 Illustration of how different inputs for how well-distributed the biomethane plants are and/or well-developed the distribution grid is, will influence the simulated, local variation in biomethane share. Based on current Danish biomethane share in July.

The "normal variation" shown in Figure 2 was used as standard, unless data clearly indicated otherwise.

4.4. Estimating local variations for storage locations

In the same way as the biomethane plants, gas storage facilities will also be distributed throughout the country. A gas storage facility in a part of the country with high biomethane production might encounter higher oxygen concentrations than a storage facility in an area with lower biomethane production. As local biomethane share is only calculated for 25 hypothetical areas without a fixed location, these cannot be directly correlated to an existing storage facility's location. Instead, the gas storage facilities are each assumed to be located in one of the 25 hypothetical areas. In the analysis tool, this is done by using a random list of the storage facilities in the country. The first is located in hypothetical area no. 7, meaning the area with the median oxygen content – halfway between the area with maximum biomethane share (area 13) and the area with lowest share (area 1). Then the next facility will be located in area 6, then area 8, area 5, area 9 etc., so that for countries with few storage facilities, they will be assumed to be located close to national average, while countries with many facilities will also have some located in areas with high and low biomethane share.

4.5. Estimating future growth in biomethane production

As the aim with the analysis tool is not only to estimate expenses for handling oxygen now, but also in a future with higher biomethane share, the future growth in biomethane plants must be simulated. As capacity and technology influences both oxygen concentration in the biomethane as well as the possibilities for avoiding/minimising oxygen at each biomethane plant [9], this must be part of that simulation.

As standard, the analysis tool assumes that future biomethane plants will be of the same size and use the same upgrading technology (see Section 5.2 for assumptions about upgrading types) as existing biomethane plants. “Use of same upgrading technology” will be based on same share on a number-of-plants basis (see Table 1 as example). As an option, it is also possible to choose two predefined options of “small plants” or “large plants” (see Table 1 below) for future growth in biomethane production, or to give user-input for desired sizes and technologies:

Table 1 Pre-defined options for future biomethane plants, if different from current capacities and technologies.

Small plants	**Share #/#**	**Avg. Size Nm³/h**
Membrane	50%	400
PSA	30%	200
Water scrubber	10%	700
Amine scrubber	10%	900

Large plants	**Share #/#**	**Avg. Size Nm³/h**
Membrane	10%	800
PSA	5%	500
Water scrubber	35%	1.700
Amine scrubber	50%	2.500

As an additional option, it is possible to choose to avoid upgrading technologies requiring catalytic removal (which is very expensive in such small scale) in the future – either based on current type/size of plants, or on ‘small plants’ or ‘large plants’ above. Current water scrubber technology uses stripping with air to remove CO_2 from the water, leading to a naturally high oxygen content (around 0.3% in Danish plants [5]) in the biomethane. This means that catalytic oxygen removal will be a necessity. If the analysis tool is asked to use “upgrading without catalyst requirements” in the future, it handles this mathematically by substituting water scrubbers with amine plants of the same size. However, in the real world, this could just as well be done with a re-designed water scrubber solution or another technology where oxygen is not added during the upgrading process, and where sulphur can be removed downstream, as is possible for modern water and amine scrubbers.

4.6. Estimating extra expenses for handling oxygen at biomethane plants

In most cases, oxygen in the biomethane can be avoided by changing the sulphur cleaning method at the biomethane plant (see Section 3). In order to estimate the total extra expense for avoiding oxygen injection with the biomethane, the extra expense for each biomethane plant is calculated. For each biomethane plant, the cost (CAPEX and OPEX combined) of the current sulphur cleaning method is compared to the cost of an oxygen-free sulphur cleaning method. If the latter is higher, the extra expense is calculated based on the difference in cost[3].

If the upgrading method itself adds oxygen, a change in sulphur solution is insufficient to avoid oxygen. If this is the case for the biomethane plant, the extra cost for installing catalytic oxygen removal is added instead. The total cost for avoiding oxygen from all the biomethane plants is the sum of all these extra expenses.

4.7. Estimating extra expenses for handling oxygen at gas storage facilities

To calculate the extra expense for removing oxygen at the storage facilities, the cost at each storage location is evaluated. If the maximum oxygen content in the injected gas surpasses the allowable concentration, catalytic cleaning is required. The cost of this is calculated based the maximum injection flow (CAPEX) and on the average injection flow and oxygen concentration (OPEX). The total expense for handling oxygen at the storage facilities is the sum of the extra expenses for each storage facility.

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[3] If the current sulphur cleaning solution had a high CAPEX, this calculation approach would not be feasible, as CAPEX expenses for the existing sulphur cleaning would still have to be paid. However, the existing sulphur-solutions (as set by the analysis tool, see Section 5.3), that need to be avoided, are all low CAPEX, high OPEX solutions. Due to this, remaining CAPEX expenses for existing sulphur cleaning will be negligible or non-existent, and the described approach can be used.

5. Assumptions and limitations

To carry out the calculations, a series of assumptions had to be made. They will be described in the following subsections.

5.1. Basic assumptions

The table below shows a series of basic assumptions and the origin/background of them:

Table 2 List of assumptions used in the analysis tool.

Assumption	Value	Explanation/reference
Actual production capacity (annual average) compared to nominal capacity for biomethane plant	90%	Due to service, disturbances, or natural variations, some of the time the plant will run below nominal capacity or not run at all. Value estimated based on Danish data for biomethane injection. A lower percentage would mean that a given biomethane share would require more biomethane plants and thus higher expenses for converting to oxygen-free production. A value of 80% instead would increase the calculated expenses with up to 12,5% depending on the current biomethane share.
Average H_2S in *untreated* biogas	2000 ppm	Often reduced during biogas production before exiting the digester. Varies, but normal value for Danish biomethane plants [13] and maximum sulphur content in background material for sulphur cleaning prices [14]. A lower value could decrease sulphur cleaning cost depending on technology. Cleaning with iron chloride and activated carbon would decrease almost proportionally, while biological cleaning would only be marginally influenced. Due to this, a lower H_2S content would generally lead to higher expenses for handling oxygen at the biomethane plants, as in many cases it will mean substituting iron chloride and activated carbon (which costs less for lower H_2S content) with biological cleaning (which is uninfluenced by H_2S content) by the analysis tool.
Extra cost of activated carbon without oxygen requirement compared to regular activated carbon.	350%	Normal activated carbon used at biomethane plants requires a surplus of oxygen to remove sulphur. Activated carbon without oxygen requirement exists, but is substantially more expensive, so not used at biomethane plants. Value based on input from supplier of activated carbon [15].
Reduced cost of FeCl by using in-situ O2	30%	Biomethane plants removing sulphur upstream of upgrading often use a combination of iron chloride and in-situ oxygen injection in the digester to precipitate sulphur. Prices are found for sulphur removal with iron chloride [14], but no source of price with in-situ oxygen was found. Varying feedback from plant owners on how effective oxygen injection is. Assumed reduction in price, based on biomethane plant being willing to invest in extra equipment.

Assumption	Value	Explanation/reference
Average injection compared to maximum injection in gas storage facilities	33%	Storage data only lists maximum injection, but the average flow (and thus how many m^3 of oxygen that actually need removal annually) will be lower. Value set based on Danish data [11].
Cost of air cooling	0.02 kWh/kWh	kWh power required per kWh heat removed. If catalytic removal is necessary at a biomethane plant, the biomethane needs to be cooled after catalytic treatment. Value based on input from cooling at a biomethane plant [16].
Conversion rate, EUR to USD	1.07	[17]
Conversion rate, EUR to DKK	7.44	[17]
Payback time for catalytic plant	10 years	
Interest rate for catalytic plant	6%	
HHV biomethane	11 kWh/Nm^3	Typical value
HHV natural gas	11,28 kWh/Nm^3	Based on average value in the Danish gas grid in 2021 [11]. Mainly imported from Germany.
Natural gas price	0,15 €/kWh	Typical 2022 price in Denmark. Lots of uncertainty on this value at the moment due to the Ukrainian war, but it only has a smaller influence on the result. It is only used here for gas consumption during catalytic removal of oxygen.
Power price	0,25 €/kWh	Typical 2022 price in Denmark. Lots of uncertainty on this value at the moment due to the Ukrainian war, but it only has a smaller influence on the result. It is only used here for gas consumption during catalytic removal of oxygen.
Cost man hours	50 €/h	

In addition, it is assumed that natural gas consumption does not decrease during the period where biomethane production increases. This assumption is not valid, as gas consumption is expected to decrease during the coming years. However, it complicates the calculations to also have the national gas consumption as a variable. Instead, results can both be evaluated with current gas consumption and with a lower gas consumption in the future (e.g. a reduction of 20%). This will give a more nuanced impression of possible expenses.

5.2. Upgrading technologies

For this analysis tool, only four different kinds of upgrading technologies are considered:

- Membrane plants
- PSA (pressure swing adsorption) plants
- Water scrubbers
- Amine scrubbers

This choice was made because it is believed to cover the most common upgrading techniques and because these are the four upgrading techniques the author has sufficient knowledge of to make calculations for current and alternative sulphur cleaning etc.

Figure 5 below shows the most used biogas upgrading technologies in Europe in 2019 [18]:

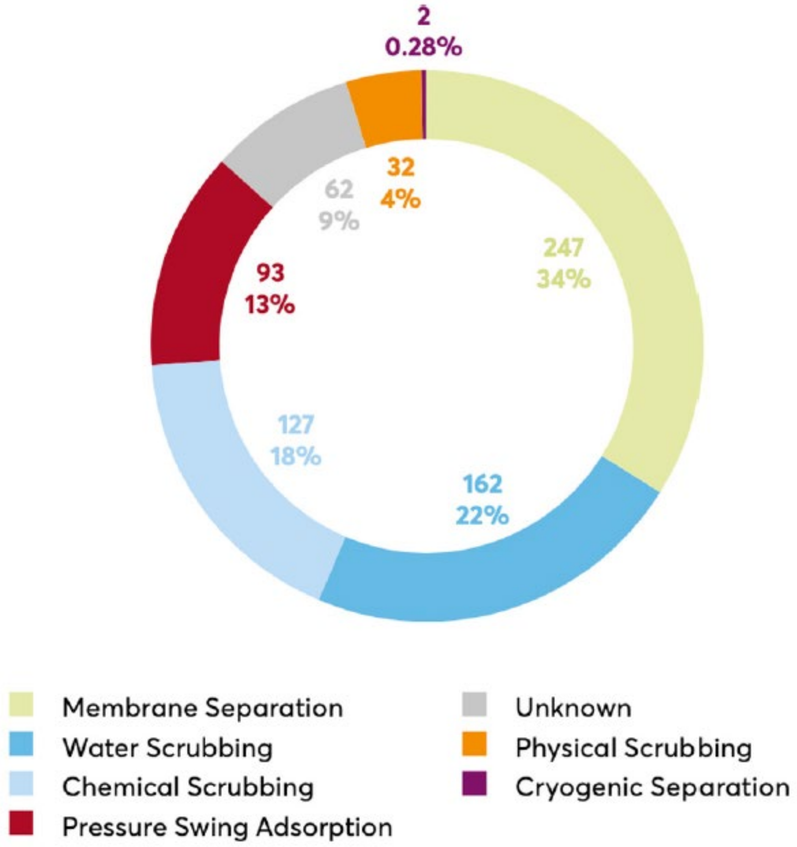


Figure 5 Most used biogas upgrading technologies in Europe 2019 [18].

As can be seen from Figure 5, more than 85% of the upgrading plants in Europe are covered by the four types listed above (assuming that most of the chemical scrubbers are amine plants). The type of upgrading techniques is only relevant for the analysis tool for deciding which methods for sulphur cleaning are applicable – mostly meaning whether sulphur must be removed upstream or can be removed downstream – and if the upgrading itself adds oxygen.

For the sake of other/unspecified upgrading techniques in the analysis tool:

- “Chemical scrubbing” is assumed to be amine scrubber (or at least be able to handle sulphur downstream like amine plants)
- “Physical scrubbing” is assumed to be a PSA plant (meaning all sulphur must be removed upstream.
- “Cryogenic separation” is assumed to be a PSA plant (which it is not, but sulphur removal must be upstream like for PSA). None of the countries, that has been considered as examples, had cryogenic separation listed as an upgrading plant.

For calculating oxygen levels in the biomethane and in the grid, the following oxygen levels are assumed (based on Danish data) *if no changes are made* to ensure that biomethane is produced with low/no oxygen [5][7][9]:

Table 3 Normal oxygen levels in biomethane depending on upgrading technology [5][7][9].

Upgrading type	Normal oxygen level in biomethane
Membrane plant	0.2%
PSA plant	0.2% *
Water scrubber plant	0.3%
Older amine plant (2017 or older)	0.2% *
New amine plant (2018 or newer)	< 0.01% #

** Assumed value based on data for membrane plants, as they use same sulphur cleaning method*

 # No deliberate oxygen added. Values of 0,01-0,02% were measured with gas chromatograph at two plants, but leak with false air intake detected afterwards. Awaiting new measurements.

5.3. Sulphur cleaning

Biogas has a natural content of sulphur. It can vary depending on the biomass used, but it will need sulphur removal somehow. Some upgrading processes can handle high sulphur concentration in the biogas, allowing for downstream sulphur removal – typically from the CO_2 off-gas. Other upgrading technologies cannot tolerate even small amounts of sulphur and require thorough upstream sulphur removal.

The most common upstream sulphur removal technique is sulphur reduction with iron chloride (or similar iron compound) and in-situ oxygen injection in the digester, followed by an activated carbon filter (requiring a surplus of oxygen) to remove remaining sulphur. This results in a relatively high oxygen concentration in the biomethane, as can also be seen from Table 3.

Two alternative methods for removing sulphur upstream without adding oxygen to the biomethane are:

- Reduction of sulphur with iron chloride in the digester, followed by a more expensive kind of activated carbon that does not require oxygen. This is a low CAPEX, high OPEX solution, and it is simple to operate [4][9].
- External biological cleaning (sometimes referred to as 'chemical wash with biological regeneration'), followed by a small guard bed with the expensive, oxygen-free activated carbon. This is a high CAPEX, low OPEX solution, but has the best overall economy for plants with capacities higher of around 300 Nm^3/h biomethane and up [4][9]. It is also a more complex process to operate and maintain, requiring more skill of the operator to ensure uninterrupted operation and sufficient sulphur removal [25].

The most common downstream sulphur removal technique on newer upgrading plants is biological cleaning of the CO_2 stream. This technique does not add oxygen to the biomethane, so if the biogas is kept oxygen-free, oxygen levels in the biomethane will be negligible, as can be seen from Table 3.

For more information on sulphur cleaning technologies, uses and economy of these, reference is made to [4].

For the purposes of the analysis tool and calculating extra expenses if the biomethane is to be "oxygen-free" (or at least very low in oxygen), the following assumptions are made for current sulphur cleaning and available, alternative method to achieve "oxygen-free" biomethane [9]:

Table 4 Assumptions for current sulphur cleaning technologies for each type of upgrading plant together with available alternatives (sulphur cleaning or catalytic oxygen removal) to avoid oxygen in the injected biomethane [9].

Upgrading technology	**Current sulphur cleaning**	**Available, alternative sulphur cleaning methods OR catalytic removal**
Membrane	Iron chloride + in-situ O_2 + activated carbon	Iron chloride + O_2-free activated carbon External biological cleaning Catalytic oxygen removal

Upgrading technology	Current sulphur cleaning	Available, alternative sulphur cleaning methods OR catalytic removal
PSA	Iron chloride + in-situ O_2 + activated carbon	Iron chloride + O_2-free activated carbon External biological cleaning Catalytic oxygen removal
Old (<2018) water scrubber	Iron chloride + in-situ O_2 + activated carbon	Catalytic oxygen removal
New water scrubber	Biological cleaning of CO_2 off-gas	Catalytic oxygen removal
Old (<2018) amine scrubber	Iron chloride + in-situ O_2 + activated carbon	Iron chloride + O_2-free activated carbon External biological cleaning Catalytic oxygen removal
New amine scrubber	Biological cleaning of CO_2 off-gas	Biological cleaning of CO_2-off-gas Iron chloride + O_2-free activated carbon External biological cleaning Catalytic removal

The analysis tool will choose whichever method is the cheapest (combined CAPEX and OPEX) for that size upgrading plant.

In general, external biological cleaning has much better overall economy than iron chloride with oxygen-free activated carbon - even for relatively small plants. As a result, this solution will be chosen in most cases by the analysis tool if oxygen-free, upstream sulphur cleaning is required. However, due to high capital cost, it will require someone being willing to lend the money for this retrofit, as the small biomethane plants will most likely have difficulties raising the money for the investment themselves.

If it is not possible to lend the money, a more expensive solution with iron chloride and oxygen-free activated carbon will be necessary. As a result, handling the oxygen at each biomethane plant will be more expensive, which could influence the decision of where (biomethane plants or gas storage facilities) oxygen is handled most cost-efficiently.

5.4. Gas storage facilities

For gas storage facilities, the following types of storages and maximum oxygen content are used based on limits in EN 16726:

Table 5 Storage facility types and maximum allowable oxygen level in each used in the analysis tool.

Storage type	Maximum oxygen level in injected gas
Salt cavern	0.001%
Aquifer	0.001%
Depleted field	0.001%
Other/unknown	0.001%

Based on input from the Danish gas storage provider [10] and discussions in [2], the technical limit for oxygen in salt caverns could perhaps be higher than for the other storage types. Additionally, the levels in Table 5 are based on a safety principle, as there is only very little/no experience with the effect of oxygen in the gas storage facilities so far. Limit values in EN 16726 could be revised if research or future experiences show higher tolerance for oxygen in the storages. However, for the sake of the calculations in this analysis tool, the limits are set based on the limits in EN 16726.

In the analysis tool, when calculating expenses for handling oxygen at the storage facilities, a catalytic plant for oxygen removal is assumed necessary if the maximum oxygen concentration in the injected gas surpasses the maximum allowable oxygen content. If oxygen limits for the storage types should be revised/increased, this will mean a shift in when/at how high national biomethane share a given gas storage facility would require installation of a catalytic plant.

6. Input and background data

In order to calculate expenses with the developed analysis tool, input data for prices and countries are required. The background for these data is described in the subsections below.

6.1. Prices for sulphur cleaning

Prices for sulphur cleaning have previously been collected by Danish Gas Technology Centre and reported in collaboration with the Danish Environmental Protection Agency in Denmark [14]. The analysis tool builds on prices from this project.

For sulphur removal not directly calculated/reported in this project (e.g. oxygen-free activated carbon), prices are estimated using the assumptions given in Table 2 in Section 5.1.

6.2. Prices for catalytic oxygen removal

For catalytic removal of oxygen, two options are available:

- Oxidation of the hydrocarbons in the natural gas
- Oxidation of hydrogen injected into the gas stream

The latter option has a lower reaction temperature (less than 100 °C [19]) but will require more difficult infrastructure – either hydrogen grid close by or water with local hydrogen production through electrolysis – and careful dosing of hydrogen to avoid hydrogen injection in the storage facilities (which storage owners are also worried about).

The former option requires substantially higher temperatures (300-500 °C depending on hydrocarbons [20]) but some of this can be recovered using a feed-effluent heat exchanger. At oxygen levels of 0.4% or above, the reaction is self-sustaining and does not require heating.

Due to a combination of uncertainties of available infrastructure and vendor input received within the time frame of this project, the analysis tool is based on catalytic reaction of oxygen with the available hydrocarbons [20].

The supplier provided prices for both small-scale (300, 1,000 and 3,000 Nm^3/h biomethane) and large-scale (100,000, 500,000 and 1,000,000 Nm^3/h natural gas) catalytic plants. The small plants were without drying (the oxygen will react to produce water), as biomethane plants already have drying installed, and the small extra OPEX from the higher water content is deemed insignificant compared to other factors. The large catalytic plants for gas storage facilities have drying included.

The price for catalytic removal will be a combination of CAPEX expenses, oxygen-independent OPEX (service, catalyst replacement, manhours, power consumption), and oxygen-dependent OPEX (loss of oxidised natural gas, expenses for drying, expenses for heating/cooling). Expenses for heating/cooling have been calculated as a function of oxygen content using Aspen Hysys and input from [20].

Based on the supplied prices, data was extrapolated to achieve prices for other flow sizes.

6.3. Input data for countries

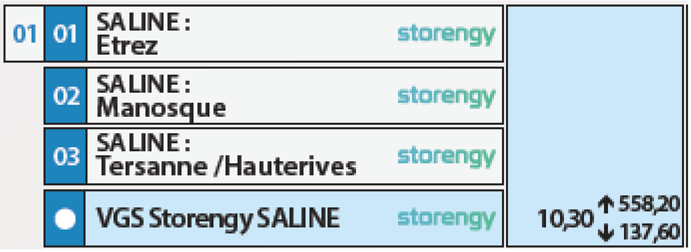
In order to demonstrate and use the developed analysis tool, data for gas consumption, biomethane plants and gas storage facilities for various countries was necessary. This data was found from the gas infrastructure maps produced each year by GIE [21].

GIE Storage Map European Biomethane Map System Development Map

Figure 6 Maps with input data for the analysis produced by GIE [21].

The latest version of the biomethane map (2021) did not contain upgrading technology, but the 2020 version did. Biomethane plants with unknown upgrading technology were assigned at random based on the distribution for the other plants. For France, no upgrading data was available for any of the plants in the 2020 map. Here, upgrading technology was assigned at random based on approximate shares specified by contact in France [22]. This method was deemed sufficient, as almost all plants are either membrane and PSA, and they are handled the same way by the analysis tool.

For the storage facility map, some facilities are owned/run by the same operator, and for these only the total sum of the injection rates was given:



01 01 SALINE : Etrez storengy
02 SALINE : Manosque storengy
03 SALINE : Tersanne /Hauterives storengy
● VGS Storengy SALINE storengy
10,30 ↑558,20 ↓137,60

Figure 7 Example of how sometimes the storage map only contains a combined value for capacity and withdrawal/injection rate. Here, the total injection capacity (137.6 GWh/day) was evenly distributed among the three physical storage facilities (45.9 GWh/day each).

Unless other input was available, the injection rate was assumed to be evenly distributed among the storages.

For the national gas consumption data, the system development map contains the following data for each country:

Total 2020	966.900	GWh
Summer	315.800	GWh
Winter	679.000	GWh
Max. Day (12/02/2021)	6.011	GWh/d
Min. Day (05/07/2020)	1.176	GWh/d

Figure 8 Example of gas consumption data in the GIE System development map. Summer consumption covers the 6-month period from April 1st to September 30th.

The lowest monthly consumption could either be calculated by multiplying the day with minimum consumption with the number of days in the month, or by dividing the summer-consumption (covering April 1st-September 30th) by 6 months. The former would probably lead to under-estimation, while the latter would lead to over-estimation. To take this into account, the analysis tool calculates both and uses the average of the two methods as the minimum monthly consumption.

7. Results

Based on the methods and assumptions described in the previous sections, an analysis tool was developed. In order to use this tool to make recommendations for most cost-efficient way of handling the oxygen, four countries were selected for evaluation:

- Denmark - because they have the highest biomethane share in Europe (around 25% at the end of 2021 [12]) because of their high limit for oxygen in biomethane (0,5% [6]) results in ‘option 2’ (handling oxygen at gas storage facilities) without evaluating best solution, and because they have significantly larger biomethane plants and use of upgrading and sulphur treatment than other European countries.

- Germany because they have a long history of biomethane production, because their low limits for oxygen (10 ppm at storages [6]) currently automatically enforces ‘option 1’ (handling oxygen at the biomethane plants), and because the low oxygen limits can hinder biomethane growth and gas trading across borders.

- France - because they also currently have low oxygen limits (10 ppm), and because of recent very large growth in the number of very small biomethane plants.

- Italy - because they also have a high limit for oxygen (0.7% [6]), and because they seem to have more uneven distribution of biomethane plants across the country (almost all biomethane plants are located in Northern Italy). For Italy, user input on how localised biomethane production was, was set to the lowest value (i.e. more localised biomethane production than average in other countries, see Section 4.3).

For each country, expenses for option 1 and 2 will be calculated and plotted as a function of increasing biomethane share assuming that future growth in biomethane plants will be similar to existing plants. Results will be shown both in total extra cost in million €/year, and as an extra cost in €¢/Nm^3 biomethane produced. The latter number should be seen relative to total biomethane production expenses (entire production chain including injection) of around 60-80 €¢/Nm^3 biomethane depending on size (Danish 2019 value) [8].

In addition to these graphs, graphs will also be shown assuming future biomethane growth based on current technologies/sizes *but* avoiding upgrading plants with need for catalytic removal (see Section 4.5). This is done to show how this change will affect the choice of most cost-efficient solution. The price for installing catalytic oxygen removal at a biomethane plant is substantially higher than the price for avoiding oxygen through alternative sulphur treatment. In a reality with high ambitions for rapid biomethane growth and a limited number of upgrading unit suppliers, it might not be as simple to limit the choice of upgrading technology, but as this option has potential to be a very cost-effective solution, it still bears consideration.

While the gas storage operators are concerned about oxygen damaging their facilities, very little experience exists of how oxygen influences the gas storage facilities. Various research is investigating this, but no results are available yet [1][2][6][10]. The oxygen limit for injection in the gas storage facilities will naturally influence the results of this project. To illustrate an example of this, results will be included for Denmark for an imagined situation where 1000 ppm oxygen is allowed in salt caverns, while 100 ppm oxygen is allowed in other types of storages.

To illustrate the difference between using external biological cleaning or iron chloride with oxygen-free activated carbon for upstream sulphur removal, an additional graph is shown for Germany, where it is assumed that due to investment issues and/or lack of the necessary technical skills, external biological cleaning is not an option for biomethane plants with capacities below 800 Nm^3/h.

A graph showing expenses based on current biomethane plants, but with a 20% reduction in gas consumption is shown for Germany to illustrate how this affects the choice of most cost-efficient solution.

Finally graphs for Italy for a higher actual-production-vs-nominal-capacity and for a lower H_2S will be shown to illustrate the effect of this on the conclusions.

In addition to the graphs for each country, Section 7.5 will show how the expenses for avoiding oxygen injection at the biomethane plants (option 1) depend on the upgrading technology and sizes of the plants. Deciding to build different types and sizes of biomethane plants in the future will influence expenses and thus the most cost-efficient way to handle the oxygen. Section 7.6 discusses the consequences of neighbouring countries deciding on different approaches.

7.1. Results for Denmark

As Denmark already has a quite high biomethane share, the graphs below only show results for biomethane shares higher than the current share. Denmark has an annual gas consumption around 2,400 million Nm^3 gas with a minimum monthly consumption of around 100 million Nm^3 gas. The existing biomethane plants are of the following types and sizes, with an overall average size of 1,400 Nm^3/h:

Table 6 Distribution in type and average size of biomethane plants in Denmark.

	Share (#/#)	Avg. Size Nm^3/h
Membrane	21%	700
PSA	0%	
Water scrubber	26%	1,300
Amine scrubber	53%	1,700
Distribution grid injection	95%	1,400
Transmission grid injection	5%	1,600

Figure 9 below shows the expenses if the future biomethane plants are built similar to the data in Table 6.

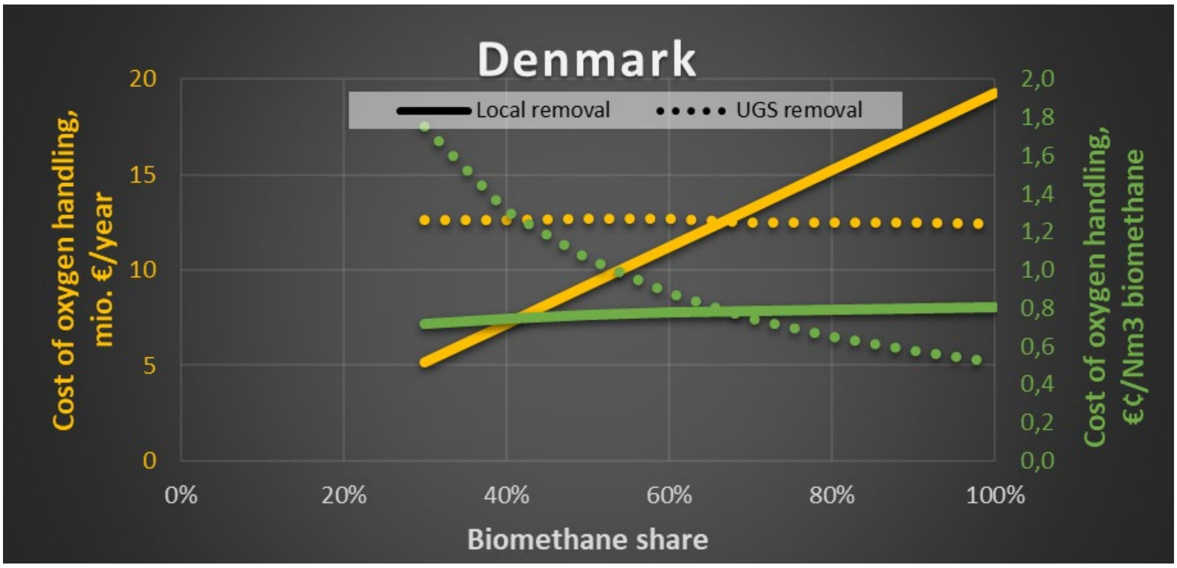


Figure 9 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants.

As can be seen from Figure 9, the annual extra expense for handling the oxygen with the currently existing biomethane plants will be approx. 5 million Euros each year if it is handled at each of the biomethane plants, while it will cost approx. 13 million Euros per year to handle it by catalytic removal at the storage facilities if necessary – so option 1 with handling at each biomethane plant is currently the cheapest solution. However, in a potential future with 100% biomethane production (as is the official target of the Danish government in 2030), the cost of handling oxygen at biomethane plants will be almost 20 million Euros, while handling at storage level will cost approx. 12 million Euros. The lower expense at 100% biomethane compared to 30% biomethane is because higher oxygen content reduces the expenses to heat the gas in the catalytic plants, as the oxidation process itself produces heat.

From a long-term perspective, if biomethane share is planned to surpass around 65%, it is cheaper to invest in catalytic removal at storage level now, than to invest in handling at biomethane plants now and either need to change approach in the future (and clean at storage facilities instead) or to have to adhere to a more expensive solution (and clean at biomethane plants).

The results above are calculated based on an oxygen limit of 10 ppm at the gas storage facilities. If instead 1000 ppm of oxygen was allowed in salt caverns and 100 ppm was allowed at other types of storage facilities (as is actually the case in Denmark due to current oxygen limit of 1000 ppm at storage points [6]), this would influence the results. Figure 10 below shows results similar to Figure 9, but with these higher oxygen limits:

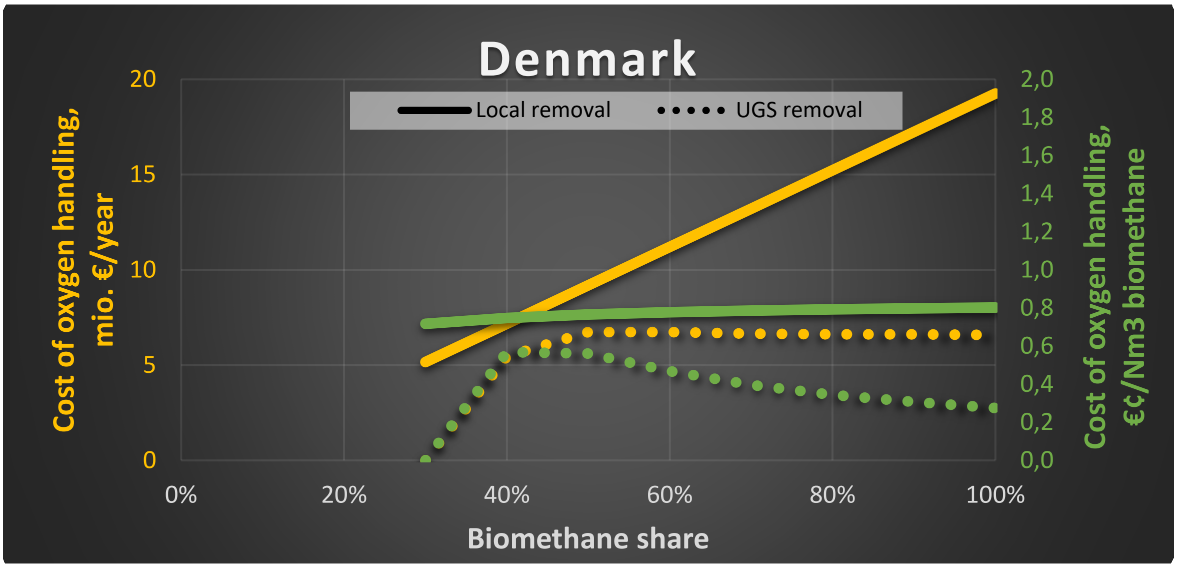


Figure 10 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants. Oxygen limit is assumed to be 1000 ppm at salt caverns and 100 ppm at other types of storage facilities.

As can be seen from Figure 10, this higher oxygen acceptance limit makes handling oxygen at the gas storage facilities significantly cheaper than before and is now the cheapest solution for any biomethane share. This change is due to fewer gas storages needing to install catalytic removal units. However, for this to actually be a cheaper solution, the consequences and extra expenses for allowing more oxygen in the gas storage facilities will have to be taken into account also.

However, these conclusions are all based on future biomethane growth similar to that of existing plants, including many conventional water scrubber plants requiring local catalytic cleaning. If it is assumed that future plants are built so catalytic cleaning is not required (with e.g. a redesigned water scrubber, amine scrubber or other, see Section 4.5), then the estimated expenses similar to Figure 9 are shown in Figure 11 below:

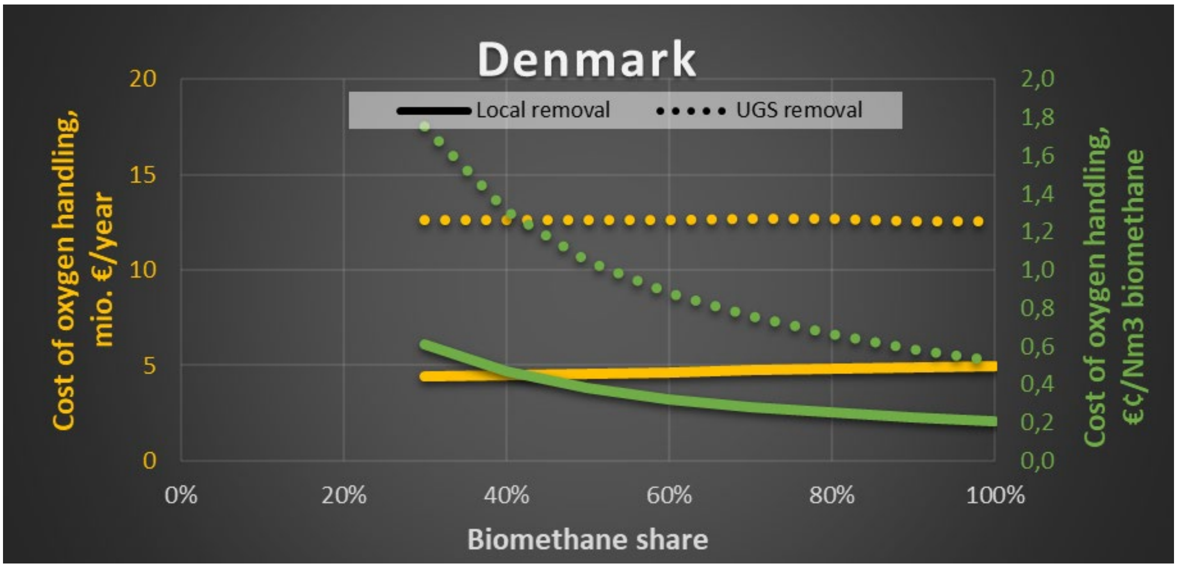


Figure 11 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities (UGS removal). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants BUT assuming upgrading type, so catalytic oxygen removal is not needed, and sulphur can be removed downstream.

As can be seen from Figure 11, the expenses for handling oxygen at storage facilities are the same as in Figure 9, but now the annual expense for handling oxygen at biomethane plants is constant at approx. 5 million Euros, primarily consisting of the expenses for retrofitting of existing biomethane plants. Due to this, option 1 (handling oxygen at the biomethane plants) will be the most cost-efficient solution both now and for higher biomethane shares. It should be noted, however, that this conversion will require investment in different sulphur cleaning technologies (higher CAPEX and lower OPEX compared to conventional solutions).

In conclusion for Denmark, if the ambition is a 100% biomethane share, handling oxygen at the storage facilities will be most cost-efficient if no restrictions are made for new biomethane plants. If new biomethane plants are required to use technologies enabling oxygen-free production without catalytic cleaning, handling oxygen at the biomethane plants will be the most cost-efficient solution.

7.2. Results for Germany

Germany has an annual gas consumption around 86,000 million Nm^3 gas with a minimum monthly consumption of around 3,900 million Nm^3 gas. The existing biomethane plants are of the following types and sizes, with an overall average size of 600 Nm^3/h:

Table 7 Distribution in type and average size of biomethane plants in Germany.

	Share (#/#)	**Avg. Size Nm^3/h**
Membrane	8%	500
PSA	31%	600
Water scrubber	28%	600
Amine scrubber	34%	600
Distribution grid injection	26%	500
Transmission grid injection	74%	700

As can be seen from Table 7 compared to

Table 6, the biomethane plants are significantly smaller than in Denmark, and a much higher ratio of biomethane plants injects directly into the transmission grid. The latter will result in higher oxygen levels in the transmission grid compared to a situation where most was injected in the distribution grid, with biomethane and oxygen only reaching the transmission grid in case of local overproduction.

Figure 12 below shows the expenses for handling oxygen in Germany if future biomethane growth is similar to that of existing plants:

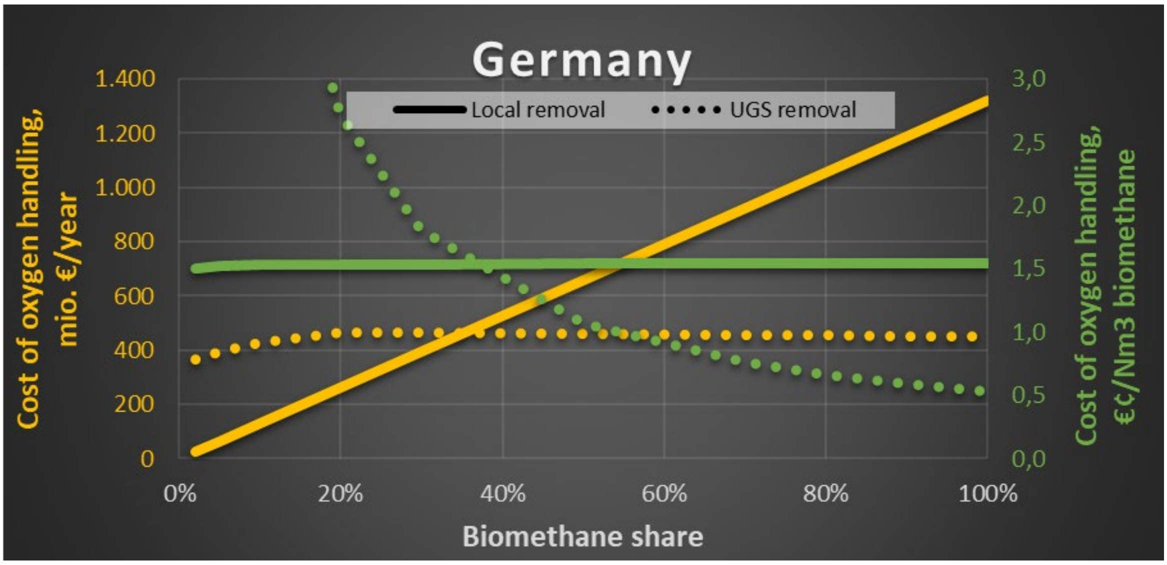


Figure 12 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants.

As can be seen from Figure 12, handling oxygen at the biomethane plants is cheaper until biomethane shares reach around 35%. If national ambitions for biomethane share in the future surpass 35%, it is cheaper to allow oxygen injection and install catalytic removal at gas storage facilities when needed.

To see the effect of combining increased biomethane production with decreasing natural gas consumption, the similar graph with a 20% reduction in gas consumption is shown below:

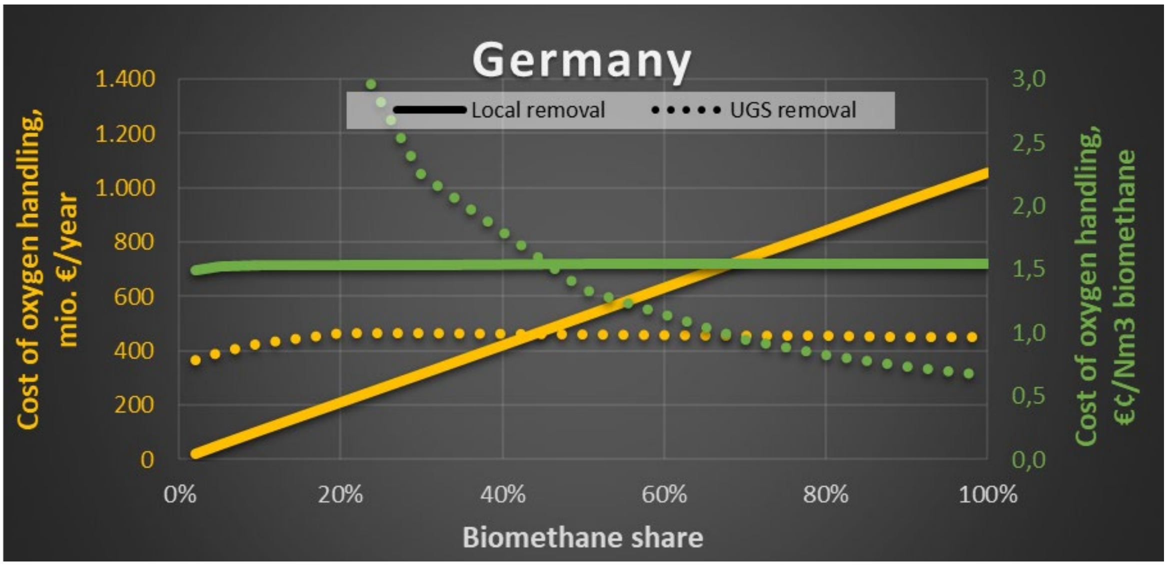


Figure 13 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants. National gas consumption reduced with 20% compared to 2021 value.

As can be seen from Figure 13, the tipping point for cheapest solution has shifted to around 45%, so no significant changes in conclusions or recommendations.

Figure 14 below shows the expenses for the alternative future, where biomethane plants are built so no catalytic cleaning is required (see Section 4.5):

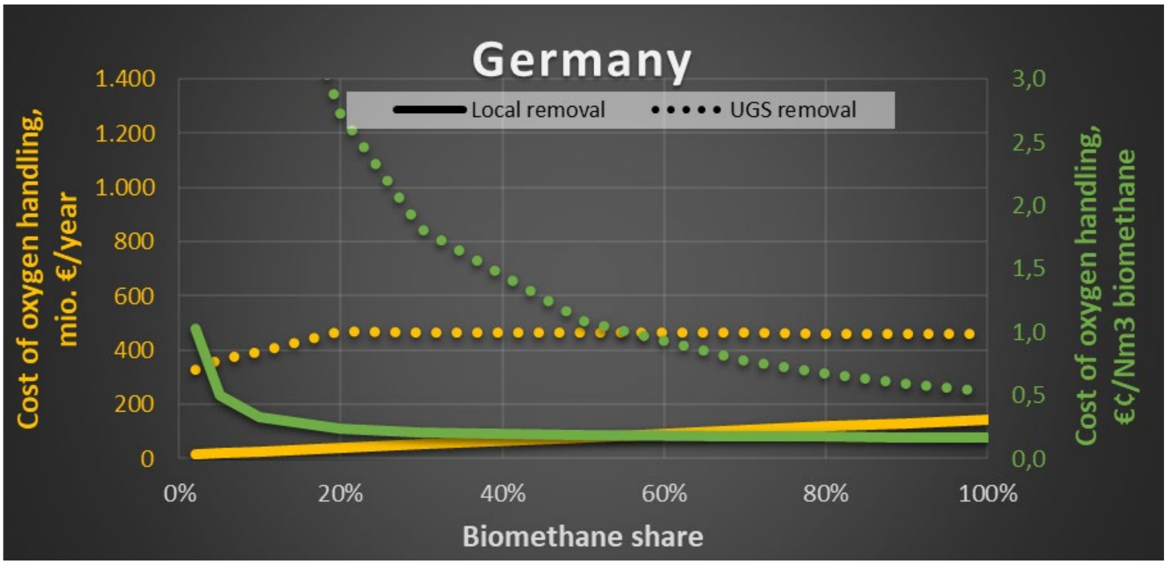


Figure 14 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities (UGS removal). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants BUT assuming upgrading type, so catalytic oxygen removal is not needed, and sulphur can be removed downstream.

As can be seen from Figure 14, this completely changes recommendations for cheapest solution. If future biomethane plants are built so catalytic cleaning is not necessary, handling the oxygen at the gas storage facilities is the cheapest solution for the entire range of biomethane shares.

Again, this solution will require the investment cost for the retrofit (typically biological cleaning) to be found/supported somehow. It is a high CAPEX, low OPEX method, and small biomethane plants might have difficulties raising the necessary investment costs for the transition.

Another complication could be that the staff at small biomethane plants often do not have a technical education (operating the biomethane plant is a secondary task, while primary task is work at the farm) [7][25]. This could lead to technical difficulties with running and maintaining a more complicated process like the external biological cleaning. The result could be plugging of the system, insufficient sulphur cleaning etc., leading to more down-time and higher actual cost of this solution [25].

As a result of lack of funding and/or technical difficulties, small biomethane plants might have to choose the more expensive oxygen-free solution for sulphur removal: iron chloride with oxygen-free activated carbon. If this is assumed to be necessary for biomethane plants with capacities less than 800 Nm^3/h, Figure 14 would have looked like this instead (note different scale on the left y-axis):

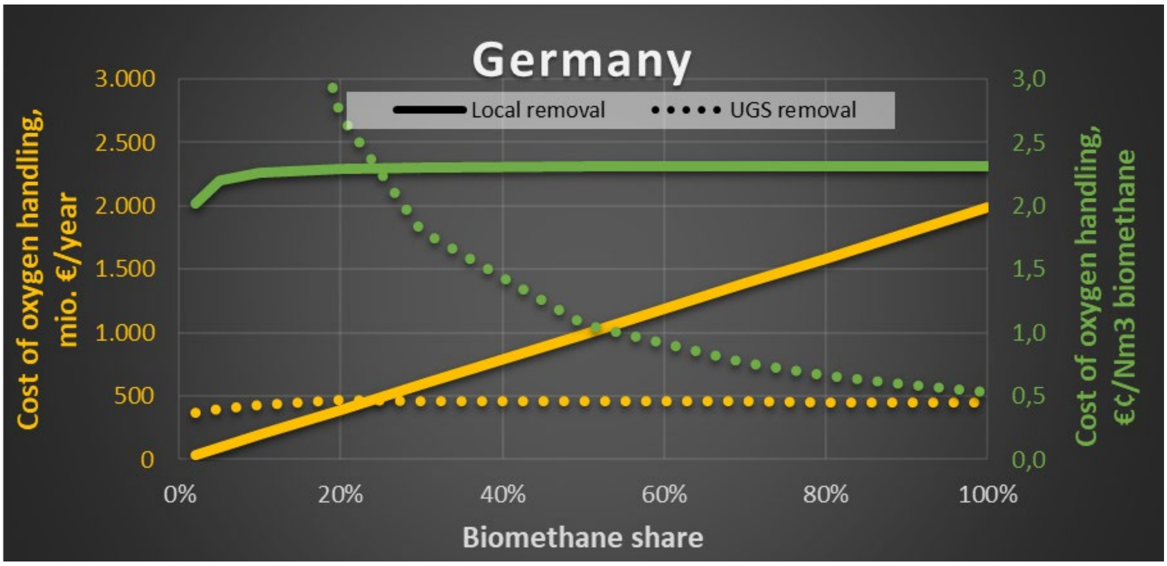


Figure 15 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities (UGS removal). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants BUT assuming upgrading type, so catalytic oxygen removal is not needed, and sulphur can be removed downstream. External biological cleaning is assumed to only be feasible at plants with capacities of 800 Nm^3/h or above.

As can be seen from Figure 15, the result is that oxygen handling at the biomethane plants is much more expensive, and thus oxygen handling at the gas storage facilities will be the cheapest solution for a biomethane share of around 25% and up.

7.3. Results for France

France has an annual gas consumption around 41,000 million Nm^3 gas with a minimum monthly consumption of around 1,600 million Nm^3 gas. The existing biomethane plants are of the following types and sizes, with an overall average size of 200 Nm^3/h:

Table 8 Distribution in type and average size of biomethane plants in France.

Type	Share (#/#)	Avg. Size Nm³/h
Membrane	75% *	200 *
PSA	23% *	200 *
Water scrubber	1% *	800 *
Amine scrubber	1% *	1,000 *
Distribution grid injection	86%	200
Transmission grid injection	14%	300

** As no data on upgrading technology was available on the biomethane map from GIE (see Section 6.3), upgrading technology was assigned at random based on input from [22] on approximate share of each technology and an assumption that the biggest plants would be scrubbers.*

As can be seen from Table 8, the biomethane plants are significantly smaller than in both Denmark and Germany. The majority of the biomethane is injected in the distribution grid, meaning local overproduction is required for a substantial amount of oxygen to reach the grid. The share of water scrubber plants is much lower than for Denmark and Germany, meaning relatively few biomethane plants will require catalytic removal to be converted to oxygen-free production.

Figure 16 below shows the expenses if future biomethane plants is built similar to existing biomethane plants:

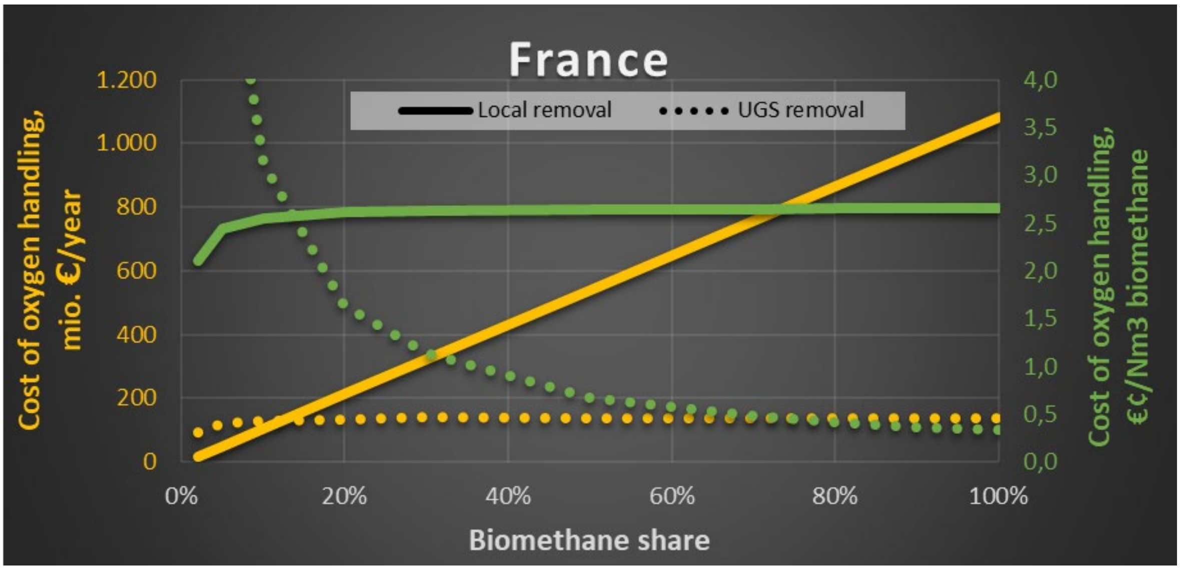


Figure 16 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants.

As can be seen from Figure 16, local removal at each biomethane plant is cheapest until a biomethane share around 15%. For biomethane shares above this, catalytic removal at the gas storage facilities is cheaper.

Since the share of water scrubbers is already very low, the results look quite similar for future growth in biomethane plants without need for catalytic removal (see Section 4.5):

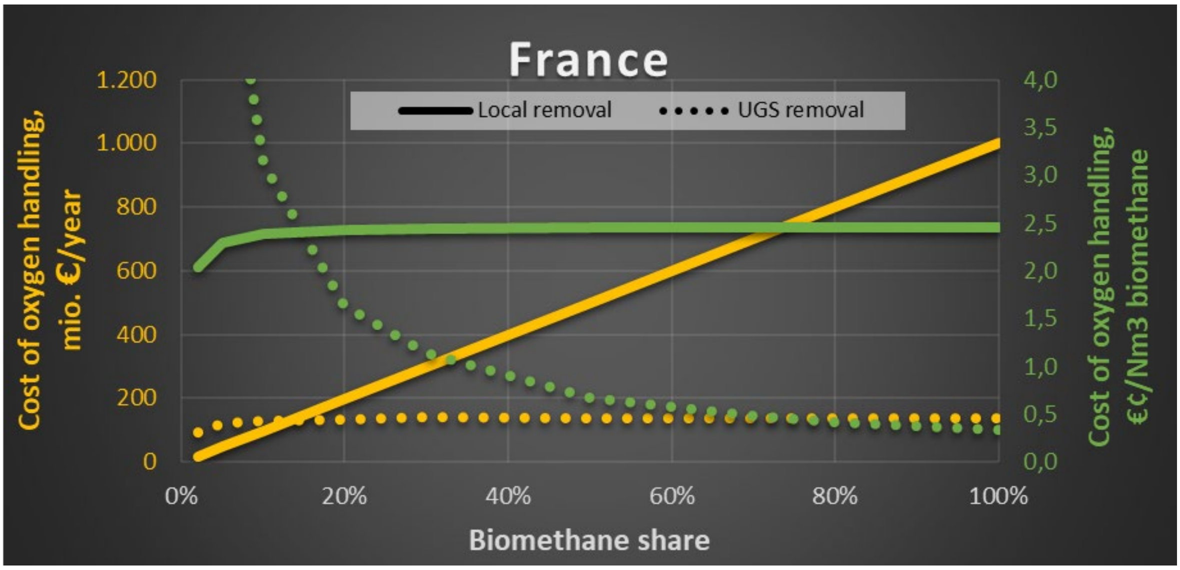


Figure 17 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities (UGS removal). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants BUT assuming upgrading type, so catalytic oxygen removal is not needed, and sulphur can be removed downstream.

As can be seen from Figure 17, this changes very little from the conclusions and recommendations from Figure 16. This is completely different from the results for Denmark and Germany, where a future with biomethane plants without need for catalytic removal meant that removal at the biomethane plants was by far the cheapest solution.

The reason for this different result is the very small biomethane plant sizes in France. In order to produce oxygen-free with membrane or PSA, either external biological cleaning or iron chloride with oxygen-free activated carbon is required. The former has a very high CAPEX, which is unfavourable for small plants because of economy of scale. In addition, it is assumed to be infeasible for biomethane plants with capacities of 200 Nm^3/h (which is the average size of French biomethane plants) or lower for economical and investment reasons. The latter is simply a very expensive solution. Due to this, handling oxygen at each biomethane plant is quite expensive even without plants needing catalytic cleaning.

If the size of the biomethane plants in the future could be increased by 100-200%, this would both give better economy of scale and probably enable the use of external biological cleaning. The expenses for 200% bigger biomethane plants and no plants requiring catalytic cleaning are shown below (note different scale on left y-axis):

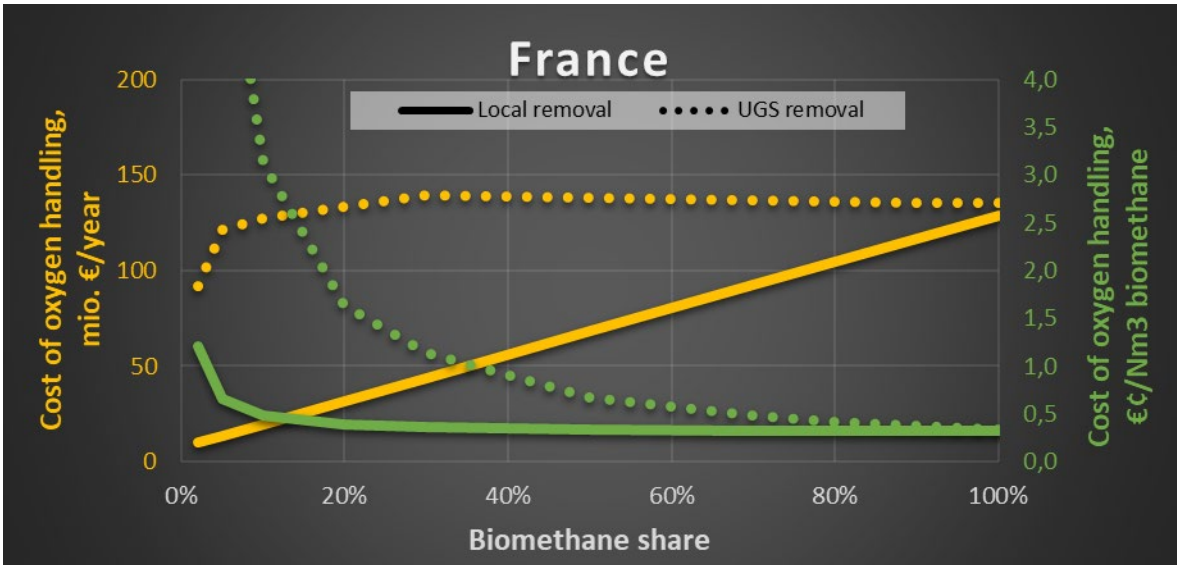


Figure 18 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities (UGS removal). Future biomethane growth is assumed to be with upgrading technologies similar to existing plants BUT assuming upgrading type, so catalytic oxygen removal is not needed, and sulphur can be removed downstream. The size of future biomethane plants is assumed to be 200% bigger than current biomethane plants of same technology.

As can be seen from Figure 18, now handling oxygen at the biomethane plants is cheaper than removal at the gas storage facilities for all biomethane shares.

7.4. Results for Italy

Italy has an annual gas consumption around 66,000 million Nm^3 gas with a minimum monthly consumption of around 3,300 million Nm^3 gas. The existing biomethane plants are of the following types and sizes, with an overall average size of 1,000 Nm^3/h:

Table 9 Distribution in type and average size of biomethane plants in France.

Type	Share (#/#)	Avg. Size Nm³/h
Membrane	63%	1,300
PSA	33%	400
Water scrubber	4%	1,000
Amine scrubber	0%	
Distribution grid injection	33%	400
Transmission grid injection	67%	1,300

As can be seen from Table 9, the biomethane plants are smaller than in Denmark, but significantly larger than in Germany and France. As in Germany, the majority of the biomethane is injected in the transmission grid. It is noted that no amine plants exist in Italy. According to [24], this is due to Italy worrying about the possibility of amines in the biomethane.

The graph below shows expenses for handling oxygen if future growth in biomethane plants is similar to that of existing plants:

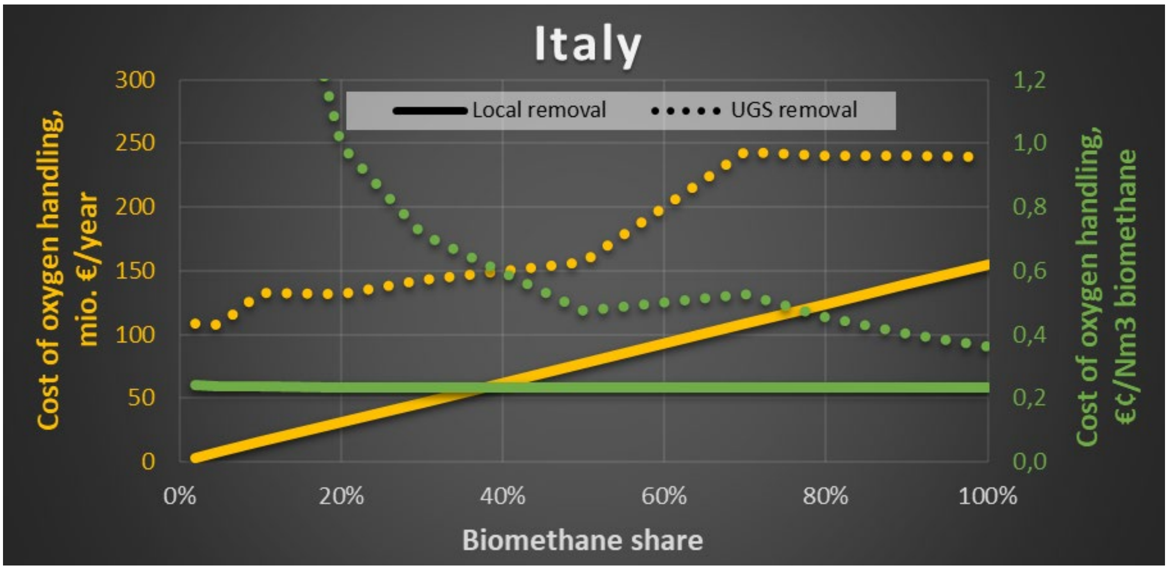


Figure 19 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants.

As can be seen from Figure 19, handling oxygen at the biomethane plants is the cheapest solution independent of biomethane share. This conclusion differs significantly from the other countries shown here, where handling oxygen at the storage facilities became the cheapest solution at a given biomethane share and up. The background for this difference is a combination of the large biomethane plants (meaning better economy of scale) and a relatively small amount of water scrubbers needing catalytic removal of oxygen.

As for the other countries, it is relevant to also look at the consequences of a future where biomethane is produced without needing catalytic cleaning at some plants. However, since Italy currently appears to be against building amine scrubbers, this is not a good substitute for the model as it was for the other countries. And since (to the author's knowledge) no existing water scrubbers can produce biomethane without adding oxygen, a future with conventional water scrubbers will require catalytic removal.

Instead, a future with new biomethane plants similar to current plants but without catalytic cleaning (see Section 4.5) is modelled by assuming membrane plants as a substitute for water scrubbers, as the sizes are similar (see Table 9). The results are shown below:

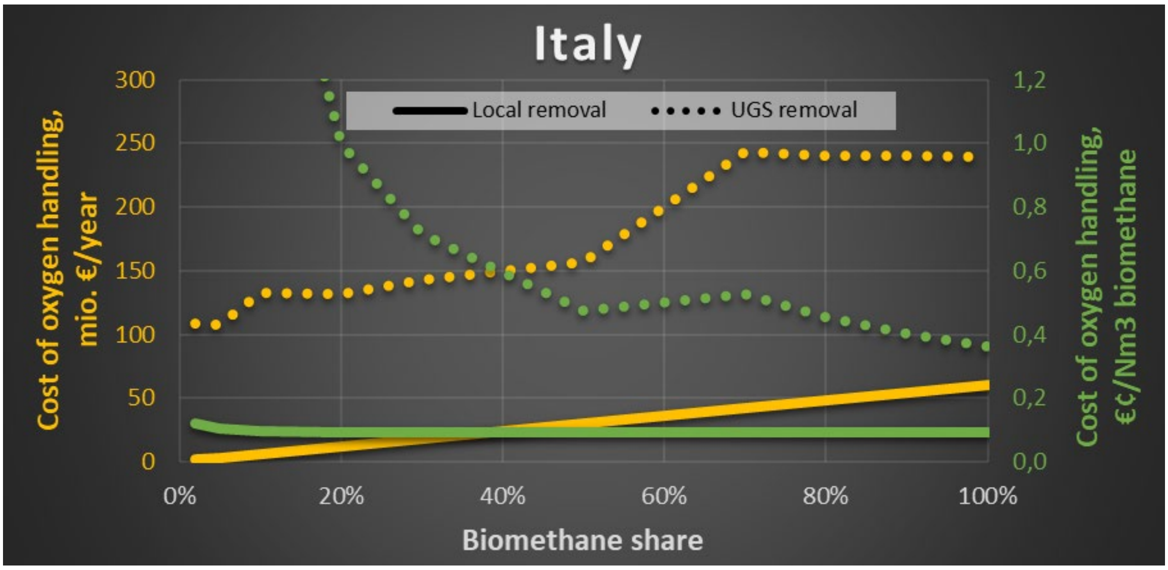


Figure 20 Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities (UGS removal). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants BUT assuming water scrubbers are substituted with membrane plants.

As can be seen from Figure 20, the overall conclusion is the same (i.e. that oxygen handling at each biomethane plant is the cheapest solution), but the total expense is lower.

To illustrate how the assumptions of H_2S concentration in the biogas and actual-production-vs-nominal-capacity influence the conclusions, the calculations from Figure 19 are repeated but with first an average production capacity of 80% of nominal capacity (instead of normal assumption of 90%)

and then with 1000 ppm H_2S (instead of normal assumption of 2000 ppm). The results are shown below:

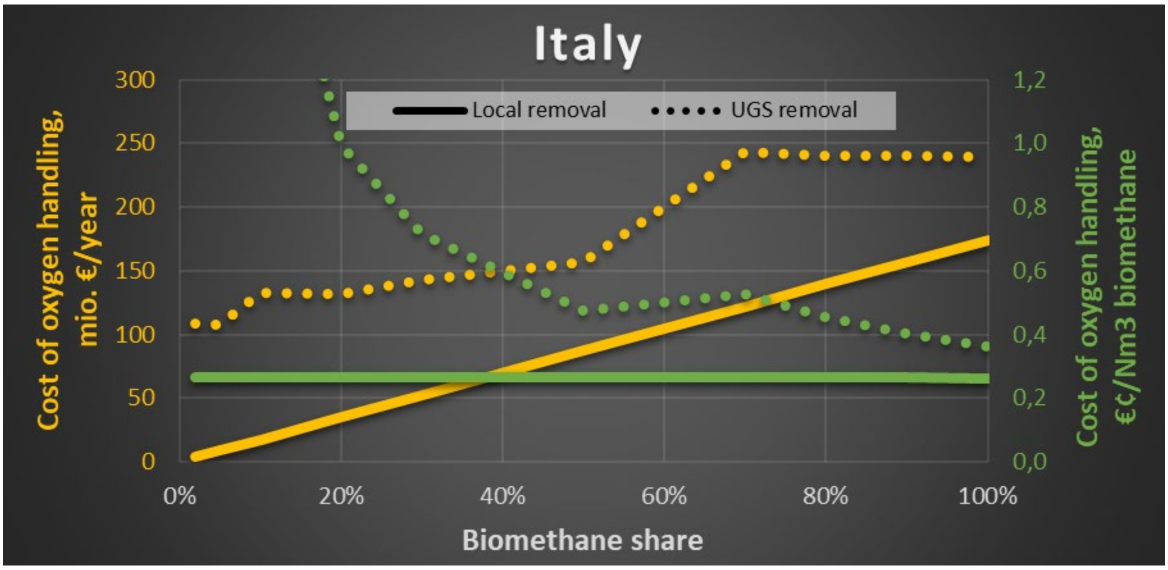


Figure 21: Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants, but average production capacity is assumed to be 80% of nominal capacity, instead of normal assumption of 90% in the analysis tool.

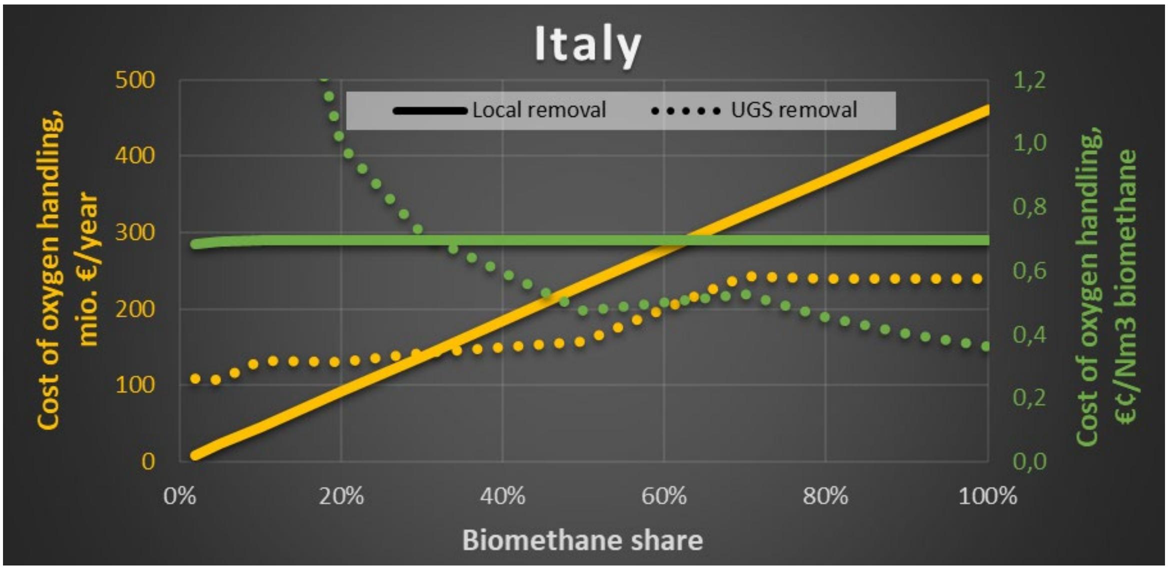


Figure 22: Expenses for handling oxygen either at the biomethane plants ("local removal") or at the storage facilities ("UGS removal"). Future biomethane growth is assumed to be with upgrading technologies and sizes similar to existing plants, but H_2S concentration in biogas is assumed to be 1000 ppm instead of normal assumption of 2000 ppm in the analysis tool.

As can be seen from Figure 21, the lower actual-vs-nominal production rate of the biomethane plants only has a relatively small influence on the expenses for handling the oxygen at the biomethane plants, and thus the conclusion is still the same: the cheapest method for handling the oxygen is at the biomethane plants independent of biomethane share.

In contrast, Figure 22 shows how a lower H_2S concentration in the biogas has a large impact on the expenses and thus conclusions. The lower H_2S concentration means that the external biological cleaning suddenly becomes significantly more expensive relative to the existing sulphur cleaning method with iron chloride, oxygen and activated carbon. Due to this, handling the oxygen at the gas storage facilities becomes the most cost-efficient solution at biomethane shares above approx. 30%.

7.5. Dependence on upgrading technology and capacity

As should be evident from the conclusion from Section 0-7.4 for each country, the choice of upgrading technology and plant capacity plays a significant role in the expenses for handling the oxygen and what solution might be the most cost-efficient for a given country. To emphasize this further, Figure 23 below shows the annual expenses in million € for handling oxygen at the biomethane plants for a hypothetical country with an annual gas consumption of 50,000 million Nm^3.

Four possibilities for biomethane plants are shown: Small and large plants as given by Table 1 in Section 4.5, and the same small and large plants as in Table 1, but avoiding upgrading plants requiring catalytic removal (see Section 4.5):

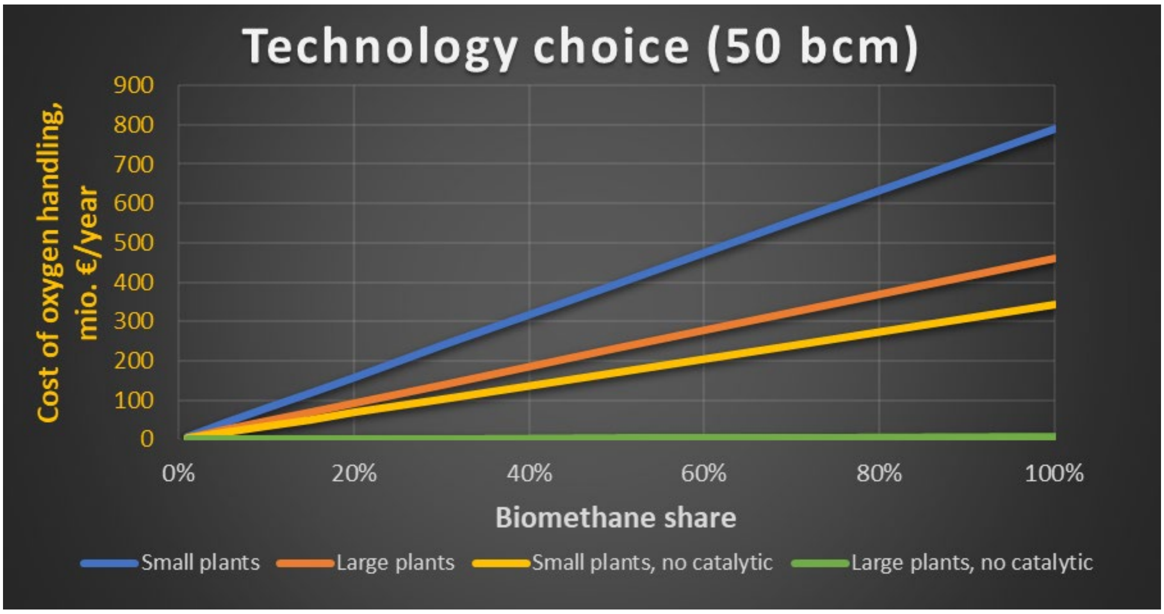


Figure 23: Expenses for handling oxygen at biomethane plants depending on type and size of biomethane plants for a hypothetical country with an annual consumption of 50,000 million Nm^3.

As can be seen from Figure 23, handling oxygen is cheaper for large biomethane plants than for small biomethane plants due to economy of size and available sulphur cleaning technologies. If need for catalytic cleaning at the biomethane plants is also avoided, then avoiding oxygen is even cheaper.

Table 10 below shows the expenses for Figure 23 as €¢/Nm^3 and compares this number to the expenses for upgrading biomethane and for the entire biomethane production value chain (Danish 2019 values) [8]:

Table 10 Expenses in €¢/Nm^3 for different scenarios as well as %-wise increase in cost compared to just upgrading price or entire biomethane production value chain (2019 prices) [8].

Scenario	**Extra expense €¢/Nm^3**	**%-extra compared to price for sulphur cleaning, upgrading and injection #**	**%-extra compared to total price of biomethane production ¤**
Small plants	1.6	10%	1.9%
Large plants	0.9	12%	1.5%
Small plants, no catalytic cleaning	0.7	4.2%	0.8%
Large plants, no catalytic cleaning	0.01	0.2%	0.02%

 # Estimated cost of sulphur cleaning, upgrading and injection: 16 €¢/Nm^3 biomethane for 'small plants' and 7.9 €¢/Nm^3 biomethane for 'large plants' (2019 prices) [8].

¤ Estimated cost of entire biomethane production: 82 €¢/Nm^3 biomethane for 'small plants' and 62 €¢/Nm^3 biomethane for 'large plants' (2019 prices) [8].

As can be seen from Table 10, the extra expense for oxygen-free production is relatively small when avoiding biomethane plants requiring catalytic oxygen removal.

7.6. Issues at borders between countries with different approaches

An issue – both now and in a possible future with a different approach to handling the oxygen issue – arises when two neighbouring countries do not handle the oxygen in the same way. One country might choose to handle oxygen at the storage facilities (i.e. allows oxygen in the gas grid), while a neighbouring country chooses to handle the oxygen at the biomethane plants (i.e. no oxygen allowed in the gas grid).

This is currently the case on the border between Germany and Denmark but could also be the case e.g. between France and Germany in the future depending on how they each choose to handle oxygen with reference to the conclusion from Section 7.2 and 7.3.

For neighbouring countries with different approaches to handling oxygen, issues will arise at the border, where oxygen must be removed from gas exported from the country with high oxygen limits to the country with low oxygen limits. First, this would result in an extra expense for biomethane growth that would not be required if the countries were to choose the same approach. Second, that extra expense has to be paid by someone, and according to current rules that extra expense is paid only by the country with high oxygen limits. Table 11 below shows examples of extra annual cost for oxygen removal depending on flow rates and biomethane share in the grid of the exporting country (assuming biomethane injection primarily in distribution grid and average oxygen concentration at border crossing).

Table 11 Examples of extra cost for removing oxygen at borders depending on flow rate and biomethane share.

Max flow 1,000 Nm^3/h	Avg. Flow 1,000 Nm^3/h	30% biomethane share Mio. €/year	100% biomethane share Mio. €/year
400	100	7.9	9.8
1,000	250	15.4	20.1
2,000	500	30.9	40.2
3,000	750	46.3	60.3
4,000	1,000	61.7	80.4

In effect, this means that a country cannot just evaluate what is the most cost-efficient approach for itself. If must consider which approach its neighbouring countries might choose, what extra expenses this will result in, and how this might influence its own decisions for best solution. Overall, it will be cheapest and easiest for the European gas sector as a whole and the future growth of biomethane production if an agreement about a common way of handling oxygen could be reached. Alternatively, an agreement on how best and most fairly to handle oxygen removal at borders between countries with different approaches in order to support free gas trade and support growth of biomethane production in all countries would be most beneficial.

8. Limitations and evaluation of assumptions

When using the results of the analysis tool as shown in Section 7, the assumptions and limitations behind should be remembered:

- The calculations do not include oxygen removal at border crossings and at oxygen-sensitive chemical industry. Depending on oxygen limits in neighbouring countries and the amount of oxygen-sensitive industry in a country, the expenses for handling oxygen at sensitive installations could be considerably higher than calculated here. Such expenses can be calculated with the analysis tool, but this will require input of flow and oxygen limits.

- This report only investigates handling oxygen at either the biomethane plants or at the gas storage facilities. A third approach could be to remove it at injection points to the transmission grid – i.e. at reverse flow stations and at biomethane plants with injection directly in the transmission grid. It is not possible from the calculations here to say whether that solution would be a more cost-efficient solution than those proposed here.

- The analysis tool only considers total CAPEX and OPEX cost when selecting the cheapest sulphur cleaning method. In most cases, this results in a recommendation to use external or upstream biological cleaning which has high investment cost, but very low operational cost. As mentioned during results in Section 7, the results and recommendations will depend on the biomethane plants being able to lend the money for this investment, as well as having the technical skills to operate them satisfactorily.

- As mentioned in Section 4.5 and Section 7, the expenses for handling oxygen at the biomethane plants will depend heavily on whether catalytic cleaning is necessary. While it is mentioned that an alternative water scrubber process without addition of air could be one solution to this, it should be noted that the author is not familiar with the development of such a process at the moment[4]. The possibility is mentioned to emphasize that water scrubbers in general are not necessarily problematic or automatically excluded from a future growth in biomethane. It is just not a cost-efficient upgrading method in its current form if a country wants to handle oxygen at each biomethane plant.

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[4] Water scrubber suppliers have not been consulted for this possibility, as it was not found to be within the direct scope of this project.

- Many assumptions are made based on knowledge of the Danish biomethane plants. These are believed to be sufficiently similar to biomethane plants in Europe for the assumptions to hold for the purpose of this analysis tool.

- It should be noted that the report's conclusions and recommendations do not consider how the proposed changes influences the cost of biomethane production. In general terms, however, it has been found that larger biomethane plants produces cheaper biomethane than smaller plants – especially for scrubber-type plants [8].

All results from this report should be seen as qualified estimates and only used as an input for comparing and evaluating best approach to the oxygen issue – not as solid prices/expenses.

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