Technology Data for energy carrier generation and conversion

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Danish Energy Agency

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Amendment sheet

Publication date

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Amendments after publication date

All updates made after the publication date will be listed in the amendment sheet below.

Date	Ref.	Description
MM YY		
MM YY		

The newest version of the catalogue will always be available from the Danish Energy Agency's web site.

Preface

The *Danish Energy Agency* and *Energinet*, the Danish transmission system operator, publish catalogues containing data on technologies for energy carrier generation and conversion. This current catalogue includes new chapters on biogas plants and biogas upgrading. For other technologies for energy carrier generation and conversion, we refer to the catalogue for advanced Bioenergy Fuels developed by Force on behalf of the Danish Energy Agency in 2013 (available on ens.dk).

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Introduction

This catalogue presents technologies for generation and conversion of energy carriers. In particular: production of hydrogen by means of electrolysis, biofuels from biomass and production/upgrade of biogas/syngas.

Most of the process are characterised by multiple inputs and multiple outputs, which include for example different fuels/feedstocks, electricity and process heat (recoverable or lost).

Upstream and downstream processes are not included - the datasheets do not provide information on prices for fuels, environmental impact from fuel procurement, or the economic consequences of the substitution of fossil fuels with liquid fuels produced from biomass.

The main purpose of the catalogue is to provide generalized data for analysis of energy systems, including economic scenario models and high-level energy planning.

These guidelines serve as an introduction to the presentations of the different technologies in the catalogue, and as instructions for the authors of the technology chapters. The general assumptions are described in section 1.1. The following sections (1.2 and 1.3) explain the formats of the technology chapters, how data were obtained, and which assumptions they are based on. Each technology is subsequently described in a separate technology chapter, making up the main part of this catalogue. The technology chapters contain both a description of the technologies and a quantitative part including a table with the most important technology data.

General assumptions

The data presented in this catalogue is based on some general assumptions, mainly with regards to the utilization and start-ups of plants and technologies.

On the one hand, plants for biofuel production and production/upgrade of biogas and syngas are assumed to be designed and operated on a continuous basis along the year, except for maintenance and outages. Therefore, they feature a high number of full load hours (around 8000 h/y) and a reduced number of start-ups (5 per year).

On the other hand, electrolysers are assumed to be designed and operated for approximately 4000 full load hours annually. In particular, use the advantage of lower power prices by producing e.g. in hours of high renewable energy production (similarly to heat pumps). The assumed number of start-ups and consequent shut-downs for electrolysers, unless otherwise stated, is 50 per year.

Any exception to these general assumptions is documented in the relative technology chapter with a specific note.

Qualitative description

The qualitative part describes the key characteristics of the technology as concise as possible. The following paragraphs are included where relevant for the technology.

Contact information

Containing the following information:

- Contact information: Contact details in case the reader has clarifying questions to the technology chapters. This could be the Danish Energy Agency, Energinet.dk or the author of the technology chapters.
- Author: Entity/person responsible for preparing the technology chapters
- Reviewer: Entity/person responsible for reviewing the technology chapters.

Brief technology description

Brief description for non-engineers of how the technology works and for which purpose.

An illustration of the technology is included, showing the main components and working principles.

Input

The main raw materials and other forms of energy consumed (e.g. electricity, heat) by the technology or facility. Moisture content of the fuel and required temperature of the input heat is specified.

Auxiliary inputs, such as enzymes or chemicals assisting the process are mentioned and their contribution described, if considered relevant.

Output

The output energy carrier as well as co-product or by-products, for example process heat. Temperature of the output heat is specified as well. Non-energy outputs may be stated as well, if relevant.

Energy balance

The energy balance shows the energy inputs and outputs for the technology. Here an illustrative diagram is shown based on data for the year 2015, thus currently available technology.

For process heat losses and produced energy carrier, it is important to specify information about temperature and pressure.

The first important assumption is that the energy content of all the fuels, both produced and consumed, is always expressed in terms of Lower Heating Value (LHV). As a consequence, because of the presence of some latent heat of vaporisation, the energy balance may result in a difference between total energy input and total energy output.

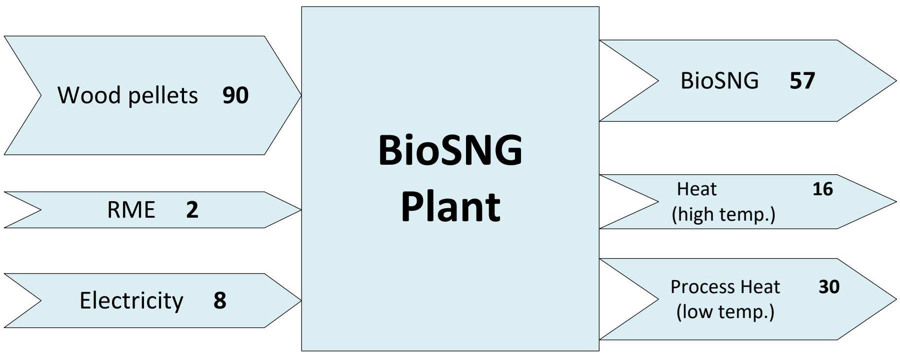

Figure 1 Example of Energy balance. All inputs sum up to 100 units.

For comparison, 100 units of total input are used to standardize the diagrams. This choice allows the reader to easily calculate the efficiency for each of the output, which will be directly equal to the energy value in the balance.

Each of the inputs and outputs has to be accounted for in the diagram, including auxiliary electricity consumption in input and process heat losses in output

Auxiliary products, as for example chemicals and enzymes, will in general only assist the process and are then not relevant for the energy balance. They should just be included as *auxiliary product input data.*

Typical capacities

The capacity, preferably a typical capacity (not maximum capacity), is stated for a single plant or generation facility. In case different sizes of plant are common, multiple technologies can be presented, e.g. Large, Medium and Small.

Regulation ability

Mainly relevant for hydrogen technologies where electricity is used as main input. Description of the part-load characteristics, how fast can they start up and how fast are they able to respond to supply changes and does part-load or fast regulation lead to increased (or lower) wear and hence increased cost.

Space requirement

Space requirement is specified in 1,000 m^2 per MW of thermal (*Typical plant capacity*). The space requirements may for example be used to calculate the rent of land, which is not included in the financial cost, since this cost item depends on the specific location of the plant.

Advantages/disadvantages

A description of specific advantages and disadvantages relative to equivalent technologies. Generic advantages are ignored; e.g. renewable energy technologies mitigating climate risks and enhance security of supply.

Environment

Particular environmental and resource depletion impacts are mentioned, for example harmful emissions to air, soil or water; consumption of rare or toxic materials; issues with handling of waste and decommissioning etc.

The energy payback time or energy self-depreciation time may also be mentioned. This is the time required by the technology for the production of energy equal to the amount of energy that was consumed during the production of the technology.

Research and development perspectives

This section lists the most important challenges to further development of the technology. Also, the potential for technological development in terms of costs and efficiency is mentioned and quantified. Danish research and development perspectives are highlighted, where relevant.

Examples of market standard technology

Recent full-scale commercial projects, which can be considered market standard, are mentioned, preferably with links. A description of what is meant by "market standard" is given in the introduction to the quantitative description section (Section 1.3). For technologies where no market standard has yet been established, reference is made to best available technology in R&D projects.

Prediction of performance and costs

Cost reductions and improvements of performance can be expected for most technologies in the future. This section accounts for the assumptions underlying the cost and performance in 2015 as well as the improvements assumed for the years 2020, 2030 and 2050.

The specific technology is identified and classified in one of four categories of technological maturity, indicating the commercial and technological progress, and the assumptions for the projections are described in detail.

In formulating the section, the following background information is considered:

Data for 2015

In case of technologies where market standards have been established, performance and cost data of recent installed versions of the technology in Denmark or the most similar countries in relation to the specific technology in Northern Europe are used for the 2015 estimates.

If consistent data are not available, or if no suitable market standard has yet emerged for new technologies, the 2015 costs may be estimated using an engineering based approach applying a decomposition of manufacturing and installation costs into raw materials, labor costs, financial costs, etc. International references such as the IEA, NREL etc. are preferred for such estimates.

Assumptions for the period 2020 to 2050

According to the IEA:

"*Innovation theory describes technological innovation through two approaches: the technology-push model, in which new technologies evolve and push themselves into the marketplace; and the market-pull model, in which a market opportunity leads to investment in R&D and, eventually, to an innovation*" (ref. 6).

The level of "market-pull" is to a high degree dependent on the global climate and energy policies. Hence, in a future with strong climate policies, demand for e.g. renewable energy technologies will be higher, whereby innovation is expected to take place faster than in a situation with less ambitious policies. This is expected to lead to both more efficient technologies, as well as cost reductions due to economy of scale effects. Therefore, for technologies where large cost reductions are expected, it is important to account for assumptions about global future demand.

The IEA's New Policies Scenario provides the framework for the Danish Energy Agency's projection of international fuel prices and CO_2-prices, and is also used in the preparation of this catalogue. Thus, the projections of the demand for technologies are defined in accordance with the thinking in the New Policies Scenario, described as follows:

"New Policies Scenario: A scenario in the World Energy Outlook that takes account of broad policy commitments and plans that have been announced by countries, including national pledges to reduce greenhouse gas emissions and plans to phase out fossil energy subsidies, even if the measures to implement these commitments have yet to be identified or announced. This broadly serves as the IEA baseline scenario." (ref. 7).

Alternative projections may be presented as well relying for example on the IEA's 450 Scenario (strong climate policies) or the IEA's Current Policies Scenario (weaker climate policies).

Learning curves and technological maturity

Predicting the future costs of technologies may be done by applying a cost decomposition strategy, as mentioned above, decomposing the costs of the technology into categories such as labor, materials, etc. for which predictions already exist. Alternatively, the development could be predicted using learning curves. Learning curves express the idea that each time a unit of a particular technology is produced, learning accumulates, which leads to cheaper production of the next unit of that technology. The learning rates also take into account benefits from economy of scale and benefits related to using automated production processes at high production volumes.

The potential for improving technologies is linked to the level of technological maturity. The technologies are categorized within one of the following four levels of technological maturity.

Category 1. Technologies that are still in the *research and development phase*. The uncertainty related to price and performance today and in the future is highly significant (e.g. wave energy converters, solid oxide fuel cells).

Category 2. Technologies in the *pioneer phase*. The technology has been proven to work through demonstration facilities or semi-commercial plants. Due to the limited application, the price and performance is still attached with high uncertainty, since development and customization is still needed. The technology still has a significant development potential (e.g. gasification of biomass).

Category 3. *Commercial technologies with moderate deployment*. The price and performance of the technology today is well known. These technologies are deemed to have a certain development potential and therefore there is a considerable level of uncertainty related to future price and performance (e.g. offshore wind turbines)

Category 4. *Commercial technologies, with large deployment*. The price and performance of the technology today is well known and normally only incremental improvements would be expected. Therefore, the future price and performance may also be projected with a relatively high level of certainty (e.g. coal power, gas turbine).

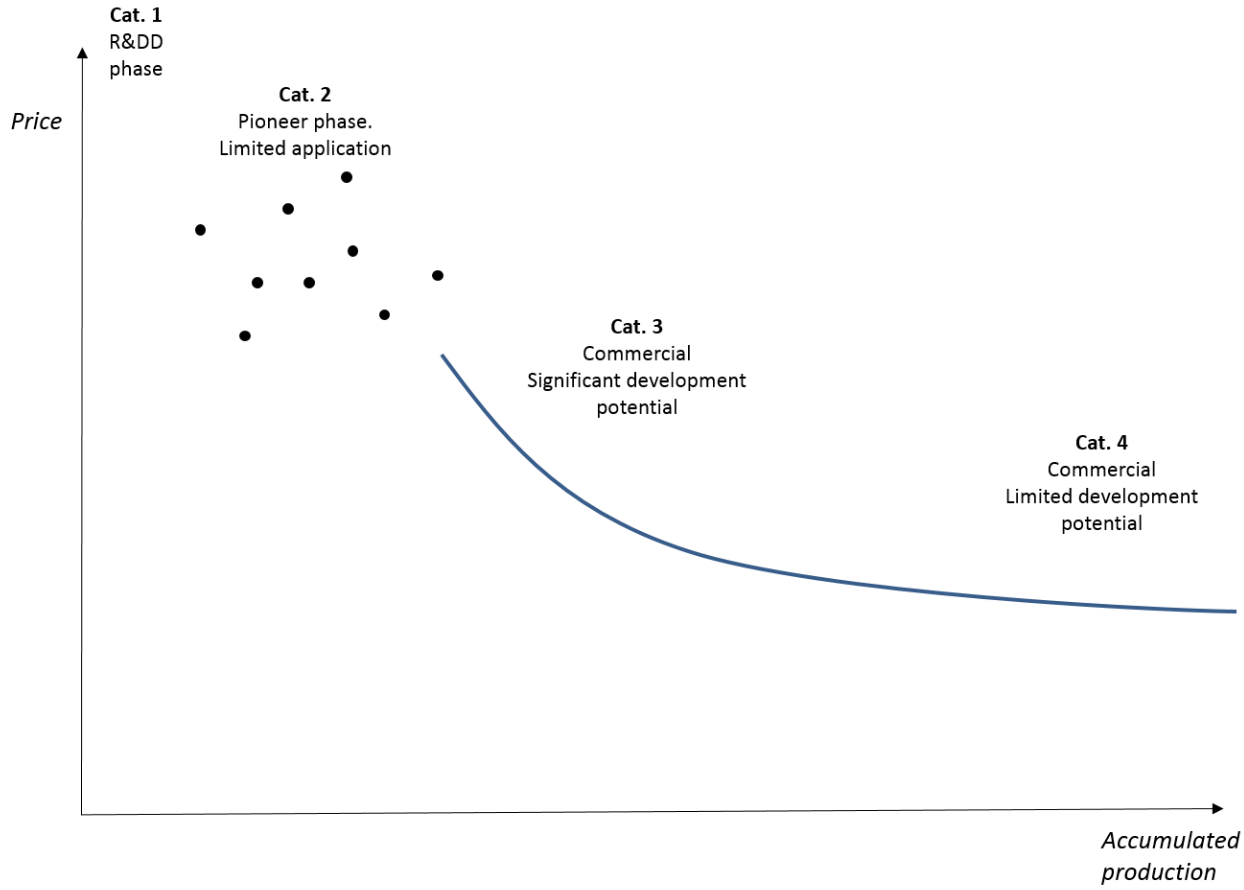

Figure 2: Technological development phases, correlation between accumulated production volume (MW) and price.

Uncertainty

The catalogue covers both mature technologies and technologies under development. This implies that the price and performance of some technologies may be estimated with a relatively high level of certainty whereas in the case of others, both cost and performance today as well as in the future are associated with high levels of uncertainty.

This section of the technology chapters explains the main challenges to precision of the data and identifies the areas on which the uncertainty ranges in the quantitative description are based. This includes technological or market related issues of the specific technology as well as the level of experience and knowledge in the sector and possible limitations on raw materials. The issues should also relate to the technological development maturity as discussed above.

The level of uncertainty is illustrated by providing a lower and higher bound beside the central estimate, which shall be interpreted as representing probabilities corresponding to a 90% confidence interval. It should be noted, that projecting costs of technologies far into the future is a task associated with very large uncertainties. Thus, depending on the technological maturity expressed and the period considered, the confidence interval may be very large. It is the case, for example, of less developed technologies (category 1 and 2) and longtime horizons (2050).

Additional remarks

This section includes other information, for example links to web sites that describe the technology further or give key figures on it.

References

References are numbered in the text in squared brackets and bibliographical details are listed in this section.

Quantitative description

To enable comparative analyses between different technologies it is imperative that data are actually comparable: All cost data are stated in fixed 2015 prices excluding value added taxes (VAT) and other taxes. The information given in the tables relate to the development status of the technology at the point of final investment decision (FID) in the given year (2015, 2020, 2030 and 2050). FID is assumed to be taken when financing of a project is secured and all permits are at hand. The year of commissioning will depend on the construction time of the individual technologies.

A typical table of quantitative data is shown below, containing all parameters used to describe the specific technologies. The datasheet consists of a generic part, which is identical for all technologies and a technology specific part, containing information, which is only relevant for the specific technology. The generic part is made to allow for easy comparison of technologies.

It has to be noted that, in case a technology has more than one input or output, rows will be added to the datasheet.

Each cell in the table contains only one number, which is the central estimate for the market standard technology, i.e. no range indications.

Uncertainties related to the figures are stated in the columns named *uncertainty*. To keep the table simple, the level of uncertainty is only specified for years 2020 and 2050.

The level of uncertainty is illustrated by providing a lower and higher bound. These are chosen to reflect the uncertainties of the best projections by the authors. The section on uncertainty in the qualitative description for each technology indicates the main issues influencing the uncertainty related to the specific technology. For technologies in the early stages of technological development or technologies especially prone to variations of cost and performance data, the bounds expressing the confidence interval could result in large intervals. The uncertainty only applies to the market standard technology. The uncertainty interval does not represent the product range (for example a product with lower efficiency at a lower price or vice versa).

The level of uncertainty is stated for the most critical figures such as investment cost and specific output shares. Other figures are considered if relevant.

All data in the tables are referenced by a number in the utmost right column (Ref), referring to source specifics below the table. The following separators are used:

; (semicolon)	separation between the four time horizons (2015, 2020, 2030, and 2050)
/ (forward slash)	separation between sources with different data
+ (plus)	agreement between sources on same data

Notes include additional information on how the data are obtained, as well as assumptions and potential calculations behind the figures presented. Before using the data, please be aware that essential information may be found in the notes below the table.

The generic parts of the datasheets for energy carrier generation and conversion technologies are presented below:

Technology	name/ decription									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Typical total plant size (MW output)										
- Inputs										
A) Energy input share (% total input(MWh/MWh))										
B) Energy input share (% total input(MWh/MWh))										
C) Energy input share (% total input(MWh/MWh))										
X) Auxiliary products inputs (kg/MWh)										
Y) Auxiliary products inputs (kg/MWh)										
- Outputs										
A) Output share (% total input (MWh/MWh))										
B) Output share (% total input (MWh/MWh))										
C) Output share (% total input (MWh/MWh))										
X) Non-energy outputs (kg/MWh)										
Y) Non-energy outputs (kg/MWh)										
Forced outage (%)										
Planned outage (weeks per year)										
Technical lifetime (years)										
Construction time (years)										
Financial data										
Specific investment (€ /MW of total input)										
- hereof equipment (%)										
- hereof installation (%)										
Fixed O&M (€ /MW of total input)										
Variable O&M (€/MWh of total input)										
Startup cost (€ /MW of total input per startup)										
Technology specific data										

Energy/technical data

Typical total plant size

The total thermal capacity, preferably a typical capacity, is stated for a single plant or facility. It represents the sum of all input and is expressed in MW thermal.

Input

All inputs that contribute to the energy balance are included as *main energy input* and are expressed as percentage in relation to the total energy input, or equivalently as MWh/MWh of total input.

The energy inputs (and outputs) are always expressed in lower heating value (LHV) and moisture content considered is specified if relevant.

Auxiliary inputs, such as **enzymes** or **chemicals** that are assisting the process but do not contribute to the energy balance are included as *auxiliary products* (under *input*) and are expressed in kg/MWh of total energy input.

Output

Similarly to the energy inputs, energy outputs are expressed as percentage value in relation to the total energy input, or equivalently as MWh/MWh of total input.

Any energy co-product or by-product of the reaction has to be specified within the outputs, including process heat loss. Since fuel inputs are measured at lower heating value, in some cases the total efficiency may exceed or be lower than 100%.

The output shares represent the partial efficiencies in producing the different outputs.

The process heat (output) is, if possible, separated in recoverable (for example for district heating purposes) and unrecoverable heat and the temperatures are specified.

Forced and planned outage

Forced outage is defined as the number of weighted forced outage hours divided by the sum of forced outage hours and operation hours. The weighted forced outage hours are the sum of hours of reduced production caused by unplanned outages, weighted according to how much capacity was out.

Forced outage is given in percent, while planned outage (for example due to renovations) is given in days per year.

Technical lifetime

The technical lifetime is the expected time for which an energy plant can be operated within, or acceptably close to, its original performance specifications, provided that normal operation and maintenance takes place. During this lifetime, some performance parameters may degrade gradually but still stay within acceptable limits. For instance, power plant efficiencies often decrease slightly (few percent) over the years, and O&M costs increase due to wear and degradation of components and systems. At the end of the technical lifetime, the frequency of unforeseen operational problems and risk of breakdowns is expected to lead to unacceptably low availability and/or high O&M costs.

At this time, the plant is decommissioned or undergoes a lifetime extension, which implies a major renovation of components and systems as required making the plant suitable for a new period of continued operation.

The technical lifetime stated in this catalogue is a theoretical value inherent to each technology, based on experience. As explained in the *General Assumptions*, different types of plants are designed for a different annual utilization and typical number of start-ups a year. The expected technical lifetime takes into account these assumptions.

In real life, specific plants of similar technology may operate for shorter or longer times. The strategy for operation and maintenance, e.g. the number of operation hours, start-ups, and the reinvestments made over the years, will largely influence the actual lifetime.

Construction time

Time from final investment decision (FID) until commissioning completed (start of commercial operation), expressed in years.

Financial data

Financial data are all in Euro (€), fixed prices, at the 2015-level and exclude value added taxes (VAT) and other taxes.

Several data originate in Danish references. For those data a fixed exchange ratio of 7.45 DKK per € has been used.

The previous catalogue was in 2011 prices. Some data have been updated by applying the general inflation rate in Denmark (2011 prices have been multiplied by 1.0585 to reach the 2015 price level).

European data, with a particular focus on Danish sources, have been emphasized in developing this catalogue. This is done as generalizations of costs of energy technologies have been found to be impossible above the regional or local levels, as per IEA reporting from 2015 (ref. 3). For renewable energy technologies this effect is even stronger as the costs are widely determined by local conditions.

Investment costs

The investment cost is also called the engineering, procurement and construction (EPC) price or the overnight cost. Infrastructure and connection costs, i.e. electricity, fuel and water connections inside the premises of a plant, are also included.

The investment cost is reported on a normalized basis, i.e. cost per MW. The specific investment cost is the total investment cost divided by the *Typical total plant size* described in the quantitative section.

Where possible, the investment cost is divided on equipment cost and installation cost. Equipment cost covers the components and machinery including environmental facilities, whereas installation cost covers engineering, civil works, buildings, grid connection, installation and commissioning of equipment.

The rent of land is not included but may be assessed based on the space requirements, if specified in the qualitative description.

The owners' predevelopment costs (administration, consultancy, project management, site preparation, approvals by authorities) and interest during construction are not included. The costs to dismantle decommissioned plants are also not included. Decommissioning costs may be offset by the residual value of the assets.

Cost of grid expansion
The costs for the connection of the plant to the system are included in the investment cost, while no cost of grid expansion or reinforcement is taken into account in the present data.

Economy of scale
The main idea of the catalogue is to provide technical and economic figures for particular sizes of plants. Where plant sizes vary in a large range, different sizes are defined and separate technology chapters are developed.

For assessment of data for plant sizes not included in the catalogue, some general rules should be applied with caution to the scaling of plants.

The cost of one unit for larger power plants is usually less than that for smaller plants. This is called the 'economy of scale'. The basic equation (ref. 2) is:

$$\frac{C_1}{C_2} = \left(\frac{P_1}{P_2}\right)^a$$

Where: C_1 = Investment cost of plant 1 (e.g. in million EUR)

C_2 = Investment cost of plant 2

P_1 = Power generation capacity of plant 1 (e.g. in MW)

P_2 = Power generation capacity of plant 2

a = Proportionality factor

Usually, the proportionality factor is about 0.6 – 0.7, but extended project schedules may cause the factor to increase. It is important, however, that the plants are essentially identical in construction technique, design, and construction time frame and that the only significant difference is in size.

For technologies that have a more modular structure, such as electrolysers, the proportionality factor is equal to 1.

The relevant ranges where the economy of scale correction applies are stated in the notes for the capacity field of each technology table. The stated range represents typical capacity ranges.

Operation and maintenance (O&M) costs

The fixed share of O&M is calculated as cost per plant size (€ per MW per year), where the typical total plant size is the one defined at the beginning of this chapter and stated in the tables. It includes all costs, which are independent of how the plant is operated, e.g. administration, operational staff, payments for O&M service agreements, network use of system charges, property tax, and insurance. Any necessary reinvestments to keep the plant operating within the scheduled lifetime are also included, whereas reinvestments to extend the life beyond the lifetime are excluded. Reinvestments are discounted at 4 % annual discount rate in real terms. The cost of reinvestments to extend the lifetime of the plants may be mentioned in a note if the data has been readily available.

The variable O&M costs (€/MWh) include consumption of auxiliary materials (water, lubricants, fuel additives), treatment and disposal of residuals, spare parts and output related repair and maintenance (however not costs covered by guarantees and insurances).

Planned and unplanned maintenance costs may fall under fixed costs (e.g. scheduled yearly maintenance works) or variable costs (e.g. works depending on actual operating time), and are split accordingly.

All costs related to the process inputs (electricity, heat, fuel) are not included.

It should be noticed that O&M costs often develop over time. The stated O&M costs are therefore average costs during the entire lifetime.

Start-up costs

The O&M costs stated in this catalogue includes start-up costs and takes into account a typical number of start-ups and shut-downs. Therefore, the start-up costs should not be specifically included in more general analyses. They should only be used in detailed dynamic analyses of the hour-by-hour load of the technology.

Start-up costs, are stated in costs per MW of typical plant size (€/MW/startup), if relevant. They reflect the direct and indirect costs during a start-up and the subsequent shut down.

The direct start-up costs include fuel consumption, e.g. fuel which is required for heating up boilers and which does not yield usable energy, electricity consumption, and variable O&M costs corresponding to full load during the start-up period.

The indirect costs include the theoretical value loss corresponding to the lifetime reduction for one start up. For instance, during the heating-up, thermal and pressure variations will cause fatigue damage to components, and corrosion may increase in some areas due to e.g. condensation.

An assumption regarding the typical amount of start-ups is made for each technology in order to calculate the O&M costs. As a general assumption, biofuel production and production/upgrade of biogas features 5 start-ups per year, while for electrolyzes 50 start-ups a years are assumed. Any change with respect to this general assumption, e.g. for a specific technology which is characterized by a different utilization, is specified in the notes.

The stated O&M costs may be corrected to represent a different number of start-ups than the one assumed by using the stated start-up costs with the following formula:

$$O\&M_{new} = O\&M_{old} - \left(Startup\ cost * n_{startup}^{old}\right) + \left(Startup\ cost * n_{startup}^{new}\right)$$

where $n_{startup}^{old}$ is the number of start-ups specified in the notes for the specific technology and $n_{startup}^{new}$ is the desired number of start-ups.

Technology specific data

Additional data is specified in this section, depending on the technology.

For example, **operating temperatures** are indicated for electrolysis and other processes in which it is a relevant parameter.

Whenever process heat is available as output, its **temperature** is specified as well.

For electrolysis technologies, parameters regarding the **regulation ability** are specified as follow:

- Ramp up time, linear to full load (minutes)
- Ramp down time, linear from full load (minutes)
- Start-up time (minutes)
- Minimum load (%)

Relevant **emissions to the environment**, including emissions to water and air, are reported in g per MWh of total input of fuel at the lower heating value.

All plants are assumed to be designed to comply with the environmental regulation that is currently in place in Denmark and planned to be implemented within the 2020 time horizon.

Definitions

The **latent heat of vaporization** is the heat absorbed when a substance changes phase from liquid to gas.

The **lower heating value** (also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered. The LHV are the useful calorific values in boiler combustion plants and are frequently used in Europe.

Using the LHV for efficiency definition, a condensing boiler can achieve a thermal efficiency of more than 100%, because the process recovers part of the heat of vaporization.

The **higher heating value** (also known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products.

When using HHV for thermal efficiency definition, the thermodynamic limit of 100% cannot be exceeded.

References

Numerous reference documents are mentioned in each of the technology sheets. Other references used in the Guideline are mentioned below:

[1] Danish Energy Agency: ”Forudsætninger for samfundsøkonomiske analyser på energiområdet” (Generic data to be used for socio-economic analyses in the energy sector), May 2009.

[2] “Economy of Scale in Power Plants”, August 1977 issue of Power Engineering Magazine

[3] “Projected Costs of Generating Electricity”, International Energy Agency, 2015.

[4] “Konvergensprogram Danmark 2015”. Social- og Indenrigsministeriet. March 2015.

[5] “Technology Data for Hydrogen Technologies”.

[6] “Technology data for advanced bioenergy fuels”, Energistyrelsen

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[8] “Energy Technology Perspectives”, International Energy Agency, 2012.

[9] International Energy Agency. Available at: http://www.iea.org/. Accessed: 11/03/2016.

1 Biogas Plants

Contact information:

Danish Energy Agency: Andreas Moltesen
Author: EA Energianalyse

Publication date

June 2017

Amendments after publication date

Date	Ref.	Description
-	-	-
-	-	-

Qualitative description

Brief technology description

Biogas plants produce a methane rich gas on the basis of biodegradable organic material. The feedstock is transported to the plant by road or pumped in pipelines. At the plant, it undergoes an anaerobic process, which generates biogas.

The technology data sheet covers larger plants. It does not include biogas from wastewater treatment plants and landfill sites.

The residual biological material can be recycled as a fertilizer in agriculture and may be separated into solids and fluids.

The biogas can be used directly in a natural gas engine for local CHP generation, in a local gas boiler or it can be upgraded to bio SNG (synthetic natural gas). Upgrading of biogas to bio SNG is treated in a separate chapter of the technology catalogue.

The biomass is received and stored in pre-storage tanks and later processed in digestion reactor tanks. The digesters are normally heated to either 35 - 40 °C (mesophilic digestion), or 50 - 55 °C (thermophilic digestion). After being processed in the main reactor, the material is stored in post-processing tanks where further gas is produced and collected. Typical processing time in the digesters is less than 25 days in Danish plants, but many plants have longer retention time in order to increase the gas yield.

Danish plants use continuous digestion in fully stirred digesters. This implies removing a quantity of digested biomass from the digesters and replacing it with a corresponding quantity of fresh biomass, typically several times a day.

Finally, the gas is treated to reduce water and sulphur contents to the desired concentrations.

The figure below shows the typical components and flow in a biogas plant.

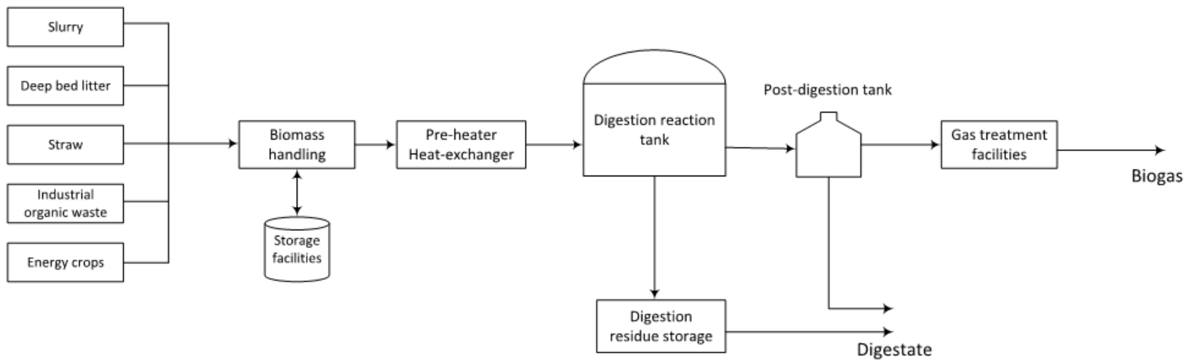

Figure 1: Typical components in a biogas plant.

Input

- Biodegradable organic material such as animal manure/slurry, organic waste from food processing and households, agricultural residues (e.g. straw), energy crops, etc.
- Electricity for mechanical processing equipment.
- Process heat for preheating and heating the reactor tanks.

Output

- Biogas.
- Digestate, e.g. for use as fertilizer.

The biogas gas typically contains 50-75% methane (CH4), 25-45% carbon dioxide (CO2) plus a minor content of hydrogen (H2), nitrogen (N2), oxygen (O2), hydrogen sulphide (H2S) and ammonia (NH3). The composition of the biogas varies with the specific mix of the input.

Energy balance

It is not practical nor usual to measure the energy content of the input material as a calorific value, as for other energy conversion technologies. Instead the input unit 'Tons per year' and the corresponding output capacity is used to define the size of the plant. Accordingly, the efficiency of the plant is not calculated in the same way as for other conversion technologies, except for straw where the lower calorific energy of the straw input is used.

The volatile solid (VS) content of the biomass represents the fraction of the solid material that may be transformed into biogas. For animal slurry the VS share is approx. 75 %, for source separated household waste it is approx. 80 % and for maize and grasses around 90 %. The methane production achieved in practice depends on processing time and the organic loading rate among other factors. For further information on the methane output from different types of biomass, see reference [14].

The digestatel contains the nutrients and the long term stable carbon of the input material and has a high value as agricultural fertilizer. Drained fractions of the non-digested residual material might be useful for combustion or thermal gasification.

The production of biogas, as well as the content of methane in the biogas, vary with the amount and quality of the organic waste used. Methane has a lower heating value of 35.9 MJ/Nm^3. Biogas with 65% methane thus has a heating value of 23.3 MJ/Nm^3. To allow comparisons it is practical to measure the output in Nm^3 methane.

The data sheets in this chapter comprise a basic plant with input of a proportional mix of resources assessed available in Denmark in year 2012 and 2020 [9][1], but excluding energy crops and straw.

This plant may represent an "average" or "model plant". An example of energy properties for a basic plant is shown in table 1.

Basic biogas plant (2015)	**Input share (by tons)**	**Methane production (GJ/ton)***	**Methane production (% of total)**
Pig and cattle slurry	79.8%	0.44	44%
Deep litter	8.0%	2.00	20%
Manure, stable	6.1%	1.57	12%
Straw	0.0%	7.27	0%
Industrial organic waste	1.0%	4.83	6%
Household waste	1.6%	3.41	7%
Energy crops	0.0%	1.5 - 3.5	0%
Other	3.5%	1 - 5	11%
Total	100%	0.80	100%

Table 1: Energy properties for basic biogas plant with a mix of input material, 2015. *Based on references [8] and [9].

As seen in table 1 the potential energy (methane) production per ton of straw and industrial waste is app.10-17 times higher than the potential energy (methane) production per ton of animal slurry. This means that, the methane output of a plant with a certain input capacity (measured in tons) can be increased by increasing the share of feedstock with relative high energy production potential. The differences in methane output is mainly due to varying water content of the different resources.

The possibilities for increasing the share of straw and deep litter material depend on the design of the plant and the pre-treatment of the feedstocks. Experimental work indicates that relatively high shares of straw may be possible [5]. The possibility of pumping the biomass puts on upper limit on the amount of It is assumed that the total amount of straw and deep litter material can contribute with up to 50% of the total methane production [9].

A plant with maximum input share of straw and deep litter material could have a mix of input material and corresponding output as shown in table 2.

[1] Interpolations are made for year 2015

Increased straw share (2015)	Input share (by tons)	Methane production (GJ/ton)	Methane production (% of total)
Slurry (pig and cattle)	73.5%	0.44	26%
Deep litter	8.0%	2.00	13%
Manure,	6.1%	1.57	8%
Straw	6.3%	7.27	37%
Industrial organic waste	1.0%	4.83	4%
Household waste	1.6%	3.41	4%
Energy crops	0.0%	1,5 - 3,5	0%
Other	3.5%	1 - 5	7%
Total	100%	1.20	100%

Table 2: Input mix and expected output for a basic plant where input of straw and deep litter material contribute to 50 % of output.

Similarly, the energy output from the plant can be increased by a higher share of industrial organic waste, which typically origins from slaughterhouses and other food industries. Table 3 shows the expected methane gas production of the basic plant with a 5% share of industrial organic waste.

Increased industrial organic waste share (2015)	Input percentage (by tons)	Methane production (GJ/ton)	Methane production (% of total)
Slurry (pig and cattle)	75.8%	0.44	34%
Deep litter	8.0%	2.00	16%
Manure,	6.1%	1.57	10%
Straw	0.0%	7.27	0%
Industrial organic waste	5.0%	4.83	25%
Household waste	1.6%	3.41	6%
Energy crops	0.0%	1,5 - 3,5	0%
Other	3.5%	1 - 2	9%
Total	100%	0.97	100%

Table 3: Input and expected methane gas production from the basic plant but with 5 % industrial organic waste

While feedstocks with higher dry matter content may yield higher methane content in the biogas they also set additional requirements to transport and pre-processing systems and may increase the auxiliary energy consumption. Feedstocks such as straw and energy crops with higher contents of lignocellulose must be mechanically chopped, ground, or otherwise treated before being fed into the digester in order to obtain an acceptable processing time [5]. Thus, higher yields when using alternative feedstocks are usually followed by increased investment and O&M costs. Also, the purchase of high yield feedstocks will increase the production costs.

Typical capacities

In 2015, there were about 25 centralised biogas plants in operation in Denmark, and a larger number of smaller plants (app. 50 farm scale biogas plants and app. 50 anaerobic digesters at waste water treatment plants and a few plants for treating waste water from industries). A centralised biogas plant in Denmark typically has an input capacity from 70.000 to 700.000 tonnes per year [5], and raw material is, typically delivered from 10 to 100 farms. In a study based on data from 16 existing Danish plants [5] an average yield of approximately 28 Nm3 methane per tons input was reported, corresponding to around 1 GJ/ton, however with large variations from approx. 17 to 52 Nm3 methane/ton. The trend is towards larger plants, driven by cost reductions related to economy-of-scale effects for the biogas plant and in particular the upgrading facilities.

Regulation ability

Biogas production in the same reactor can be increased by adding organic materials with high methane potential, however, there is a biological limit to how fast the production can be regulated. For example, a biogas plant digesting only animal slurry during summer, may increase the gas yield from 14-14.5 m^3 methane per tonne to about 45-50 m^3 methane per tonne during a period of 3 to 4 weeks if biomass with a higher methane production potential is added [3].

Regulation of the production may require additional feedstock storage capacity, e.g. in case of a constant supply of biomass from stables. But the additional income from gas sales may not balance the extra costs of storing feedstock and digested biomass. Also, the emission of greenhouse gasses may increase [3].

A typical smaller plant with CHP production has a gas storage of approximately a half-day's production to accommodate price and demand variations.

Regulation is not relevant for biogas plants with upgrading plants and connection to the central natural gas grid.

Space requirement

The space requirements will vary depending on the design and lay-out. Biogas plants are typically placed in open farm land.

Advantages/disadvantages

Advantages:

- Methane emission is mitigated, with relatively low CO_2 abatement costs [6] fossil fuels are substituted
- Saved expenses in slurry handling and storage.
- Environmentally critical nutrients, primarily nitrogen, phosphorus and potassium, can be redistributed from intense farmlands to other areas. The risk of leaching of nitrates is reduced.
- The fertilizer value of the digested biomass is better than the raw materials. The fertilizer value is also better known, and it is therefore easier to administer the right dose to the crops.
- For waste fractions with a high water content, co-digestion of manure and waste can often provide a low cost option compared to other forms of waste handling, such as incineration.
- Compared to other forms of waste handling such as incineration, biogas digestion of solid biomass has the advantage of recycling nutrients to the farmland – in an economically and environmentally sound way.
- Application of digestate reduces smell compared to application of raw slurry

- Using straw in biogas plants does not deplete the content of carbon in the topsoil compared to using straw for heating (combustion)

Disadvantages:

- Use of straw and other solid biomass resources in biogas production yields a lower energy output than if the same feedstock was used for thermal gasification and/or combustion.
- The successful operation of biogas plants is relatively complex and requires large experience
- The consumption of large quantities of biomass with low dry-matter content (manure) makes transport and sourcing radius a critical parameter.
- Use of heat from biogas fueled decentralized CHP plants is dependent on the heat demand in the local district heating system. A low heat demand can otherwise limit operation during summer season.

Environment

Biogas can substitute fossil fuels in the energy system and thereby avoid emissions of CO_2.

Furthermore, biogas can prevent significant emissions of the greenhouse gas methane to the atmosphere when the biomass is digested in biogas plant, during storage and application on the field. However, an amount of biogas risks to leak from the plants.

In a study of 15 Danish plants, it was assessed that these biogas plants can reduce greenhouse gas emission by 60-180 kg CO_2 equivalent per ton of biomass digested [5]. This assessment includes the substitution of fossil fuels, reduced methane loss due to digestion and collection and a methane leakage from the plants of 2% of the produced biogas. The figures include methane reductions from relatively large amounts of waste (28% of input), which is assumed treated as manure (stored anaerobicly and afterwards spread out in the fields). The substitution of fossil fuels varies, depending on the energy system and on how the plants are operated.

The gas leakages shall be reduced as far as possible during the entire process to avoid emissions of the greenhouse gas (methane) and odour problems in the neighbouring environment. An investigation in 2015, covering nine Danish biogas plants showed an average emission as high as 4.2%. Through by a systematic effort to stopping leakages it was, however, possible to reduce emissions to 0.8% b [12]. 2 % is assessed to be a realistic average level in the future for existing plants. The goal of the biogas industry in Denmark is to reduce total methane leakages to 1 % by 2020, including losses from upgrading facilities-

Odour problems from biogas plants is often reported as a problem, but can be avoided with proper filtering of the off-gasses and good management during operation. The anaerobic treated organic waste product is almost odour-free compared to raw organic waste.

Biogas contains sulphur, which may represent an environmental problem due to emissions of SO_2.

The content of sulphur (H_2S) in the biogas will vary depending on the feedstock material. When animal slurry is the main source, the raw gas typically contains 3.000-10.000 mg/m^3 [2]. The sulphur content can be reduced fully or partially by a number of technologies, or a combination of these, including precipitation with iron chloride in the digester tanks, adsorption with activated carbon filters, or by a biological scrubber [2].

Biogas engines tolerate small amounts of sulphur in the gas, which however causes SO_2 emissions to the environment. When the gas is used for upgrading to bio SNG complete sulphur removal may be necessary, but this is normally included in the upgrading plant. The cost of sulphur removal is in the range 0.005 – 0.07 DKK per m^3 biogas when the gas is used for engines and 0.03-0.13 DKK per m^3 for complete removal, depending on the flow and the H_2S concentration [2].

Research and development

The Danish biogas R&D activities focus on a number of areas to increase energy production and improve the economy of the plants. Among these are the possibilities of reducing storage of animal slurry before digestion, reduction of methane leakage from tanks and processing equipment, biological optimisation, additional processing time, and use of material with higher dry-matter content e.g. deep litter material and straw [5], [6].

Further development activities are related to optimisation of control systems and logistics, for instance transport systems integrated with larger stable systems, and possibilities for higher dry-matter content in the animal slurry [6].

Examples of market standard technology

The current market standard in Denmark is relatively large plants, which supplies upgraded gas to the natural gas grid. An example is the NGF Nature Energy Holsted plant, which is commissioned in 2016. The plant produces 13 million m^3 upgraded biogas with an input of approximately 400.000 tons per year [13].

Prediction of performance and costs

Data for 2015

Over the recent years there has been a considerable growth in the number of biogas plants in Denmark as well as neighboring countries, and biogas technology is in general placed in development category 3; *Commercial technologies, with moderate deployment.* However, there are major differences in the technologies from country to country with respect to the feedstock, the sizes of the plants, as well as the use of the gas. In Germany, the focus has been on the use of energy crops in smaller plants, which supply gas for heat and power production. Sweden has a larger number of plants based on sewage water and household waste and focus is on upgrading the gas to supply the transport sector [6]. In Denmark, the growth in biogas production has focused on the use of animal slurry and agricultural residues, which today accounts for some 75% of the production. There is an expected potential for a considerable further growth [7].

Older plants producing cleaned but not upgraded biogas for use in gas engines for electricity production is well proven in Denmark, but the current development increasingly focusses plants for production of upgraded gas (SNG) for use in the natural gas network [5].

The basis for cost and performance for the years 2015 and 2020, as shown in the data sheets, is the larger Danish plants intended for upgraded biogas production.

Assumptions for the period 2020 to 2050
It is expected that the investment costs will decrease gradually due to learning curve effects, but not as significant as for other technologies, since many elements of a biogas plant is related to general industries, e.g. civil construction works and general process equipment, where learning curve effects are limited. As described, the technology is expected to be defined by a relatively nationally defined development and learning curve effects shall be seen in that context. For the period 2015 – 2020 the total biogas production in Denmark is expected to double from 7 PJ to 15 PJ [10]. It is estimated that such a doubling of installed capacity a learning curve progress rate of 0.9 will lead to a 10 % reduction in costs. For the periods 2020 to 2030 and 2030 to 2050, respectively, the accumulated build production capacity is also expected to double [11], considering a combination of installation of new plants and retrofit/replacements of old plants. Thus, similar reductions in costs are expected for each of these periods. It is important to notice that the further construction of biogas plants after 2020 is dependent on the future political framework conditions.

Operation costs (excluding costs of feedstock) are expected to decrease with half of the rates expected for investments. The O&M costs are measured per ton input, so a higher energy yield will further affect the energy price.

The biogas production is assumed to remain constant with constant input shares of the various feedstock. This may not be true if, for instance methods for improved energy yield are developed and implemented.

Uncertainty
The general uncertainty when calculating energy generation costs for a biogas plants is high, but the investment costs seem to contribute less than the operation costs. Data from existing biogas plants in Denmark show that the energy production per ton input as well as other cost determining factors is quite different from plant to plant [5]. Key parameters in relation to the energy output are composition of the input material and the processing time. The data in this technology catalogue consider a fixed composition of the input and a fixed processing time.

In relation to the costs, biomass purchase, transportation, auxiliary energy, and labor costs are important but may vary widely [5].

Data sheets

The capacity of biogas plants is commonly stated as tons per year and for most of the input material a calorific value is not relevant (e.g. manure). For compatibility with the template the energy of the biogas output is assumed to be 100%. Thus, the stated auxiliary energy consumption is stated in percent of the output energy.

The data sheets consist of a sheet for a basic plant using a mix of available feedstock sources as listed in table 1 and described in [8] and [9], but excluding straw, energy crops, garden waste and aquatic biomass.

The supplementary data sheet contains values for input of straw and industrial organic waste. The values refer to a part of a total plant processing only the straw or waste. It is thereby possible to model the production and costs of a plant with input of straw or waste by adding a 'basic plant'-part and a 'straw/waste input' part.

## Technology		Biogas plant, basic configuration

Technology	Biogas plant, basic configuration									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Typical total plant size (MW output)	9.2	8.7	8.7	8.7	8.3	9.6	8.3	9.6	A	
- Inputs										
Biomass (tons/year)	365,000	365,000	365,000	365,000	365,000	365,000	365,000	365,000	A B	5/8/9
Aux. electricity (% of output energy)	3.7	3.8	3.8	3.8	1.9	6.7	1.9	6.7	A	5/8/9
Aux. electricity (kWh/ton input)	8.2	8.0	8.0	8.0	4.3	14.0	4.0	14.0		
Aux. process heat (% of output energy)	8.4	8.9	8.9	8.9	7.2	12.0	7.2	12.0	A	5/8/9
Aux. process heat (kWh/ton input))	18.6	18.6	18.6	18.6	16.0	25.0	15.0	25.0		
- Outputs										
Biogas (%)	100	100	100	100	96	110	95.8	110.0	F	
Biogas (GJ/ton input)	0.80	0.75	0.75	0.75	0.72	0.83	0.72	0.83	G	9
Forced outage (%)	0	0	0	0						
Planned outage (days per year)	10	10	10	10						
Technical lifetime (years)	20	20	20	20						
Construction time (years)	1	1	1	1						
Financial data										
Specific investment (mio €/MW output)	1.81	1.71	1.54	1.39	1.54	1.90	1.25	1.54	A H C	8/5
- of which equipment	-	-								
- of which installation	-	-								
Total O&M (€/MW/year)	198,785	194,715	197,702	195,722	154,398	245,575	150,001	252,439		
Total O&M (€/(ton input/year))	5.03	4.63	4.70	4.66	3.52	6.43	3.42	6.61	A D I	8/5
- of which O&M, excl el. and heat (€/(ton input/year))	4.11	3.67	3.49	3.31	2.81	5.05	2.54	4.56	A D I	8/5
- of which electricity (€/(ton input/year))	0.52	0.55	0.80	0.93	0.29	0.97	0.47	1.64	K	
- of which heat (€/(ton input/year))	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41		
Technology Specific data										
Methane emission (Nm3 CH4/ton input/year)	0.44	0.42	0.42	0.42	0.17	0.88	0.17	0.88	J	12

Notes:

A The production, investment- and operation costs are based on a plant with a yearly input of 365,000 tons and a mix of available feedstock sources as described in [9] and [8], but excluding straw, energy crops, garden waste and aquatic biomass. The available feedstock composition for 2015 is obtained by interpolation of 2012 and 2020 potentials. The feedstock composition after 2020 is assumed constant.
The output of a specific plant will vary depending on the actual feedstock composition.

B Values are assumed valid for a range 200,000 - 400,000 tons per year

C The investment includes a straw fired boiler for process heat.

D All O&M considered fixed, assuming 8760 hours operation per year. Does not include costs for biomass purchase and transport. Data for biomass included in biogas plant, basic configuration, 2015, is inluded below. Source: Reference [5].

Biomass	Share, 2015	Share, 2020	Price per ton (€), incl transpor
Manure (pig and cattle)	79.8%	83.8%	3.36
Deep bed material	8.0%	8.5%	6.71
Manure, stable	6.1%	0.2%	6.71
Straw	0.0%	0.0%	67.4
Industrial organic waste	1.0%	1.2%	40.3
Household waste	1.6%	1.2%	18.9
Energy crops	0.0%	0.0%	34.9
Other	3.5%	5.1%	27.9

F For compatibility with the template the energy of the biogas output is assumed to be 100%. (For most of the input material a calorific value is not relevant)

G A calorific value of methane of 35.9 MJ/Nm3 is used. The input material composition and the output is assumed constant after 2020.

H Learning curve effects have been assumed 2015-2020: 10% reductions, 2020-2030: 10% reductions, 2030-2050: 10% reductions

I Learning curve effects have been assumed 2015-2020: 5% reductions, 2020-2030: 5% reductions, 2030-2050: 5% reductions

J Corresponding to 2% of the produced biogas, wit lower value 0.8% and upper value 4.2%. This will vary and can be reduced.

K The cost of auxiliary electricity consumption is calculated using the following electricity prices in €/MWh: 2015: 63, 2020: 69, 2030: 101, 2050: 117. These prices include production costs and transport tariffs, but not any taxes or subsidies for renewable energy.

Technology Biogas plant, additional straw input in the feedstock mix

Technology	Biogas plant, additional straw input in the feedstock mix									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Biogas from additional straw (MW output)	1.00								A B	
- Inputs										
Straw input (% of additional output)	199%	182%	182%	182%					A B	5/8/9
Straw input (tons per year)	4,337	3,957	3,957	3,957						
Auxilliary electricity input (% of additional output)	3.12%	2.85%	2.85%	2.85%						5/8/9
Auxilliary electricity input (kWh/ton straw)	63.00	63.00	63.00	63.00					A	
Additional process heat (% of additional output)	0.92%	0.84%	0.84%	0.84%						5/8/9
Auxilliary process heat (kWh/ton straw input)	18.60	18.60	18.60	18.60					A	
- Outputs										
Biogas (%)	100.0%	100.0%	100.0%	100.0%					A C	
Biogas (GJ/ton straw input)	7.3	8.0	8.0	8.0					A C	9
Residual organic material									D	
Forced outage (%)	0	0	0	0						
Planned outage (days per year)	10	10	10	10						
Technical lifetime (years)	20	20	20	20						
Construction time (years)	1	1	1	1						
Financial data										
Investment (€/MW)	407,676	371,930	371,930	371,930					AEG	8/5
Investment (€/ton straw input/year)	94.00	94.00	94.00	94.00					AEG	
Total O&M (€/MW/year)	47,387	44,727	52,704	56,692					AFG	8/5
Total O&M (€/ton straw input/year)	10.9	11.3	13.3	14.3					AFG	
- of which O&M, excl el. and heat (€/(ton input/year))	6.55	6.55	6.55	6.55						
- of which electricity (€/(ton input/year))	3.97	4.35	6.36	7.37					K	
- of which heat (€/(ton input/year))	0.41	0.41	0.41	0.41						
Technology Specific data										
Methane emission (Nm3 CH4 input/year)	4.0	4.4	4.4	4.4	1.8	9.2	1.8	9.2	H	12

Note

A The data sheet shows the expected energy output and values for the input of industrial organic waste specifically. The values refer to a virtual part of a total plant processing the straw. A plant including increased share of straw may be composed by adding a basic plant part and straw processing part.

B Values are assumed valid for adding a smaller part of straw to a total plant. Maximum share not assessed.

C For compatibility with the template the energy of the biogas output is assumed to be 100%. (For the input material a calorific value is not relevant)

D The energy content of residual organic material has not been evaluated due to lack of sources.

E Investment in straw preparation equipment (57 Eur/ton/year) and proportional share of basic plant included. Biogas processing time

F All O&M considered fixed, assuming 8760 hours operation per year. Does not include fuel for process heat, electricity, biomass purchase and transport, see e.g. [5] and [8].

G The value will vary with the quality of the input. Assumed average value used corresponding to 320 Nm3 CH4 / ton VS, TS 42%, vs/ts 90%. [8].

H Learning curve effects have not been considered. Will depend on actrual deployment of technology.

J Corresponding to 2% of the produced biogas, wit lower value 0.8% and upper value 4.2%. This will vary and can be reduced.

K The cost of auxiliary electricity consumption is calculated using the following electricity prices in €/MWh: 2015: 63, 2020: 69, 2030: 101, 2050: 117. These prices include production costs and transport tariffs, but not any taxes or subsidies for renewable energy.

Technology

Biogas plant, additional industrial organic waste in the feedstock mix

Technology	Biogas plant, additional industrial organic waste in the feedstock mix									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Biogas from additional ind. organic waste (MW output)	100%								AB	
- Inputs										
Ind. organic waste input (% of additional output)	125-200%	125-200%	125-200%	125-200%					L	
Ind. organic waste input (tons per year)	6,529	6,529	6,529	6,529						5
Aux. electricity (% of additional output)	0.77%	0.77%	0.77%	0.77%						5
Aux. electricity (kWh/ton waste input)	10.30	10.30	10.30	10.30					A	
Aux. process heat (% of additional output)	1.39%	1.39%	1.39%	1.39%						5
Aux. process heat (kWh/ton waste input))	18.60	18.60	18.60	18.60					A	
- Outputs										
Biogas (% of total input)	100.0%	100.0%	100.0%	100.0%					AC	
Biogas (GJ/ton ind. org. waste input)	4.8	4.8	4.8	4.8					ACG	5/9
Residual organic material									D	
Forced outage (%)	0	0	0	0						
Planned outage (days per year)	10	10	10	10						
Technical lifetime (years)	20	20	20	20						
Construction time (years)	1	1	1	1						
Financial data										
Investment (€/MW output)	276050	276050	276050	276050					AEH	8/5
Investment (€/ton waste input / year)	42.28	42.28	42.28	42.28					AEH	
Total O&M (€/MW/year)	49500	49904	52056	53132					AFH	8/5
Total O&M (€/ton waste input/year)	7.6	7.6	8.0	8.1					AFH	
- of which O&M, excl el. and heat (€/(ton input/year))	6.5	6.5	6.5	6.5						
- of which electricity (€/(ton input/year))	0.65	0.71	1.04	1.21					K	
- of which heat (€/(ton input/year))	0.41	0.41	0.41	0.41						
Technology Specific data										
Methane emission (Nm3 CH4 input/year)	4.0	4.4	4.4	4.4	1.8	9.2	1.8	9.2	H	12

Note

A The data sheet shows the expected energy output and values for the input of industrial organic waste specifically. The values refer to a virtual part of a total plant processing the industrial organic waste. A plant including including increased share of industrial organic waste may be composed by adding a basic plant part and an ind. org. waste processing part.

B Values are assumed valid for adding a smaller part of straw to a total plant. Maximum share not assessed.

C For compatibility with the template the energy of the biogas output is assumed to be 100%. (For the input material a calorific value is not relevant)

D The energy content of residual organic material has not been evaluated due to lack of sources.

E Investment in straw preparation equipment (57 Eur/ton/year) and proportional share of basic plant included. Biogas processing time is 25 days

F All O&M considered fixed, assuming 8760 hours operation per year. Does not include fuel for process heat, electricity, biomass purchase and transport, see e.g. [5] and [8]. O&M

G The value will vary with the quality of the input. Assumed average value used corresponding to 320 Nm3 CH4 / ton VS, TS 42%, vs/ts 90%. [8].

H Learning curve effects have not been considered. Will depend on actrual deployment of technology.

J Calculated with a constant production 8760 hours per year

K The cost of auxiliary electricity consumption is calculated using the following electricity prices in €/MWh: 2015: 63, 2020: 69, 2030: 101, 2050: 117. These prices include production costs and transport tariffs, but not any taxes or subsidies for renewable energy.

L The conversion efficiency depends on the specific types of industrial waste used at the biogas plants.
Fatty biomasses may be converted with high efficiences (>70 %) whereas for example the conversion of protein rich biomasses is closer to 50 %.

References

[1] "Danish Climate Strategy", Ministry of Environment, February 2003.

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2 Biogas Upgrading

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Qualitative description

Brief technology description

Biogas produced from various kinds of organic material, such as organic waste and residues, animal manure or energy crops, can be upgraded to biomethane using different technologies. After upgrading, the gas can be injected into the natural gas grid.

The input for upgrading facilities is raw biogas from an anaerobic digester with a typical methane (CH_4) content of 50-70% and a content of 30-50% carbon dioxide (CO_2) plus a minor content of hydrogen, nitrogen (N), oxygen (O), hydrogen sulphide (H_2S) and ammonia (NH_3). The composition of the biogas varies based on the specific mix of the input.

Before injecting the gas into the natural gas grid, it is necessary to remove the content of CO_2, thereby increasing ("upgrading") the heating value of the gas. Depending on the composition of the raw biogas, it is also necessary to remove water moisture, particles, hydrogen sulphide (H_2S), ammonia (NH_3) and nitrogen (N). As it is rather expensive to remove nitrogen (N), this is rarely done. Hydrogen sulphide needs to be removed before further use as it is a corrosive gas. Upgrading can also take place by catalytic conversion of the CO_2 to methane by adding hydrogen. This technology is described in another chapter.

Quality requirements for biomethane is described in Gasreglementet section C-12. Bestemmelser om gaskvaliteter. (14. december 2012)[2].

Typically, the investment costs for a complete upgrading system connected to a natural gas grid can be categorised using the following main components excluding the biogas plant itself,

- The upgrading plant
- Additional equipment to treat the methane slip (where necessary)
- Compressor units (where necessary)
- Grid connection plant,

[2] https://www.retsinformation.dk/Forms/R0710.aspx?id=144715

The heating value of upgraded biogas is approximately 10% lower than the heating value of natural gas, which causes challenges for example in relation to proper billing of costumers. One approach to solving the problem is to add propane to the upgraded gas thereby increasing the heating value. Propane addition is however associated with considerable costs and the Danish gas distribution companies have therefore decided to solve the problem through measurements of the gas quality rather than adding propane. By connecting the upgrading plants at MR stations, gas companies are able to keep track of the gas quality in different parts of the distribution network and thereby also ensures proper billing of costumers. Therefore, costs related to propane addition are not considered in this technology sheet.

Upgrading

The main purpose of upgrading is the removal of CO_2, and the capacity of the upgrading plant is usually stated in Nm^3 raw biogas. The grid connection plant encompasses equipment for measuring gas quality, odorisation of the gas and the concrete mechanical grid connection. Other options include further measurements of the gas quality within distribution grids.

Today there are five available upgrading technologies but some are less commercially mature than others:

- Water scrubbing
- Amine scrubbing
- Pressure swing adsorption (PSA)
- Membrane separation
- Organic physical scrubbing

Another technology – cryolithic separation – is under development and little data is currently available. Also, enzymatic upgrading technology is under development.

Currently, the most common upgrading technology is water scrubbing, followed by chemical/amine scrubbing and PSA. Today, there are no PSA pants in operation in Denmark. The vast majority of the existing upgrading facilities are located in Germany and Sweden.

In a water scrubber, the absorption process is purely physical. The biogas is put in contact with water by spray or bubbling through to wash out the CO_2 but also hydrogen sulphide, since the gases are more soluble in water than methane. The pressure in a water scrubber plant is typically higher than the natural gas distribution grid pressure at a connection point, in which case no further compression is necessary for grid injection of the biomethane.

Amine scrubbing uses chemical absorption of CO_2 in amines, which are regenerated in a stripper when heated. This process has the highest efficiency in terms of methane conservation. Amine scrubbing can be integrated using high-temperature excess heat (120-150°C) from other processes and the excess heat from the upgrading plant itself can also be used in low-temperature (65°C) applications, for example biogas digesters. In addition, electricity is required for compression for grid connection.

The PSA separates some gas components from a mixture of gases under high pressure according to the molecular characteristics of the components and the affinity for an adsorbent material (often active carbon). The process then swings to low pressure to desorb the adsorbent material.

The membrane separation method utilises membranes, which consist of hollow fibres bundled together. The membranes are permeable to ammonia, water and carbon dioxide. Nitrogen and methane only passes through the membrane to a very low extent while oxygen and hydrogen sulphide pass the membrane to some extent. Typically, the process is carried out in two stages. Before reaching the membranes the gas passes through a filter that catches water and oil droplets that would otherwise affect the efficiency of the membranes. Besides that, hydrogen sulphide is typically removed by means of active coal.

Organic physical scrubbing is like the water scrubbing technology with the difference that the CO_2 is absorbed in an organic solvent such as the traded solvents Selexol or Genosob.

The figure below shows the specific investment costs per raw biogas inlet for the water scrubber, amine scrubbing, PSA, membrane separation (Membrane) and organic physical scrubbing (Genosorb). As the figure clearly illustrates, the economy of scale is significant up to a certain point.

The technology data sheet in this catalogue only focus on the water scrubbing plant, but as seen from the figure below it is expected that the investments costs of the five different technologies are at comparable levels [2].

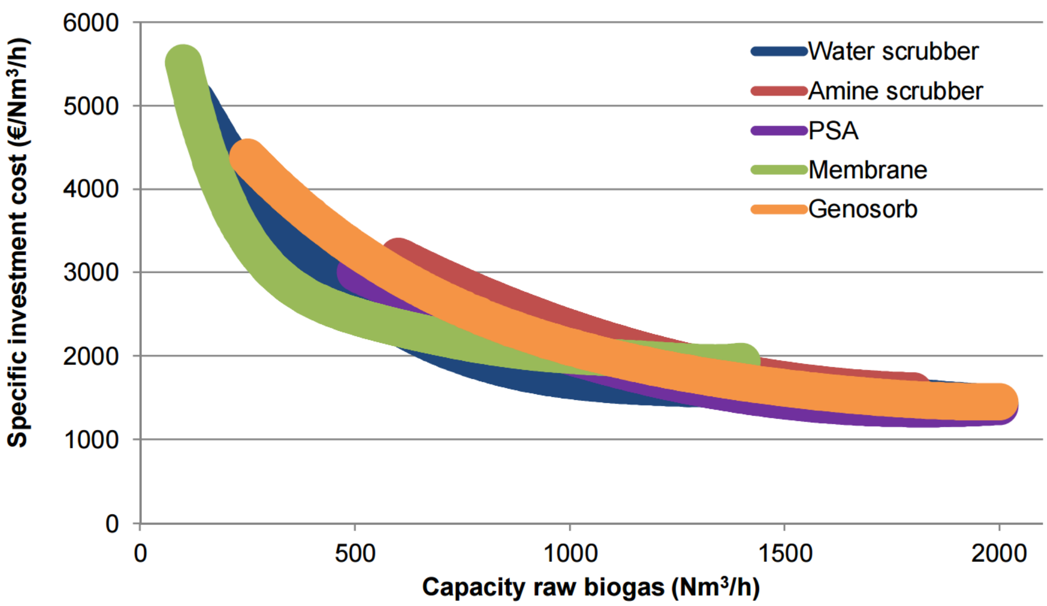

Figure 1: Specific investment costs for different biogas upgrading technologies. Genosorb is organic physical scrubbing. Source: SGC (2013).

Treatment of off-gases

The waste gases from an upgrading plant contain methane in a small concentration, but seldom enough to maintain a flame without addition of natural gas or biogas. One way of limiting the methane slip is to mix the off-gas with air used for combustion for heating the biogas digesters. Alternatively, the methane can be oxidized by regenerative thermal or catalytic oxidation.

The need for off-gas treatment depends on the methane slip from the specific plant. Plants using water scrubbing technology or PSA technology would often require tail-end solutions to decrease the methane slip [2].

Grid connection plant
In conjunction with the gas treatment plant, a grid connection facility should be established. For larger upgrading plants the local distribution network will in many cases not be able to take all the produced gas at all seasons. In these situations, the gas needs to bes further pressurised from 4-7 bar to 40 bar, to be fed into the natural gas transmission network. In addition, measurement regulation and odorisation equipment is required. Further to this, but not included in the data sheet costs, is the connection pipeline to the gas grid.

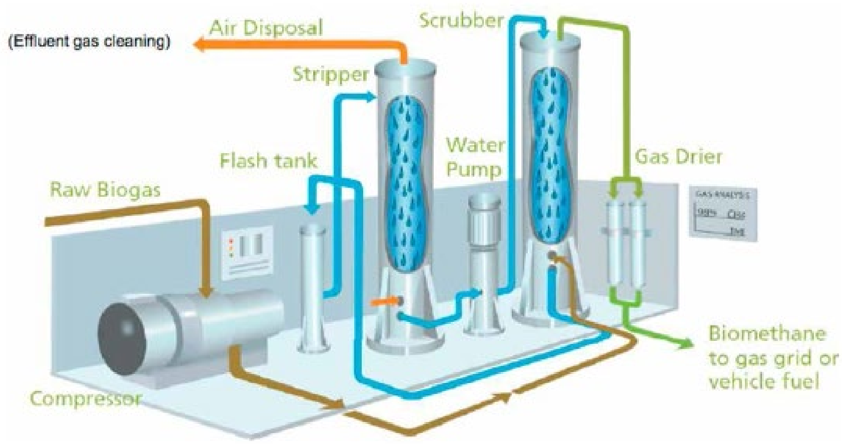

Figure 2: Principle of the water scrubber plant. Source: SGC (2013).

Input

- Raw biogas from a biogas plant.
- Electricity (or heat depending on the technology) for upgrading process.
- Electricity for compression.
- Smaller amounts of water and various chemicals.

Output

- Upgraded biogas with 95-99 vol. % methane, carbon dioxide and some nitrogen and oxygen [7].
- Waste gas containing mostly CO_2.

Energy balance

As shown in the figure below, the power consumption of the upgrading processes varies, but it ranges from approximately 0.2 to 0.3 kWh/Nm^3 raw biogas. As an exception, the amine scrubber has a heat demand of around 0.5 kWh/Nm^3 raw biogas, but a lower electricity consumption. The heat should be supplied at 120-150 °C and 80% of the heat can be reused in low-temperature

(65°C) applications [2].

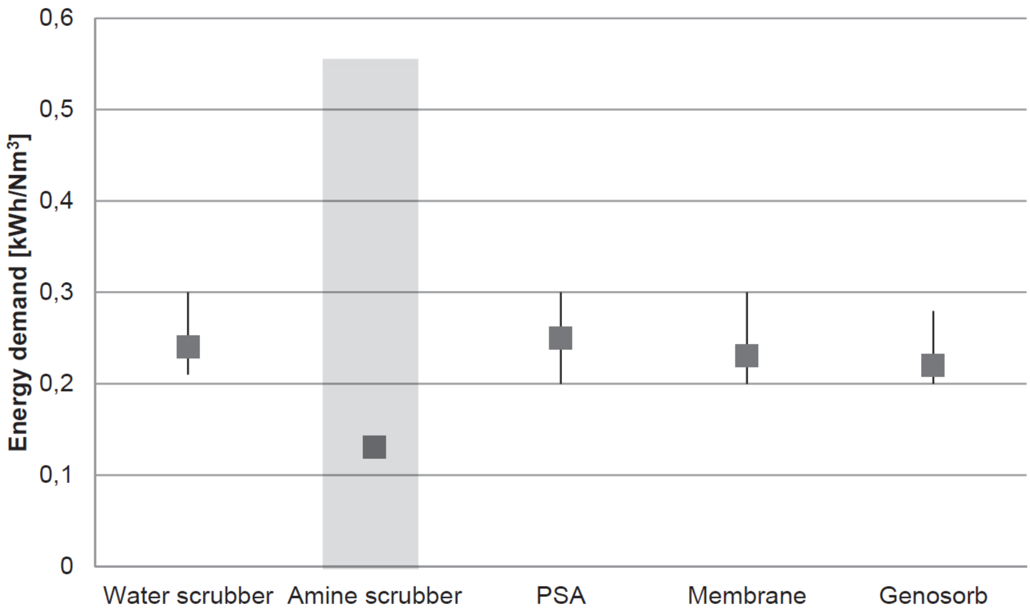

Figure 3: Electricity consumption (kWh/Nm^3 raw biogas, indicated as box and line) for the upgrading technologies, water scrubber, chemical/amine scrubber, PSA, membrane separation and organic physical scrubbing (Genosorb). Heat consumption shown as column. Source: SGC (2013).

In the upgrading process, there is typically a methane slip of up to around 1%, meaning that approximately 99% of the inlet methane exits as product [2]. Details for each technology are given in the section about environmental issues below.

When comparing the energy balance of the upgrading technologies it is important to consider excess pressure compared to required grid connection pressure.

Typical capacities

Different upgrading facilities are available from several suppliers in a broad range of capacities.

Typical capacities vary from upgrading technology and from location to location. In Sweden, the most common sizes are around 600, 900 and 1,800 Nm^3 raw biogas/h, while the most common in Germany is around 700 and 1,400 Nm^3 raw biogas/h.

Denmark has in 2016 around 18 biogas plants that supply biomethane to the natural gas grid. Typical sizes for newer plants in Denmark are in the range of 1.000 – 2000 m^3 biomethane per hour.

Regulation ability

Biogas upgrading plants can down regulate to 50% of full load [5].

Advantages/disadvantages

Upgrading of biogas to biomethane and injection in the natural gas grid makes it possible to decouple demand and consumption. Local use of raw biogas for CHP has until now made production dependant on local heat demand. Upgrading to biomethane creates a renewable fuel which can be transported and stored in the central gas grid and used where and when needed throughout Europe in conventional gas applications.

A disadvantage is the electricity consumption and relatively large investments connected with the upgrading.

Compared with another green gas technology, namely Bio SNG based on thermal gasification of biomass, upgraded biogas production is easier to decentralize, has less environmental impacts (emissions from chimneys), and the residuals has a good value for agriculture. Biomethane is a more mature technology where Bio SNG is still at demonstration level.

The different upgrading technologies each have their advantages and disadvantages respective to each other, but this will not be further discussed here.

Environment

Besides the energy consumption for operation, biogas-upgrading technologies have two other major environmental issues depending on the technology: the consumption of water and chemicals and a methane slip/emission.

Only the water scrubber and the amine scrubber use water – respectively 0.0004-0.004 m^3/Nm^3 and 0.00003 m^3/Nm^3 raw biogas. The chemical consumption for the water scrubber and amine mainly consist of anti-foaming. Furthermore, the amine scrubber has a demand for amine to account for the loss of amines in the process. During normal operation only minor amounts of amine are lost [2].

The removal of hydrogen sulphide requires active charcoal for both PSA, physical scrubbing (Genosorb), membrane separation and amine scrubbing. The highest reported chemical requirement is 0.00003 kg/Nm^3.

The highest methane slip among the technologies is reported to be the one from PSA with 1.8%-2%, followed by the water scrubber with 1%, 0.5% for membrane separation and the lowest slip from amine scrubbing of 0.1%. In principle, psychical scrubbers have a higher slip than the other technologies but the methane is utilized internally. The methane slip can be eliminated if the off-gas from the upgrading plant is treated in a regenerative thermal oxidation (RTO) plant.

Research and development

As noted above it is expected that the research and development and the competition between the different upgrading technologies will lead to incremental improvements of the technology and, to some extent, a reduction of costs.

Cryogenic upgrading

Regarding biogas and biomethane there may be a potential in the development of cryogenic treatment for upgrading biogas and for the condensation of upgraded biomethane to liquefied biogas. However, today the technology deployment is limited by operational problems.

Compared to other upgrading technologies cryogenic upgrading may have a lower energy demand for upgrading, no contact between gas and chemicals, production of pure CO_2 as a side product and the possibility to produce liquefied biomethane (LBG) and to remove nitrogen from the gas stream.

Enzymatic upgrading

The Danish Energy Technology Development and Demonstration Program (EUDP) supports new enzymatic upgrading technology in the project "Demonstration of a Novel Biogas Upgrading Technology". An enzymatic upgrading process has been developed and will be demonstrated in a full-scale biogas upgrading plant using biogas from waste water treatment. The demonstration plant has been in operation from mid-2015.

The CO_2 is captured in a non-volatile solvent with a biocatalyst in an absorber column. The biocatalyst accelerates the CO_2 absorption using enzymes. Afterwards the CO_2 is removed from the solvent in a stripper column. The technology integrates enzymes to create an industrial biocatalyst that can be readily incorporated into conventional chemical absorption processes for CO_2 removal. The demonstration includes large-scale production of enzymes and biocatalyst. The enzymatic upgrading process is anticipated to be more energy-efficient and cost-effective than commercially available upgrading technologies. A reduction in biogas upgrading cost by 25 % is expected.

Examples of market standard technology

NGF Nature Energy Holsted Water scrubber upgrading plant 2015, 13 mio Nm^3 biomethane per year. http://holsted.natureenergy.dk/Anlaegget

Sønderjysk Biogas Bevtoft, 2016, 21 mio Nm^3 biomethane per year. Applies amine upgrading technology. http://www.soenderjyskbiogas.dk/biogasanlaegget/

Bigadan Horsens Bioenergi, 2014, 10 mio Nm^3 biogas per year. Water scrubber and amin based upgrading plants. http://bigadan.com/c/cases/horsens-bioenergi

Assumptions and perspectives for further development

On a global scale, there has been a significant increase in the number of plants – especially since 2006. In Denmark, the market took of in 2014.

Until around 2008 PSA and water scrubber plants were dominating, but since then also the chemical scrubber (mainly amine scrubbers), the organic physical scrubber and membrane technologies have played an increasingly important role (see figure below).

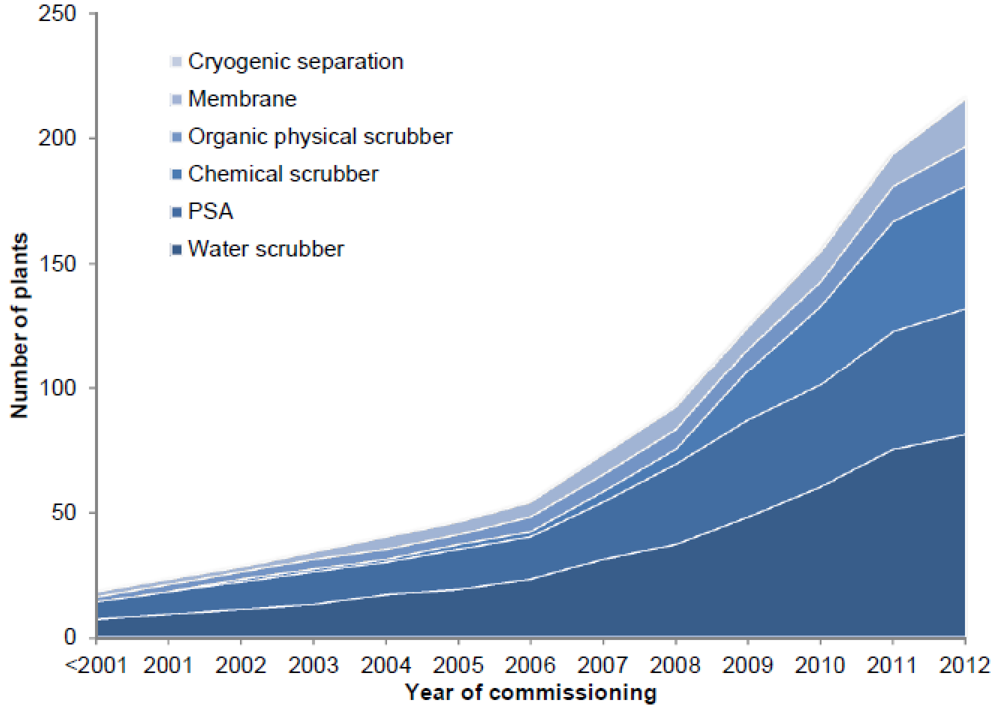

Figure 4 Global development in the number of upgrading plants and year of commissioning for the various technologies. Source: SGC (2013).

Currently, the biomethane production costs for the different mentioned commercially available technologies are around the same level. Just a few years back, amine systems were still only used as demonstration plants, whereas today the systems are sold and constructed in different standardized sizes. Water scrubbing and PSA have been mature technologies for many years, and only incremental technology development is expected, while cryogenic upgrading is a technology under development and demonstration.

An important aspect of biomethane market deployment is technical standards. Therefore, work is ongoing to establish a common European standard for injection of biomethane into the natural gas grid systems and for use as vehicle fuel within the European Biogas Association (EBA) and CEN project committee CEN/TC 408.

In Denmark, there is still relatively few upgrading plants but it is assessed that most new biogas plants will have upgrading facilities, so that the total production of upgraded biogas will amount to 8 PJ in year 2020 out of a total biogas production of 14 PJ [6].

Based on the above, the upgrading technology in general is considered to lie in between the two categories "3 *Commercial technologies with moderate deployment*" and "4 *Commercial technologies, with large deployment"*.

It is assumed that the growth will continue so that the Danish production of upgraded biogas will double in the period 2015 to 2020 and in the period 2020 to 2030. However, the total growth rate of the industry is likely to be smaller, considering less growth potentials in other countries where many plants are already operating. Thus, a moderate learning curve rate of 0.90 for investment and O&M costs is here assumed for each of the periods 2015-2020, 2020-2030 and 2030-2050.

Further, it is here assumed that one or more of the newer and currently less developed technologies (e.g cryogenic and membrane technologies) will take over from 2030 and that this can lead to lower methane slip (close to zero) and 50% reduction of the electricity consumption, which is already achievable today with the amine scrubbing technology [2, 7].

Additional remarks

Methanation of biogas by addition of hydrogen is an alternative technology, in which the CO_2 is converted to methane instead of releasing it to the atmosphere.

Data sheets

Data for an upgrading plant with a biogas input of 1.000 Nm^3 is presented below. For the projection years 2015 and 2020, the data sheet is based on a water scrubber plant. By 2030, one or more of the newer and currently less developed technologies (e.g. cryogenic and membrane technologies) are expected to take over leading to a reduction in the plant's electricity consumption.

Data sheets

Technology **Biogas upgrading**

Technology	Biogas upgrading									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Typical total size (MJ output/s)	5.92	5.92	5.92	5.92					A G	
Typical total size (Nm3 biogas/h)	1,000	1,000	1000	1000					A B	1/4
Capacity (Nm3 biomethane/h)	594	594	594	594					A B	
- Inputs										
Biogas (% of biogas input)	100%	100.0	100.0	100.0						
Auxilliary electricity for upgrading (% of biogas input)	4.3%	4.3%	2.2%	2.2%	3%	4.3%	1.6%	3.2%	A D J	1/2/4/7
Auxilliary electricity for compression (% of biogas input)	1.0%	1.0%	1.0%	1.0%					A F	2/4
Heat (% of biogas input)	0.0%	0.0%	0.0%	0.0%						2/4
- Outputs										
Biomethane (% of biogas input)	99.0%	99%	100%	100%					I	2
Waste gas (% of biogas input)	1%	1%	0.1%	0.1%					I	
Waste heat (% of biogas input)	5.3%	5.3%	3.2%	3.2%						
Forced outage (weeks per year)	1	1	1	1						
Planned outage (weeks per year)	1	1	1	1						
Technical lifetime (years)	15	15	15	15						
Construction time (years)	0.5	0.5	0.5	0.5						
Financial data										
Specific investment, upgrading and methane reduction (€/MJ/s input)	335,000	302,000	272,000	245,000	268,000	318,000	172,000	287,000	C D	1/2/5/7
Specific investment, grid injection at 40bar (€/MJ/s input)	134,000	121,000	109,000	98,000	107,000	127,000	69,000	115,000	F	5
Fixed O&M (€/MJ/s input / year)	11,800	10,600	9,500	8,600	9,400	11,200	6,000	10,100		2
- of which fixed O&M costs upgrading and methane reduction, excl. el. (€/MJ/s input / year)	8,400	7,600	6,800	6,100	6,700	8,000	4,300	7,200		2
- of which fixed O&M costs grid injection, excl. el. (€/MJ/s input / year)	3,400	3,000	2,700	2,500	2,700	3,200	1,700	2,900	H	2
Variable O&M ((€/GJ input)	0.93	1.03	0.88	1.02					H	
- of which electricity (€/GJ input)	0.93	1.03	0.88	1.02					E	2/4/7
Technology specific data										
Methane slip / emission (%)	1%	1%	0.1%	0.1%					I	2
Minimum load (% of full load)	50									7
CO2 removal, %	98.5									1

Notes:

A Corresponding to 1.000 Nm3 biogas input, assuming a methane content of the raw biogas of 60% and an average gross conversion efficiency of approx. 98,5%.

B Values are assumed valid for a range 500-1,500 Nm3 biomethane per hour

C Values include upgrading, methane reduction and grid injection facilities

D Based on a water-scrubber technology based plant, alternative technologies have comparable values in terms of total upgrading costs.
For a plant of double capacity (2000 Nm3/h) the realtive price is expected to be 20-25% lower [1,3]

E The cost of auxiliary electricity consumption is calculated using the following electricity prices in €/MWh: 2015: 63, 2020: 69, 2030: 101, 2050: 117. These prices include production costs and transport tariffs, but not any taxes or subsidies for renewable energy.

F Injection in natural gas grid at 40 bar

G Based on a lower calorfic value of 36 MJ/Nm3 and 8760 hours per year

H O&M costs are estimated to 2.5% of investment per year, in accodance with [2]

I Assuming that, by 2030, methane slip can be reduced to levels seen today for amin scrubbing technology. Methane slip is assumed to be the same as waste gas assuming that the plant is not equipped with a regenerative thermal oxidation (RTO) plant. If the the off-gas from the upgrading plant is treated with a regenerative thermal oxidation (RTO) plant the methane slip can be eliminated.

J Assuming that, by 2030, one or more of the newer and currently less developled technologies (e.g. cryogenic and membrane technologies) will take over.
This can lead to a 50% reduction of the electricity consumption, which is already achievable today with the amine scrubbing technology.

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