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The future of anaerobic digestion and biogas utilization

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ABSTRACT

One of the common tendencies of animal production activities in Europe and in developed countries in general is to intensify the animal production and to increase the size of the animal production units. High livestock density is always accompanied by production of a surplus of animal manure, representing a considerable pollution threat for the environment in these areas. Avoiding over-fertilization is not only important for environmental protection reasons but also for economical reasons. Intensive animal production areas need therefore suitable manure management, aiming to export and to redistribute the excess of nutrients from manure and to optimize their recycling.

Anaerobic digestion of animal manure and slurries offers several benefits by improving their fertilizer qualities, reducing odors and pathogens and producing a renewable fuel – the biogas.

The EU policies concerning renewable energy systems (RES) have set forward a fixed goal of supplying 20% of the European energy demands from RES by year 2020. A major part of the renewable energy will originate from European farming and forestry. At least 25% of all bioenergy in the future can originate from biogas, produced from wet organic materials such as: animal manure, whole crop silages, wet food and feed wastes, etc.

1. Introduction

The overall pollution prevention targets, the objectives of the Kyoto agreement as well important issues related to human and animal health and food safety require increasingly sustainable solutions for handling and recycling of animal manure and organic wastes, where biogas from anaerobic co-digestion of animal manure, combined with pre- and post-treatment technologies, play an increasing important role.

The large amounts of animal manure and slurries produced today by the animal breeding sector as well as the wet organic waste streams represent a constant pollution risk with a potential negative impact on the environment, if not managed optimally. To prevent emissions of greenhouse gases (GHG) and leaching of nutrients and organic matter to the natural environment it is necessary to close the loops from production to utilization by optimal recycling measures (Fig. 1).

Biogas can be produced from nearly all kind of biological feedstock types, within these from the primary agricultural sectors and from various organic waste streams from the overall society. The largest resource is represented by animal manure and slurries from cattle and pig production units as well as from poultry, fish, fur, etc. In the EU-27 alone, more than 1500 mill. tonnes of animal manure are produced every year (Table 1). European agriculture handles more than 65% of livestock manure as slurry, a liquid mixture of urine, feces, water, and bedding material (Menzi, 2002). Another agricultural substrate suitable for anaerobic digestion is represented by energy crops, of which most common are grain crops, grass crops and maize. Maize silage is among the most promising energy crops for biogas production (Braun et al., 2008).

When untreated or poorly managed, animal manure becomes a major source of air and water pollution. Nutrient leaching, mainly nitrogen and phosphorous, ammonia evaporation and pathogen contamination are some of the major threats. The animal production sector is responsible for 18% of the overall green house gas emissions, measured in CO_2 equivalent and for 37% of the anthropogenic methane, which has 23 times the global warming potential of CO_2. Furthermore, 65% of anthropogenic nitrous oxide and 64% of anthropogenic ammonia emission originates from the worldwide animal production sector (Steinfeld et al., 2006).

If handled properly, manure can be a valuable resource for renewable energy production and a source of nutrients for agriculture.

In the main part of northern Europe, the animal farms must store the produced slurry specially designed storage tanks, with a total capacity corresponding to 6–9 months of slurry production. Storage of slurry is necessary due to restrictions of its application

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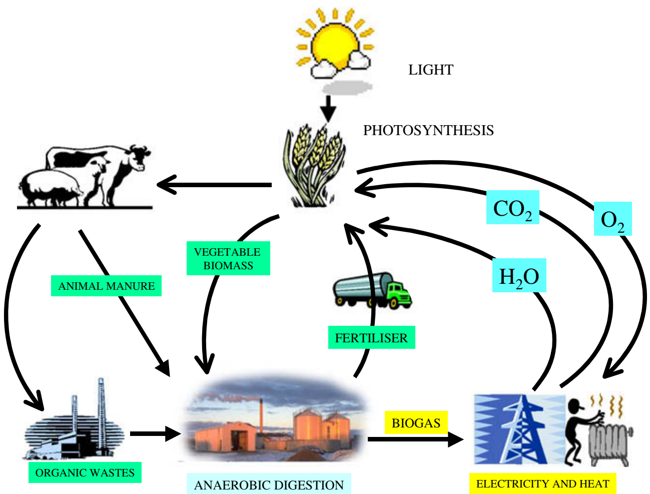

Fig. 1. Schematic representation of the sustainable cycle of anaerobic co-digestion of animal manure and organic wastes (Al Seadi, 2002).

period as crop fertilizer to only 4–6 months interval, close to or during the growing season. This restrictions aim to reduce nutrient leaching to ground water by increased utilization efficiency by the crops, if applied during germination and vegetative growth. In countries where there are no restrictions of the period of application, the storage time is shorter and slurry application seasons are often determined by the existing storage capacity, rather than considerations about nutrient utilization efficiency (Petersen et al., 2006).

There is a positive relationship between N surplus and GHG emissions. Each kg of N surplus corresponds with a GHG emission of approximately 30–70 kg CO_2-equivalents (Oenema et al., 2006). Biogas production from anaerobic digestion of animal manure and slurries is an effective way of reducing greenhouse gas emissions, in particularly ammonia and methane (Nielsen et al., 2002). The produced digestate can be further refined after the anaerobic treatment. One of the simplest methods is by separation with a decanter centrifuge into a solid and a liquid fraction. The dry matter content of the solid fraction is typically 25–35%. It contains 60–80% of the dry matter and phosphorus content of the original slurry, but only 20–25% of the nitrogen and 10–15% of the potassium (Møller et al., 2006). Separation facilitates the export of nutrients from the areas with excess of manure and the redistribution of nutrient to other areas in need of nutrients.

Throughout recent years, limited success was achieved by testing several physical, chemical and biological pre-treatment methods, aiming to increase hydrolysis of the lignocelluloses structure of manure fibers and by this to increase the biogas yield of digested manure (Møller et al., 2006). Separation can also be used as a pre-treatment of liquid manure, in order to produce a concentrated solid fraction which increases significantly the biogas potential unit of per digested volume.

2. Anaerobic digestion of animal manure

Anaerobic digestion of animal manure has the general goal of convert organic residues into two categories of valuable products: on one hand biogas, a renewable fuel further used to produce green electricity, heat or as vehicle fuel and on the other hand the digested substrate, commonly named digestate, and used as fertilizer in agriculture. Digestate can as well be further refined into concentrated fertilizers, fiber products and clean water, all suitable for recycling.

Co-digestion of animal manure with various biomass substrates increases the biogas yield and offers a number of advantages for the management of manure and organic wastes (Nielsen et al., 2002) and for mitigation of green house gas (GHG) emissions. Anaerobic co-digestion of manure and digestible organic wastes from food industry is very important for the corporate economy of the biogas plants and for the socio-economic reasons (Braun

Table 1
Estimated amounts of animal manure in EU-27 (based on Faostat (2003)).

Country	Cattle (1000 heads)	Pigs (1000 heads)	Cattle (1000 livestock units)	Pigs (1000 livestock units)	Cattle manure (10^6 tons)	Pig manure (10^6 tons)	Total manure (10^6 tons)
Austria	2051	3125	1310	261	29	6	35
Belgium	2695	6332	1721	529	38	12	49
Bulgaria	672	931	429	78	9	2	11
Cyprus	57	498	36	42	1	1	2
Czech R.	1397	2877	892	240	20	5	25
Denmark	1544	13,466	986	1124	22	25	46
Estonia	250	340	160	28	4	1	4
Finland	950	1365	607	114	13	3	16
France	19,383	15,020	12,379	1254	272	28	300
Germany	13,035	26,858	8324	2242	183	49	232
Greece	600	1000	383	83	8	2	10
Hungary	723	4059	462	339	10	7	18
Ireland	7000	1758	4470	147	98	3	102
Italy	6314	9272	4032	774	89	17	106
Latvia	371	436	237	36	5	1	6
Lithuania	792	1073	506	90	11	2	13
Luxembourg	184	85	118	7	3	0	3
Malta	18	73	11	6	0	0	0
Netherlands	3862	11,153	2466	931	54	20	75
Poland	5483	18,112	3502	1512	77	33	110
Portugal	1443	2348	922	196	20	4	25
Romania	2812	6589	1796	550	40	12	52
Slovakia	580	1300	370	109	8	2	11
Slovenia	451	534	288	45	6	1	7
Spain	6700	25,250	4279	2107	94	46	140
Sweden	1619	1823	1034	152	23	3	26
UK	10,378	4851	6628	405	146	9	155
EU-27	91,364	160,530	58,348	13,399	1284	295	1578

and Wellinger, 2003). Biogas from co-digestion of animal manure and suitable organic wastes is also a very attractive solution from a socio-economic point of view, when biogas externalities, including environmental, human and animal health benefits are quantified and integrated in the overall economic benefits. For the socio-economic point of view, admixture of organic waste to animal manure digestion brings about important benefits concerning increased production of biogas and energy sales, savings related to organic waste treatment, improved fertiliser value of digestate and reduction of GHG emissions from manure and organic wastes (Nielsen et al., 2002; Olesen et al., 2005; Hjorth et al., 2008).

There are many types of biogas plants in Europe, categorised according to the type of digested substrates, according to the technology applied or according to their size. The biogas plants digesting manure are categorised as agricultural biogas plants, and they usually co-digest manure and other suitable organic residues, many of them of agricultural origin as well. A common classification of the agricultural biogas plants is: (1) the large scale, joint co-digestion plants and (2) the farm scale plants. There is not a sharp delimitation between these two categories as elements of technology from one category are also common to the other.

The EU-countries where the agricultural biogas plants are most developed are Germany, Denmark, Austria and Sweden and to a certain level the Netherlands, France, Spain, Italy, United Kingdom and Belgium. The technology is under current development in countries like Portugal, Greece and Ireland as well as in many of the new, Eastern European, member states, where a large biomass potential is identified.

2.1. The joint biogas plant concept

The joint biogas plants co-digest animal manure collected from several farms, mixed with suitable organic residues from the food and feed industries and from the overall society. The joint biogas plants are usually of large scale, with digester capacities ranging from, e.g., few hundreds m^3 up to several thousands m^3.

One of the pioneer countries in developing agricultural biogas plants for manure and organic wastes co-digestion was Denmark, were the joint biogas plant concept was developed throughout the last two decades and represents today an integrated system of manure and organic waste treatment, nutrient recycling and renewable energy production, generating intertwined agricultural and environmental benefits.

Fresh animal manure and slurry are collected from the pre-storage tanks at the farms, transported to the biogas plant and mixed and co-digested with digestible organic wastes. The anaerobic digestion process takes place at thermophilic (53–58 °C) or mesophilic (30–40 °C) temperatures, during 12–25 days. The hydraulic retention time decreases with the digestion temperature. Before being added to the reactor content, specific substrates and animal by-products are submitted to a controlled pre-sanitation, aiming to inactivate pathogens and to break their propagation cycles. The digested biomass is transferred to the storage tanks, which are usually covered with a gas proof membrane for the recovery of the remaining biogas production. The biogas plants can be equipped with installations for separation of fiber and liquid fractions.

Digested biomass is transported back to the farms, at the storage tanks placed out in the fields, as pathogen free and nutritionally defined liquid fertilizer and integrated in the crop fertilizer plan at each farm. The farms receive back only that amount of digested biomass which they are allowed by the law to apply on their fields, according to the regulation on nutrient loading/ha. The excess of digested biomass is sold by the biogas plant to crop farms in the region.

The produced biogas is, e.g., used for combined heat and power generation, or for upgrading and utilization as vehicle fuel, like in Sweden (Nielsen et al., 2002; Persson et al., 2006). The produced power is sold to the grid and the heat is distributed through the district heating system to the consumers. Some of it is used by the biogas plant as process heating.

The biogas production cycle represents an integrated system (Fig. 2) of renewable energy production, resources utilization, organic wastes treatment and nutrient recycling and redistribution, generating intertwined agricultural and environmental benefits, as listed below:

- Renewable energy production.
- Cheap and environmentally healthy organic waste recycling.
- Less greenhouse gas emission.
- Pathogen reduction through sanitation.

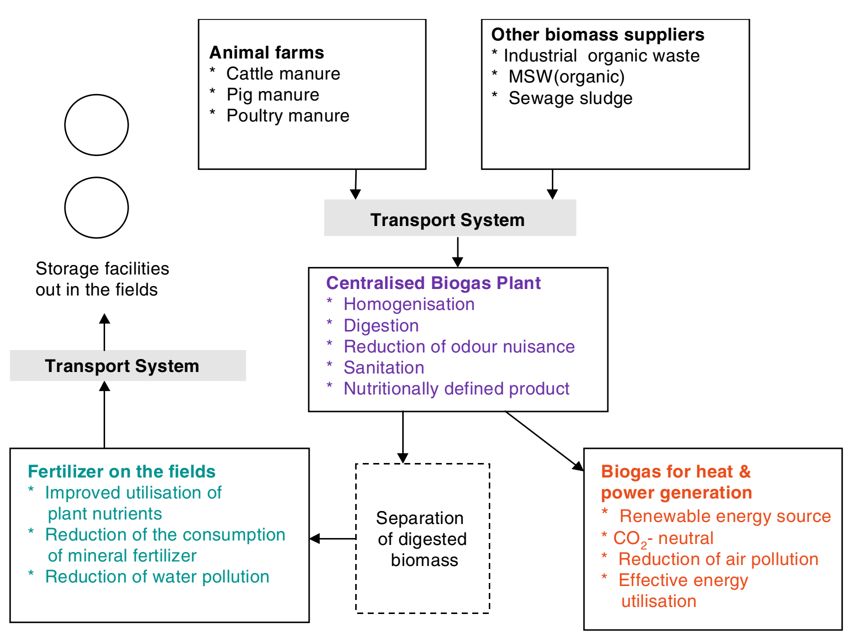

Fig. 2. The main streams of the integrated concept of centralized co-digestion plant (Holm-Nielsen and Al Seadi, 2004).

- Improved fertilization efficiency (Holm-Nielsen et al., 1997).
- Less nuisance from odors and flies (Birkmose, 2007).
- Economical advantages for the farmers.

2.2. The farm scale biogas plants

The farm scale biogas plants co-digest animal manure and slurry from one single farm or, rarely two or three smaller neighboring farms. The applied technology is similar to the joint biogas plants and the farm scale plants are usually established at large pig farms, confronting themselves with environmental problems due to excess of slurry production. The farm scale biogas plants apply also pre- and post-treatment and separation technologies.

2.3. Quality management of digested manure and optimal recycling as crop fertiliser

The quality management of digested manure implies quality control of the three main components of the anaerobic digestion cycle: the feedstock, the digestion process, and the digestate (Fig. 3).

This is done by some main measures (Al Seadi, 2002) such as:

- Selection and excluding from AD of the unsuitable waste categories, types and loads, based on the complete declaration of each load: origin, content of heavy metals, persistent organic compounds, pathogen contamination, other potential hazards, etc.
- Source sorting and separate collection of digestible wastes, preferably in biodegradable recipients.
- Periodical sampling and analyzing of the biomass feedstock.
- Extensive pre-treatment and on site separation (for unsorted waste).
- Pre-sanitation, for safe veterinary recycling.
- Process control (temperature, retention time, etc.) to obtain a stabilized end product.
- Periodical sampling, analyzing and declaration of digestate
- Handling, storage and application of digestate throughout "good agricultural practice".
- Integrating digestate in the fertilization plan of the farm.

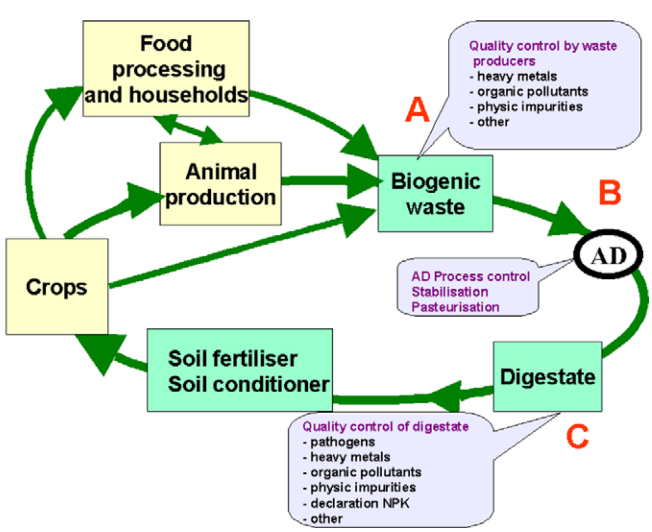

Fig. 3. Schematic representation of the closed cycle of anaerobic digestion of biogenic waste and the three main steps (A, B and C) of the quality management process (Al Seadi, 2002).

2.3.1. Nutrient load per ha

The application of digestate as fertilizer must be done on the basis of a fertilization plan of the farm. Inappropriate handling, storage and application of digestate as fertilizer can cause ammonia emissions, nitrate leaching and overloading of phosphorus. The nitrogen load on farmland is, e.g., regulated inside EU by the EU nitrate-directive (91/676/EEC nitrate). This piece of legislation aims to protect the ground and surface water environment from nitrate pollution. There are still some European countries which have a more permissive national regulation in this area, but the aim is that all EU-countries should implement the nitrate-directive as a minimum (Table 2).

The experience from Denmark shows that an environmental and economic suitable application of digested manure should fulfill the phosphorus requirement of the crops. The nitrogen requirement can this way be fulfilled up to 60–80%, depending on crop type, yield per ha, type of soil, conditions of culture, etc. The remaining nitrogen requirement can be supplied from chemical fertilizers.

2.3.2. Good agricultural practice for the application of digested manure

In order to achieve the environmental and economic benefits from the application of digested manure as fertilizer, some basic principles of good agricultural practice must be fulfilled (Holm-Nielsen et al., 1997):

- Always have a well established crusting surface in the storage tank with digested manure, to avoid ammonia volatilisation during storage.
- For the same reason, the digested manure must be pumped in at the bottom of the storage tank, to avoid stirring.
- The stored digested manure should be stirred just before it is applied to the crops, to ensure that sediments including the phosphorous are mixed into the entire volume.
- The storage tank for digested manure must be placed in sheltered from wind and other climate evaporation conditions.
- The digested manure must be incorporated in the soil immediately after application, or even better applied by injection in the top soil.
- Dragging or trailing hoses must be used when digested manure is applied in growing crops.
- The optimum weather conditions for application of digested manure as fertiliser includes: high humidity, low temperature and no wind.
- It is a possible to add acid to the digested manure when it is applied. This decreases the pH value and thereby the liability of ammonia to volatilise.

2.4. Veterinary aspects of utilization of digested manure as fertilizer

The modern technologies of manure and biogenic waste treatment should not result in new routes of pathogens and diseases transmission between animals, humans and the environment. For

Table 2
Example of national regulations of the nutrient loading on farmland. *Source*: Al Seadi (2002).

	Maximum nutrient load (kg N/ha y)	Required storage capacity	Compulsory season for spreading
Austria	100	6 months	28/2–25/10
Denmark	170 (cattle) 140 (pig)	9 months	1/2-Harvest
Italy	170–500	90–180 days	1/2–1/12
Sweden	Based on livestock units	6–10 months	1/2–1/12
UK	250–500	4 months	–

this reason, the recycling of the co-digested manure on agricultural land must be regulated in order to provide veterinary safety.

2.4.1. European regulation of organic waste treatment and recycling

The European countries have various national regulations concerning treatment and recycling of organic wastes, herewith also national veterinary legislation regarding pathogen control in digestate. In order to ensure an unified European standard and by this the same quality and safety measures all over Europe, a common EU regulation was adopted *"laying down the health rules concerning animal by-products not intended for human consumption"* (Commission of the European Communities, 2002). The document outlines the methods and the sanitary measures regarding the treatment of animal waste and the criteria for the future regulation of this area (Table 3) (Kirchmayr et al., 2003). Furthermore a working document (Commission of the European Communities, 2001) concerning the biological treatment of biowaste, regulating the treatment and utilization of all kinds of organic waste is about to be elaborated by the European Commission. The aim of all these regulations is to promote the biological treatment of organic waste in European countries by harmonizing the national organic waste management measures and regulations, to prevent any negative impact on the environment and to ensure that the recycling of treated and untreated organic waste not only provides benefits for the agriculture but also results in ecological improvement. Furthermore, common regulations aim to ensure the functioning of the internal market and to avoid obstacles to trade and distortion and restrictions of competition.

3. What should be done?

There is a range of policy compliance that can be achieved from anaerobic co-digestion of animal manure. Anaerobic digestion is a multi-purpose technology (Lukehurst, 2006) with the potential to fulfill a number of national and European environmental, agricultural and energy policy objectives (Table 4).

The strategy concerning further and broader development of biogas production and for overcoming barriers could include (Al Seadi, 2004; Holm-Nielsen and Al Seadi, 2004; Holm-Nielsen and Oleskowicz-Popiel, 2007):

Table 3
Health rules concerning animal by-products not intended for human consumption (EU-legislation doc., 1774, 2002).

Category and description	Rules for utilization
1. Animals suspected to be infected with TSE, specific risk material: – Animals, other than farm and wild animals, spec. pets, zoo and circus animals – Catering waste from means of transport operating internationally	Always destruction – incineration
2. Manure from all species and digestive tract content from mammalians: – All animal materials collected when treating wastewater from slaughter-houses or from category 2 processing plants, except from category 1 slaughter-house wastewater treatment plants – Products of animal origin, containing residues of veterinary drugs. Dead animals, others than ruminants	For AD must be pressure sterilised, for 20 min at 133 °C and 3 bars NB: Manure and digestive tract content can be used for AD without pre-treatment
3. All parts of slaughtered animals, declared fit for human consumption, or not affected by any signs of diseases: – Hides, skins, etc.	For AD must be sanitized in separate tanks for 1 h at 70 °C

Table 4
The multi- purpose legislative value of biogas from AD in Europe (Lukehurst, 2006).

Need	Legislation
Environmental	*Climate change:* • Reduce energy consumption • Cut emissions from: transport sector – Electricity production and distribution – Livestock production • Increase renewable energy production by 10% by 2010 *Water quality:* • Reduced risk of diffuse N pollution/increased NH_4 available for take up (Nitrate-Directive – 91/676/EEC)
Agriculture	*Nutrient management schemes:* • Better control of ammonia emissions • Easier management of P_2O_5/fiber separation • Reduced applications of mineral fertilizer
Health	*Health and hygiene:* • Improved bio-security from pathogen reduction (Animal By-Product Directive – 1774/2002/EC) • Treatment of animal by products, kitchen, catering and restaurant waste and utilization for energy and biofertiliser production • Reduced sources for flies and rodents • Reduced odors from manure spreading
Waste reduction, recovery and recycling	*Waste disposal legislation and policy:* • Reducing amount disposed to landfill (The Landfill Directive – 1999/31/EC) • Increase recycling and recovery (Packaging and Packaging Waste Directive – 94/62/EC)

- Programmes to stimulate recycling of organic resources/organic wastes, especially of wet organic wastes.
- Support programmes for manure processing, with high energy recovery and safe measures of bio-security.
- Harmonization of animal manure storage and handling requirements.
- Focus on industrialized animal production, such as large scale pig production and similar business animal farms, with no or little land area for the recycle of nutrients through crop production.
- An overall strategy of mandatory harmony between animal production and farmland area suitable for manure application.
- Demands for maximum limits of nitrogen and phosphor loading rate on farmland.
- Improvement of the present technologies and reduced costs.
- R&D on small scale systems, going from economy of scale to economy of numbers.
- Improved post-treatment and separation technologies, aiming to overcome transport constraints.
- Finding and implementing new post-treatment technologies.
- Concentration on finding solutions to eliminate or avoid the bad odor in the vicinity of biogas plants.
- Programmes for active implementation and dissemination of biogas technologies and knowledge transfer to other countries around the world.
- An overall policy to stimulate green electricity production from renewable sources and to encourage use of renewables in combined heat and power systems.
- Stimulation of wider use of district heating networks, district cooling or heat recovery to processing industries, converting heat to cooling, especially in the warm climate areas, subtropics and tropics.

3.1. Biogas utilization applications

Biogas can be utilized in several ways; either raw or upgraded. As a minimum, biogas has to be cooled, drained and dried immediately after production, and almost always it has to be cleaned for the content of hydrogen sulphide (H_2S). The H_2S content in biogas, at levels higher than 300–500 ppm, damages the energy conversion technique (Holm-Nielsen et al., 2004). Today biological cleaning reduces the content of hydrogen sulphide to a level below 100 ppm.

There are various biogas utilization purposes:

- Production of heat and/or steam (the lowest value chain utilization).
- Electricity production with combined heat and power production (CHP).
- Industrial energy source for heat, steam and/or electricity and cooling.
- Upgraded and utilization as vehicle fuel (Persson et al., 2006).
- Production of chemicals and/or proteins (Born, 2005).
- Upgrading and injection in the natural gas grids (Kristensson et al., 2007).
- Fuel for fuel cells.

A remarkable example of upgrading biogas and using it for vehicle fuel is Sweden, where the market for such biogas utilization has been growing rapidly in the last decade, so there are today 15.000 vehicles driving on upgraded biogas gas in Sweden, and the forecast is of 70.000 vehicles, running on biogas supplied from 500 filling stations, by year 2010–2012 (Persson et al., 2006).

An efficient way of integrating the biogas into the energy sector is the upgrading of biogas to natural gas quality (biomethane) and injecting it into the existing natural gas grid. As biogas cannot always be used nearby the production facilities, in the farming areas, injecting upgraded biogas as biomethane into the natural gas grids widens up the opportunities to transport and utilize biogas in the large energy consumption areas, where the population concentration is situated.

3.2. Biogas – reliable and flexible, renewable energy source

Penetration of biogas on the energy market will probably accelerate, as problems of economics and market acceptability are overcome. This is emerging in the end of this decade, as a consequence of the growing share of renewables in the worlds energy supply, including demand of security of energy supply. The rate at which biogas can enter the market is highly a matter of creating favorable national political and economical frame conditions.

In, e.g., EU-countries, where only about 6% of the gross consumption originated from renewables in 2001, the share of renewables is expected to reach 12% by 2010, according to the objectives of the White Paper of RES of the EU-Commission from 1997 (Commission of the European Communities, White Paper of RES, 1997). The EU policy concerning renewable energy sources (RES) has set forward a fixed goal of supplying 20% of the European energy demands from RES by year 2020. A major part of the renewable energy will originate from European farming and forestry as biomass conversion to gaseous, liquid and solid biofuels, where the biogas production has its own, consolidated platform. At least 25% of all bioenergy (Holm-Nielsen et al., 2007) can in the future originate from biogas produced from wet organic materials such as animal manure, crop silages, wet organic food and feed residues, etc.

Biogas has definite advantages, even if compared to other renewable energy alternatives. It can be produced when needed and can easily be stored. It can be distributed through the existing natural gas infrastructure and used in the same applications like the natural gas. Apart from utilization for renewable electricity and heat production, biogas can replace fossil fuels in the transport sector.

The future development of biogas from manure co-digestion includes the use of new feedstock types such as by-products from food processing industries, bio-slurries from biofuels processing industries as well as the biological degradation of toxic organic wastes from pharmaceutical industries, etc. Careful process control by on-line measurements of important parameters will optimize the process and increase the biogas yield. Reducing capital costs and management costs are furthermore targets of the future development of biogas systems.

4. Conclusions

There is a considerable potential of biogas production from anaerobic digestion of animal manure and slurries in Europe, as well as in many other parts of the world. Anaerobic digestion of animal manure offers several environmental, agricultural and socio-economic benefits throughout improved fertilizer quality of manure, considerable reduction of odors and inactivation of pathogens and last but not least production of biogas production, as clean, renewable fuel, for multiple utilizations.

The last decade brought about huge steps forward, in terms of maturation of biogas technologies and economic sustainability for both small and large scale biogas plants.

One of the driving forces for integrating biogas production into the national energy systems will continue to be the opportunities offered by biogas from anaerobic co- digestion of animal manure and suitable organic wastes, which solves some major environmental and veterinary problems of the animal production and organic waste management sectors.

Rewording manure processing for biogas production and for the environmental benefits provided by this would ensure the future development of the manure based biogas systems.

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