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THEME ENERGY.2009.3.2.2
Biowaste as feedstock for 2nd generation

VALORGAS

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D5.1 - Evaluation of potential technologies and operational scales reflecting market needs for low-cost gas upgrading systems

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D5.1 Evaluation of potential technologies and operational scales reflecting market needs for low-cost gas upgrading systems

The VALORGAS project is primarily concerned with the production of biogas from food waste. With respect to small-scale biogas upgrading systems, especially those that may be applied in countries such as India, the feedstock is likely to be more mixed and may also contain agricultural and animal wastes. For this reason the scope of the current deliverable includes upgrading systems within this broader context.

1. Biogas production and utilisation in Europe

Anaerobic digestion is a biological process where organic waste is converted into biogas by microorganisms under anaerobic conditions. In nature, the fermentation process occurs in places where biological material is fermented in an oxygen-deprived environment such as swamps and wetlands. In engineered systems, biogas is mainly produced through fermentation of various organic wastes, viz. manure, municipal sewage sludge, industrial wastes and energy crops etc., in anaerobic digestion (AD) and sewage treatment plants. Biogas is also produced during anaerobic degradation of domestic garbage in landfills. Biogas produced from sewage treatment plants is sometimes referred as sewage gas while the biogas produced from landfill is called landfill gas. The worldwide biogas production is unknown, but the production of biogas in the European Union has steadily increased over the last few years from 5.9 Mtoe (69 TWh) in 2007 to around 8.3 Mtoe (97 TWh) in 2009 (EurObserv'ER, 2010). In 2009, biogas produced from agricultural biogas plants and centralised co-digestion plants accounted for 52% of total biogas production (Figure 1). Biogas production from wastewater treatment plants and landfill gas production from landfills accounted for 12% and 36%, respectively (EurObserv'ER, 2010).

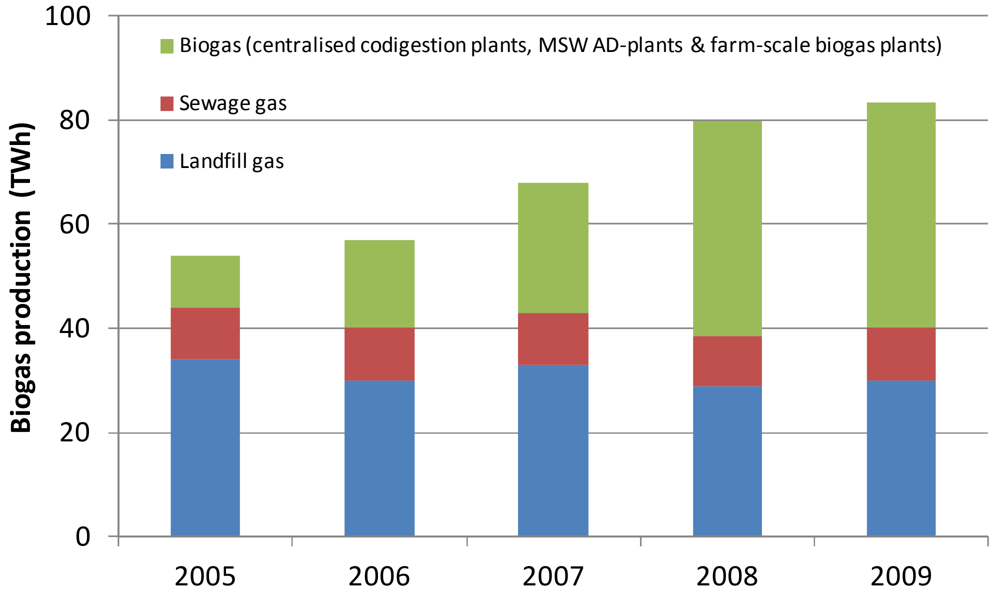

Figure 1. Biogas production in the European Union between 2005 and 2009 (Source: EurObserv'ER, 2008; 2010)

Biogas is considered as a sustainable renewable energy source that can be used for cooking, lighting, heating and power generation. Most often the produced biogas is combusted on site in a gas engine or boiler to generate heat and/or electricity. However, the upgrading of biogas to biomethane (a gas consisting of mainly methane, comparable to natural gas), sometimes combined with injection into a natural gas grid and/or direct use as fuel, has recently been gaining popularity on economic and environmental grounds.

Germany, Austria, Denmark, France, Sweden, Switzerland and the Netherlands are the leading European countries in biogas utilisation for vehicle fuel or grid injection. In most cases, however, biogas is still primarily used for heat and electricity production in combined heat and power (CHP) plants. The Netherlands was the first country to inject biomethane from landfill biogas into the natural gas grid. Use of landfill gas for grid injection is strictly forbidden in Switzerland, Austria and Germany due to the presence of halocarbon derivatives that could react when combusted and form furanes and dioxins. Sweden, Germany and Switzerland are the main users of biogas for vehicle fuel. In France and the UK Veolia is utilising biomethane produced from landfill gas as a vehicle fuel in a small number of cases.

2. Feedstocks used for biomethane production in Europe

Many different feedstocks are used for biogas production. A general distinction can be made between biomass from agriculture such as by-products (manure) or dedicated energy crops and from various waste streams (Table 1). Savola (2006) classifies the raw materials into (1) urban waste (including wastewater, industrial waste, household waste, restaurant and catering waste, park and garden waste), (2) agricultural by-products (including manure and harvest residues), and (3) dedicated energy crops (for example grasses, grain, maize, sugar beet).

Table 1. Classification of feedstocks for biogas production (adapted from Savola, 2006).

Agriculture & residues	Urban waste streams	Energy crops
Manure	Landfill	Energy crops, catch crops
Harvest residues	Sewage sludge	
Landscape management	Municipal solid waste	
Grass	Food waste	
Other by-products	Other waste	

The potential biomass for biogas production in EU is large. According to projections, the use of biomass for energy generation in Europe has increased from 69 Mtoe (2003) to 180 Mtoe (2010) and should be tripled to 225-250 Mtoe by 2030 in order to meet the European renewable energy targets (Ericsson and Nilsson, 2009).

Most European countries produce their biomethane from feedstocks such as biowaste, sewage sludge (municipal wastewater treatment biosolids), energy crops and manure alone (Figure 2) or by co-digestion (Figure 3) in variable proportions. Sweden produces a significant amount of biomethane from sewage sludge digestion alone or in combination with biowaste, energy crops and manure. Dutch biomethane is mainly extracted from landfill gas. In Germany, biomethane is mainly produced from energy crops, despite questions about sustainability. This issue is duly addressed by practicing crop rotation and integrated approaches such as the Vaxstkraft project in Vasteras (Stockholm region, Sweden). In the latter case, energy crops are an additional substrate (less than 20% of the whole feedstock): clover is cultivated and is at the same time a way of preparing and improving soils for food cultures. Co-digestion of different feedstocks viz., sewage sludge/biowaste, manure/biowaste, manure/energy crop and etc., is commonly practiced in Germany, Sweden and Switzerland to improve biogas yields and also to recover as much as possible biodegradable waste (Figure 3).

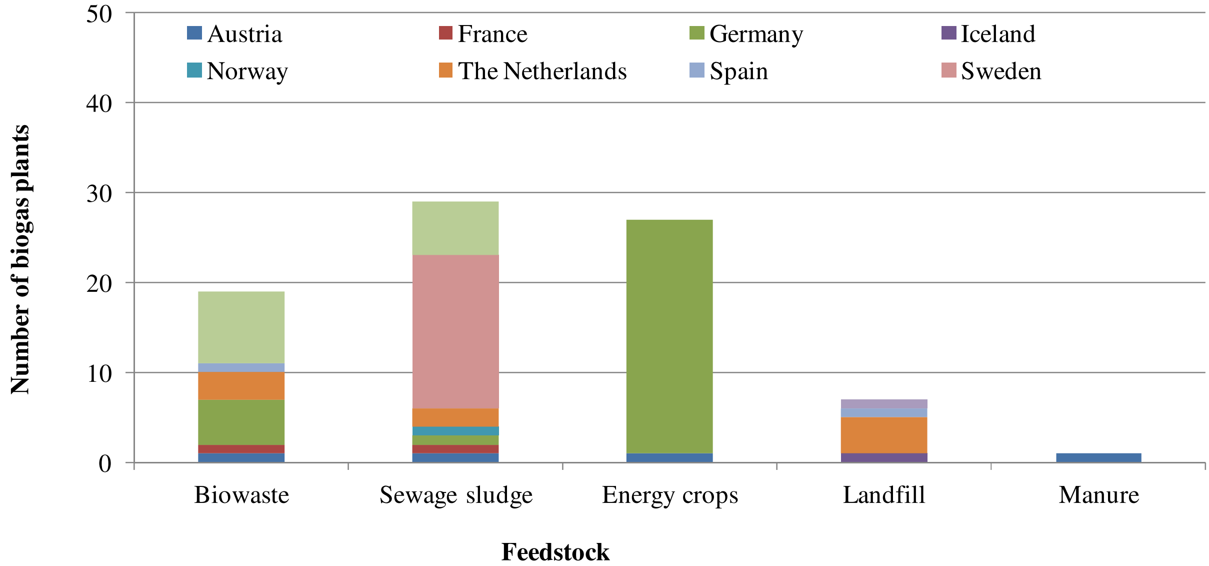

Figure 2. Feedstock type and biogas plants with an upgrading unit in Europe in 2008 (Source: IEA Bioenergy, 2009).

3. Biomethane production costs from different feedstocks in Europe

The cost of biomethane production is a very important factor in uptake of the technology since the price of the biogas has to be reasonable, and preferably lower than the price for competitive fuels. The results from an EU study showed that the cost for production of the biogas is strongly dependent on a number of factors, such as type of production plant, the substrate used and local conditions (Mårtensson, 2007). The investment cost of a production plant affects the production cost, and the investment in a plant varies greatly. An important factor is the feedstock used, since the pretreatment required for different substrates varies. If the gas is produced in an existing wastewater treatment plant the production cost will be lower than if a new production plant is constructed. The costs for transport of the feedstock must be taken into consideration as well, and this is dependent on distances and water content of the feedstock. Local conditions vary, and this can be a decisive factor for the production cost. Thus, cost estimation for production of biogas is a complex subject and predications may vary according to the methodology adopted as well as with feedstock and production system.

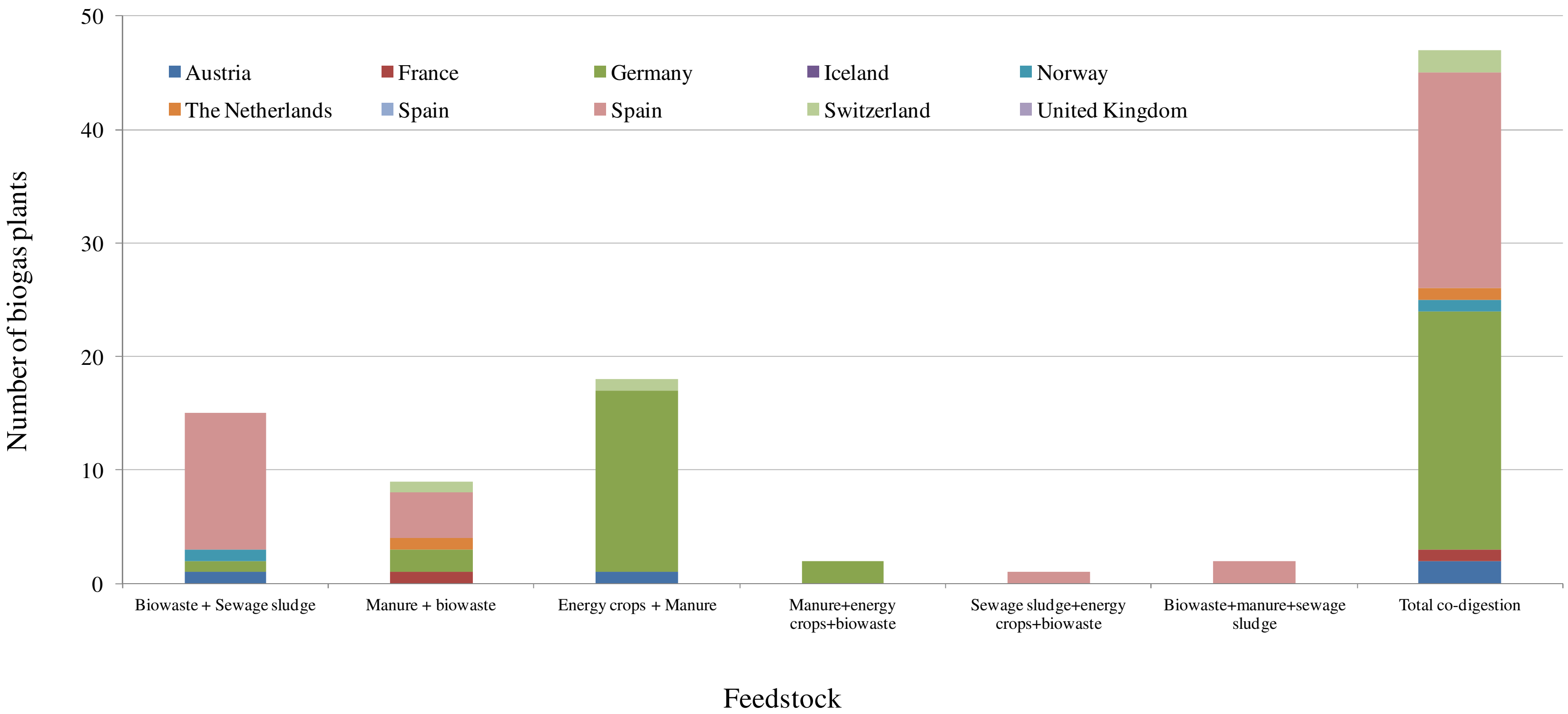

Figure 3. Co-digestion feedstock and number of biogas plant with an upgrading unit in Europe in 2008 (Source: IEA Bioenergy, 2009)

3.1 Sewage sludge

The cost of biogas production is lowest for sewage sludge as the production usually takes place at an existing wastewater treatment plant. The digesters already exist and the cost of the upgrading is the main cost. According to Linné and Jönsson (2004), the cost estimate for upgraded and pressurised gas in Stockholm, Sweden is 0.22-0.48 € Nm^{-3} excluding value added tax (VAT). Costs for the refuelling station are not included, since these vary considerably according to local conditions.

3.2 Organic waste

The cost for production of the raw biogas from a new production plant treating organic waste has been estimated at 0.43 € Nm^{-3} (Hägglund, 2007). The total production cost, including upgrading and compression, is estimated at about 0.65 € Nm^{-3} (Mårtensson, 2007). The cost of production from slaughterhouse waste and other organic waste at *Svensk biogas* in Linköping, Sweden is estimated to be 0.44-0.54 € Nm^{-3} (Mårtensson, 2007). This gas is upgraded but not pressurised: if pressurised, an additional 0.11 € Nm^{-3} is required (Mårtensson, 2007).

3.3 Energy crops

The costs for biogas production from energy crops in Sweden is between 0.68 and 0.85 € Nm^{-3} (Sweco Viak, 2006). This cost is however dependent on several factors such as subsidy received, local conditions, distance of gas pipe required, operational costs, costs of the substrates, and gas yield (Mårtensson, 2007). The calculation is based on an income of 5% and assumes that the gas is delivered through a gas pipe 10 km from the production plant (Mårtensson, 2007). When the gas is bought by a gas distributor for further distribution a cost of 0.16-0.27 € Nm^{-3}, including refuelling and VAT, can be added, and still gives a selling price lower than that for petrol and diesel (Sweco Viak, 2006). The estimated cost for production of biogas from crops given by *Swedish Biogas International* is 0.42-0.63 € Nm^{-3}, excluding distribution and at a pressure of 4 bar (Mårtensson, 2007). As mentioned above compression is about 0.11 € Nm^{-3}, and hence the total cost is 0.53-0.74 € Nm^{-3} (Mårtensson, 2007). The higher cost for the substrate when crops are used is partially compensated for by lower treatment costs in the biogas plant: for example there is no need for hygienisation.

3.4 Manure

Biogas production from manure is probably the most expensive alternative and can vary from 0.47 – 0.95 € Nm^{-3} under Swedish conditions (Mårtensson, 2007). According to *The Rural Economy and Agricultural Societies,* the cost of on farm-based biogas production in Sweden is 0.065 € kWh^{-1} (Svensson, 2006). The costs for upgraded and pressurised biomethane production, excluding VAT, are calculated as 0.95 € Nm^{-3} (Svensson, 2006). The price of the gas at the refuelling station, including VAT, is then 1.18 € Nm^{-3}. Although the price for biogas production from manure is higher than from other substrates, it is still lower than the petrol price. However, the investment costs for farm-scale biogas production can also vary to a large extent. In some cases the farmer construct the plant himself and in this way the investment cost is reduced greatly, compared to buying the plant.

Mårtensson (2007) reported that the cost of raw biogas on the Stora Svenstorp farm outside Götene in Västergötland County, Sweden, where the farmer constructed the plant himself was

0.016 € kWh^{-1}. This was much lower than the cost of 0.065 € kWh^{-1} for the raw gas production calculated by *The Rural Economy and Agricultural Societies* (Svensson, 2006). If the raw gas is produced at 0.016 € kWh^{-1} and the conditions are the same as for the calculations made by *The Rural Economy and Agricultural Societies*, (0.32 € Nm^{-3} for gas pipe, upgrading and refuelling station), then the price of the gas at the refuelling station would be 0.59 € Nm^{-3} (Mårtensson, 2007).

4. Biogas upgrading in Europe

There is more than 20 years of experience in gas upgrading in Europe. The same upgrading technologies used for industrial gas separation can be used for the production of biomethane for vehicle fuel use and grid injection. Biogas upgrading for vehicle fuel use and grid injection started in the late 1980s. In 2011, there are 137 biogas upgrading units in Europe (Figure 4). The total raw gas capacity used for biogas upgrading in Europe was 115155 Nm^3 $hour^{-1}$ in 2011 (IEA Bioenergy 2011). Of this, water scrubbing (46440 Nm^3 $hour^{-1}$) followed by chemical scrubbing (32170 Nm^3 $hour^{-1}$) and PSA (20230 Nm^3 $hour^{-1}$) are the most popular commercial upgrading technologies (Figure 5).

Most of the biogas upgrading units in Europe are located in Sweden and Germany (Figure 6). The first upgrading plant in Germany was built in 2006 and today Germany has the biggest installed biogas upgrading capacity in the world (Figure 3), with about 58 units in operation. Changes in the legislative framework have led to a boom in biogas upgrading. It is anticipated that within the next 10 years, around 1,000 biogas upgrading plants will be constructed in Germany (Weiland, 2010). Pressure swing adsorption (PSA) is likely to be the leading technology but high pressure water scrubber (PWS) and chemical absorption with amines and membrane technology are also gaining importance. The upgraded gas is mainly used in grid injection and in CHP plants, and only a small part is used in the transport sector. Further, biomethane as vehicle fuel is free of tax up to 2018 in Germany (Weiland, 2006), and consideration is also being given to making a mixture of 20% biomethane and 80% natural gas free of tax. There are 39 upgrading plants in Sweden and the upgraded gas is currently used mainly as vehicle fuel.

5. Quality standards for biomethane in Europe

Production of biomethane of a quality suitable for vehicle use involves cleaning and upgrading of biogas to biomethane with a composition and quality similar to that of natural gas. Currently, there is no international standard regarding the gas quality for grid injection or vehicle use. Several countries have defined national standards, however, (e.g. Austria, Denmark, Germany, the Netherlands, Sweden and Switzerland), and have developed specific regulations on the use of biomethane for vehicle fuel or grid injection (Table 2). These standards vary from country to country and also differ according to the end use. Germany and Switzerland have two levels of requirement for the upgraded biogas with different restrictions applied for the injection of low and high quality gas. Sweden has one standard that has been defined for biogas utilised as vehicle fuel. In 2010, a mandate of the European Commission has been submitted to CEN to produce a set of biomethane standards for vehicle use and grid injection (Table 2).

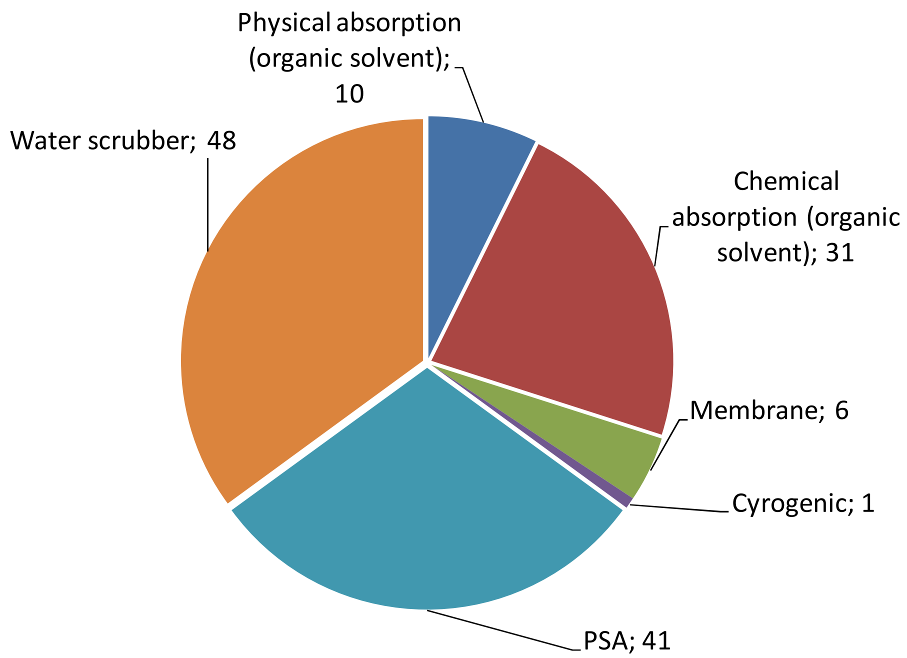

Figure 4. Biogas upgrading in Europe – number of biogas upgrading units and technologies (Source: IEA Bioenergy 2011).

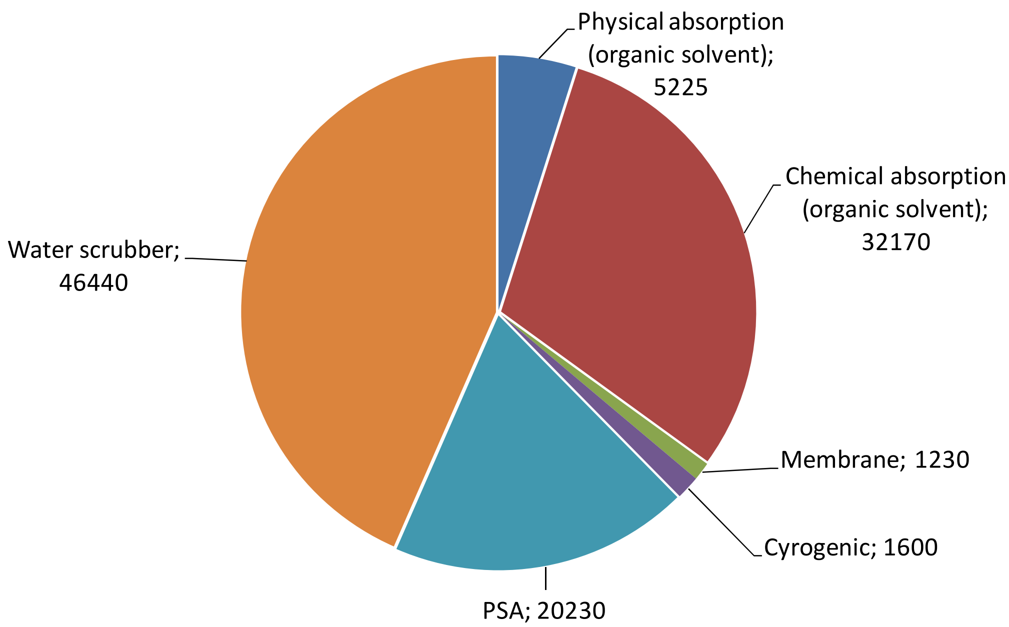

Figure 5. Biogas upgrading in Europe – biogas upgrading technologies and capacities (in m^3) (Source: IEA Bioenergy 2011).

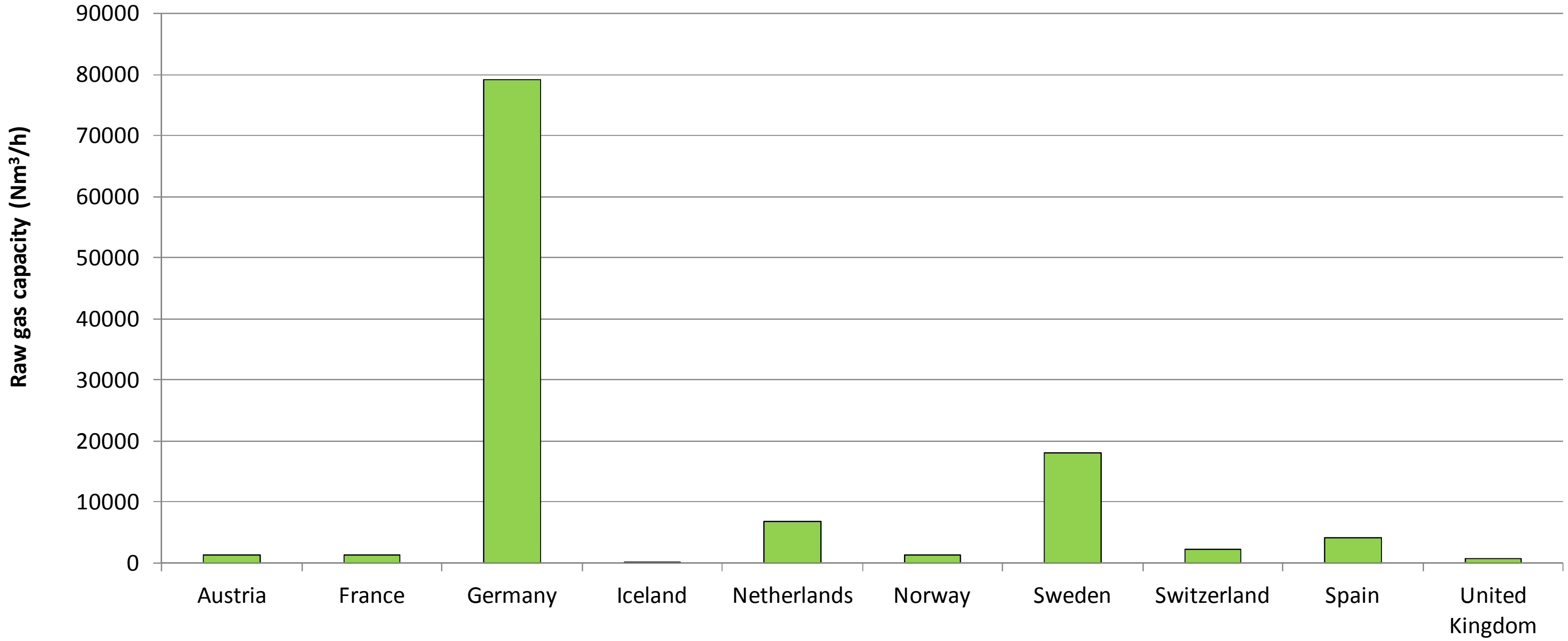

Figure 6. Biogas upgrading in Europe – raw gas capacities in major European countries in Nm^3 $hour^{-1}$ (Source: IEA Bioenergy 2011).

Table 2. Selected national biomethane standard requirements for grid injection or utilisation as vehicle fuel in Europe (Adapted after IEA Bioenergy 2009)

Compound	France[1]		Germany[2]		Sweden[3]	Switzerland[4]		Austria[5]	Holland[6]
	L gas	H gas	L gas	H gas		Limited injection	Unlimited injection		
Lower Wobbe Index (MJ Nm^{-3})					43.9-47.3				
Higher Wobbe Index (MJ Nm^{-3})	42.48-46.8	48.24-56.52	37.8-46.8	46.1-56.5				47.7-56.5	43.46-44.41
CH_4 (vol-%)					97	>50	>96		>80
CO_2 (vol-%)	<2		<6			<6		<2[6]	
O_2 (vol-%)	<0.01		<3		<1	<0.5		<0.5[6]	
H_2 (vol-%)	<6		<5			<5		<4[6]	<12
$CO_2+O_2+N_2$ (vol-%)					<5				
Water dew point (°C)	<-5 (at MOP downstream from injection point		<t[4]		<t[4]-5			<-8[7]	-10[8]
Relative humidity (%)			0.55-0.75			<60%			
Total S (mg Nm^{-3})	<100 (instant content) <75 (Annual average)		<30		<23	<30		<5	<45
MON (Motor octane number)					>130				
NH_3 (mg Nm^{-3})					<20				
H_2S (mg Nm^{-3})						<30			

[1]National guidance no. 2004-555 (2004) and technical specifications (2006); [2]Standards DVGW G260 and G262; [3]Standard SS155468; [4]Directive SSIGE G13; [5]Directive OVGW G31 and G33; [6]Proposition for Dutch gas suppliers.

Several cities in Europe use biomethane as a transportation fuel for buses in the public transportation system. Municipalities using refuse collection trucks running on bio-methane also exist in some European countries e.g. Sweden. There are, however, important differences between the European countries in their use of biomethane. According to the International Association for Natural Gas Vehicles (IANGV, www.iangv.org), there were more than 12 million natural gas vehicles (NGVs) worldwide in October 2010 and this is projected to increase to 50 million vehicles by 2020 (IANGV, 2011). Biomethane can be used in vehicles operated on natural gas without any engine modification. The minimum quality parameter for natural gas vehicles is 86 % CH_4 content (European Commission, 2001); however, a methane content of 95 to 97 % is generally expected by many engine manufactures. Bifuel vehicles can use either biomethane/compressed natural gas (CNG) or gasoline/diesel. The two fuels are stored in separate tanks and the engine runs on one fuel at a time. Bifuel vehicles can switch back and forth from gasoline/diesel to biomethane, manually or automatically. For vehicle use, biomethane is compressed to 250 bar due to the low energy per unit volume of the biogas. The compressed gas is then stored on site, transported by road or distributed through the natural gas grid.

6. Small-scale biogas upgrading in Europe

In Europe, the highest percentage of the total production of biogas comes from the many small-scale digesters producing small quantities of biogas (50-200 Nm^3 $hour^{-1}$). For these plants it is not feasible to upgrade the gas to natural gas quality and to inject this upgraded biomethane into the natural gas grid or use it as commercial fuel at a gas station. The cost for quantity and quality control together with the high performance requirement for gas transport/injection makes this option too expensive for small-scale applications. Other conditions apply, however, when the gas is not used commercially but only locally within a small community or farm. Therefore, small-scale biogas upgrading can be made economically viable by reducing the main cost elements in upgrading i.e. electricity and water costs. This can be achieved through measures such as electricity generation from the produced on-farm biogas; use of ground water for water scrubbing; regeneration of the wash water and/or upgrading at low temperature (15-20 °C); and use of low-cost high pressure storage containers and compressing to high pressures (250-270 bars) so as to reduce the electricity costs at filling station. In conditions where the cost of water is negligible as most of the water is recycled, and the electricity requirement is not too high, the costs can be further reduced by incorporating less complex control systems, using low-cost fabricating materials, mass production of the units, and incentives from the government etc.

Table 3. List of small-scale biogas upgrading plants (<50 Nm^3 $hour^{-1}$ raw biogas) in Europe (Source: Petersson and Wellinger 2009; IEA Bioenergy 2011)

S.No.	Place	Substrate	Utilisation	CH4 requirements (%)	Technology	Plant capacity (Nm^3 $hour^{-1}$ raw gas)	In operation since
1	Kalmari farm, Laukaa, Finland	Energy crops, manure	Vehicle fuel	96	WS	30	2005
2	Pucking, Austria	Manure	Gas grid	97	PSA	10	2005
3	Ulricehamn, Sweden	Sewage sludge	Vehicle fuel	97	PSA	20	2003
4	Lilla Edet, Sweden				PSA	25	2005
5	Rümlang, Switzerland	Biowaste	Vehicle fuel	96	PSA	30	1995
6	Bachenbülach, Switzerland	Biowaste	Gas grid and vehicle gas	96	PSA	50	1996
7	Samstagern, Switzerland	Biowaste	Gas grid	96	PSA	50	1998
8	Biorega,						
9	Otelfingen, Switzerland	Biowaste	Vehicle gas	96	PSA	50	1998
10	Biosling, Norway		Gas grid, vehicle fuel	97	WS		NA
12	Zalaegerszeg, Hungary	Sewage sludge	Gas grid, Vehicle fuel	97	WS	50	NA
13	Collendoorn	Landfill gas	Gas grid	88	M	50	1993

Note: PSA: Pressure swing adsorption; WS: water scrubber; M: Membrane technology

Table 3 shows the list of small-scale upgrading plants in Europe. For the purposes of the VALORGAS project, upgrading units with a maximum raw gas flow of 50 m^3 $hour^{-1}$ are considered as small-scale units. For unknown reasons, the number of small-scale biogas upgrading units in Europe has decreased from 23 in 2010 to 13 in 2011 (Petersson, and Wellinger, 2009; IEA Bioenergy, 2011). Of these, approximately 10 plants are active in upgrading biogas for vehicular quality (97 % methane). The remaining plants are mainly involved in grid injection. The main upgrading technologies for vehicle fuel quality in Europe are PSA (35 %) and water scrubbing (35 %).

7. State-of-the-art of upgrading technologies in Europe

The following section gives a brief review of existing biogas upgrading technologies for scrubbing carbon dioxide (CO_2) and/or hydrogen sulphide (H_2S) and use of the upgraded biomethane as vehicle fuel or grid injection based on the literature (see also reviews e.g. Lastella et al., 2002; Abatzoglou and Boivin, 2009; Zhao et al., 2010). The technologies currently being utilised or developed for biogas upgrading include adsorption, absorption (physical and chemical), permeation and cryogenic. These technologies focus on the separation of methane, CH_4 (typically present at around 50–70 % by volume in raw biogas) and CO_2 (25–45 % in raw biogas). Whilst several of the technologies can also remove moderate concentrations of other contaminants, the majority will require the reduction of high concentrations of contaminants such as water, H_2S and siloxanes (if present) prior to upgrading by CO_2 removal.

7.1 Pressure swing adsorption

Pressure Swing Adsorption (PSA) is a versatile technology for the separation and purification of gas mixtures (Sircar, 2002). The PSA process was developed in the 1960s and since then has been one of the most widely used industrial gas separation technologies, mainly due to its flexibility, relatively low capital cost and efficiency. The PSA process is based on the ability of various adsorbent materials selectively to retain one or more components of a gas mixture under varying pressure conditions (Figure 7). These adsorbent materials are highly porous and can separate gas components under high pressure according to molecular size (Patterson et al., 2011). For instance, separation of CH_4 (molecular size of 3.8 Å) from CO_2 (molecular size 3.4 Å) is achieved by using an adsorbent with a pore size of 3.7 Å. Carbon dioxide is therefore able to enter into the matrix of the absorbent material and is retained, whilst CH_4 is not able to enter the material but passes through interstitial spaces (Gladstone, 2007). The adsorbed component of the gas stream is then desorbed from the solid adsorbent by reducing the pressure, thus allowing the regeneration and re-use of the adsorbent material (Sircar, 2002; Cruz et al., 2005; Rasi et al., 2008). The adsorbents are usually packed into columns which are then arranged in sequence according to the raw gas composition or the required quality of output gas.

The reason that PSA technology is so flexible is the wide range of adsorbent materials available to separate the components of various gases and liquids (Patterson et al., 2011). Adsorbent materials being utilised and developed include activated carbon (Sircar et al., 1996; Siriwardane et al., 2001; Grande and Rodrigues, 2007; Pinto et al., 2008), natural zeolites (alumina silicates) (Ackley et al., 2003; Siriwardane et al., 2003), synthetic zeolites (Inui et al., 1988; Sherman, 1999), activated aluminas (Alpay et al., 1996), silica gels (Lou et al., 1999) and polymeric sorbents (Kikkinides and Yang, 1993). The ability to combine various adsorbents within the overall PSA process provides added flexibility. For instance, activated carbon impregnated with potassium iodide can react catalytically with oxygen and H_2S to form water and sulphur (Pipatmanomai et al., 2009). The reaction is best achieved at 7 to 8 bar and 50 to 70 °C. The activated carbon beds also need regeneration or replacement when saturated. Where high concentrations of contaminants such as H_2S or siloxanes are present in the raw biogas, initial removal/reduction of these may be required prior to upgrading with PSA. This is because at high concentrations these contaminants cannot be desorbed from the adsorbent media. The advantages of PSA technology are more than 97% CH_4 enrichment, low power demand, and low emission and removal of nitrogen and oxygen (Patterson et al., 2011). The main disadvantage of PSA technology is the need for an additional H_2S removal step before PSA and for post-treatment of tail gas. The process is also relatively more expensive than other upgrading technologies. According to De Hullu et al. (2008), the cost of the PSA method is 0.40 € Nm^{-3} biogas.

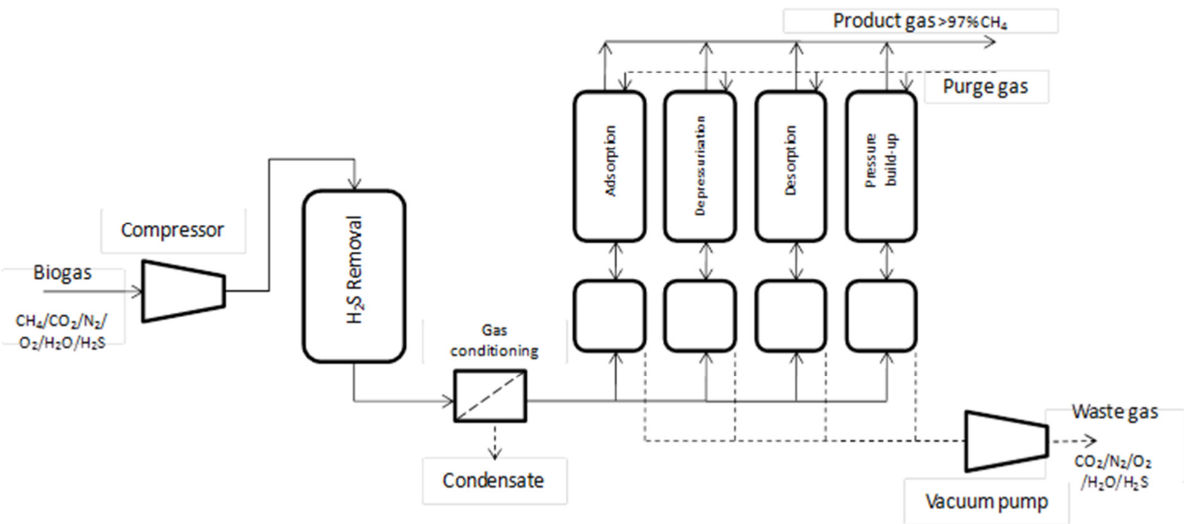

Figure 7. Pressure-swing adsorption schematic

There are several commercial PSA upgrading units in Europe. Of Sweden's 32 biogas upgrading plants, 7 are based on PSA processes (Petersson, 2008). The anaerobic digestion plant at Pliening in Germany processes around 40 000 tonnes $year^{-1}$ of maize and other forage crop silage to generate around 920 Nm^3 $hour^{-1}$ of biogas (Schmack Biogas, 2007). The produced biogas is upgraded to >96% CH_4 using PSA incorporating a carbon molecular sieve adsorbent (CarboTech AC GmbH). Similarly, Austria's first biogas grid injection project in Pucking, Upper Austria generates raw biogas from the anaerobic digestion of chicken and pig manure. Approximately 10 Nm^3 $hour^{-1}$ of raw biogas is produced which is upgraded using PSA incorporating carbon molecular sieves (Linsbod, 2005). The resulting 6 Nm^3 $hour^{-1}$ of upgraded biogas (>97% methane), which is enough to supply biomethane to around 40 flats, is then injected into the local gas distribution grid. In addition to biogas from AD, PSA can also be used for the upgrading of landfill gas (Cavenati et al., 2005; QuestAir Technologies Inc, 2006; QuestAir Technologies Inc, 2007).

7.2 Water scrubbing

Water scrubbing or absorption in water is the most widely used gas upgrading technology in Europe. The upgrading technology relies on the basic principle that CO_2 is more soluble in water than CH_4. CO_2 is scrubbed from the raw biogas, thus increasing the CH_4 content in the upgraded gas (Figure 8). This method is also effective at removing H_2S. However, any condensed moisture or particulates present within the raw gas stream have to be removed prior to the water scrubbing step. The raw gas is then pressurised (to around 9–12 bar) and introduced to the bottom of the scrubbing tower whilst water is flushed into the top of the tower in a counter current flow. The scrubbing tower is packed with high surface area media (e.g. pall rings) to provide a high contact area between gas and water. As the raw biogas moves up the column against the flow of water, CO_2 and H_2S become dissolved within the liquid stream (Persson et al., 2006). Upgraded gas leaves the top of the column. Any CH_4 dissolved within the water is usually captured by depressurising the water to 2–4 bar within a flash tank. Gases released are then returned to the bottom of the column (Håkansson, 2006). Upgraded gas is then available for drying and compression to around 200 bar for storage. Scrubbing water can be used once in a single pass system, or re-circulated following removal of dissolved gases (Rasi et al., 2008). Stripping with air is generally not recommended when high levels of H_2S are handled since the water quickly becomes contaminated with elementary sulphur which causes operational problems.

In Sweden there were about 15 water scrubbing plants in operation or under construction in 2007 (Persson, 2007). The biogas plant in Linköping (Sweden) is an excellent example of the use of water scrubbing technology to upgrade biogas for vehicle fuel use. The plant digests around 45000 tonnes year^{-1} of slaughterhouse waste (ca. 55 %) and food waste (ca. 45 %) in a mesophilic one-stage process with a 30-day retention time (Swedish Gas Centre, 2008a). In addition, two more upgrading plants based on water scrubbing with capacities of 500 and 1400 Nm^3 hour^{-1} were installed in 1997 and 2002 respectively (Swedish Gas Centre, 2008a). With the addition of the biogas from an adjacent sewage treatment plant (upgraded using PSA with 150 Nm^3 hour^{-1} capacity), a total of 65000 MWh of upgraded biogas is produced annually which supplies the town's buses, refuse vehicles and a number of public filling stations (Swedish Gas Centre, 2008a).

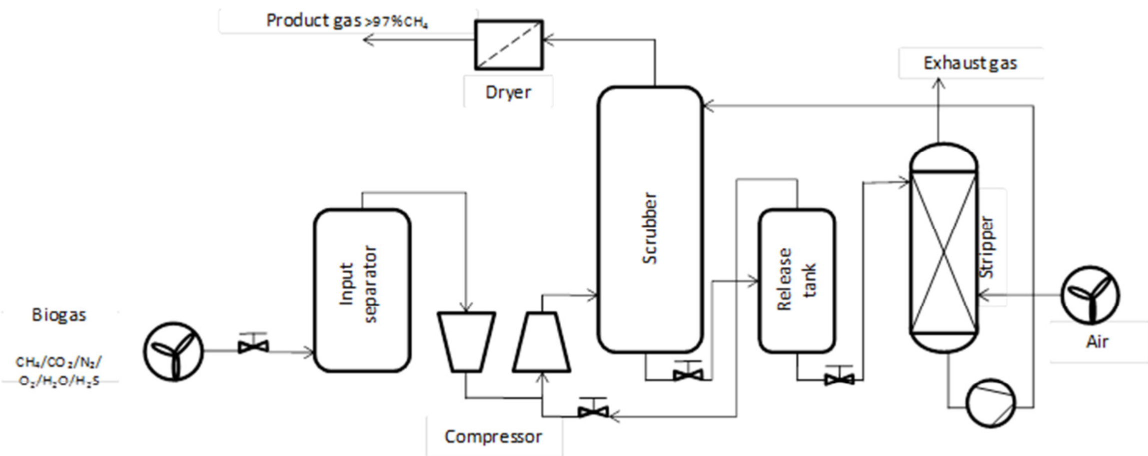

Figure 8. Flowsheet for water scrubbing technology (Adapted after ISET, 2008)

In Lille (France), a pilot project from 1994–1999 demonstrated the upgrading of surplus biogas from the digestion of sewage sludge and its use in local bus fleets (Patterson et al., 2011). Following the success of the trial the decision was made to phase out diesel buses and replace these with biogas vehicles. At the beginning of 2007, there were 200 gas powered buses in operation fuelled by a mixture of upgraded biogas and CNG. Biogas is generated from the digestion of biodegradable municipal waste at a dedicated Organic Recovery Centre (ORC). Raw biogas is upgraded in two water scrubbing towers each with a capacity of 600 Nm^3 $hour^{-1}$, and an annual production of 4 million Nm^3 $year^{-1}$ (Persson et al., 2006). A new biogas bus depot with 100 buses was constructed adjacent to the ORC facility.

The advantages of water scrubbing are that no special chemicals are required except relatively inexpensive glycol, and both CO_2 and H_2S are removed in the process. The disadvantages of water scrubbing are that it requires a lot of water even with regeneration; and there are limitations on H_2S removal, because the CO_2 decreases pH of the solution and corrosion to the equipment is caused by H_2S. According to De Hullu et al. (2008), the cost of the water scrubbing method is 0.13 € Nm^{-3} biogas.

7.3 Physical absorption

In physical absorption processes, a non-reactive fluid is used physically to absorb the unwanted component of the gas stream (Patterson et al., 2011). Spent absorbents are then regenerated by depressurising and/or heating. The most widely used absorbent for biogas upgrading available on the market is Genosorb 1753 which is used in the Selexol™ process. The solvent, manufactured by Clariant, is a mixture of dimethyl ethers and polyethylene glycols and can remove H_2S, CO_2 and moisture from gas streams.

The biogas facility at Laholm on the western coast of Sweden produces around 2.4 million m^3 $year^{-1}$ of CH_4 from the anaerobic co-digestion of up to 70 000 tonnes $year^{-1}$ of manure, abattoir, industrial and household waste (IEA BIOENERGY, 2005). The raw biogas has a CH_4 content of around 75% and this is upgraded to natural gas quality by Selexol™ scrubbing (500 Nm^3 $hour^{-1}$ capacity) following sulphur removal. The Wobbe index is adjusted to that of natural gas by adding 5–10% propane. The upgraded gas is then added to the local gas grid (including refuelling stations) and is used to power a local district heating scheme.

7.4 Chemical (amine) scrubbing

Chemical absorption involves formation of reversible chemical bonds between the solute and the solvent. Regeneration of the solvent therefore involves the breaking of these bonds, and correspondingly a relatively high energy input (Figure 9). Chemical solvents generally employ either aqueous solutions of amines (i.e. mono-, di- or tri-ethanolamine) or of alkaline salts (i.e. sodium, potassium and calcium hydroxides). The advantages of chemical absorption are complete H_2S removal, high efficiency and reaction rates compared to water scrubbing, and the ability to operate at low pressure. Because of these advantages, the process is commonly used in industrial applications, including natural gas purification (Palmeri et al., 2008). The disadvantages are the additional chemical inputs needed and the need to treat waste chemicals from the process. The final price of upgraded biogas using this technique is estimated to be 0.17 € Nm^{-3} biogas, according to De Hullu et al. (2008).

7.4.1 Chemical absorption of CO_2

The literature shows that multiple and often contradictory theories exist about the removal of CO_2 in gas streams. Kumar et al. (2002) discussed in detail CO_2 absorption using aqueous amino acid salt solutions. Biswas et al. (1977) reported that bubbling biogas through a 10% aqueous solution of mono-ethanolamine (Nelder and Mead) reduced the CO_2 content of biogas from 40 to 0.5–1.0 % by volume. MEA solution can be completely regenerated by boiling for 5 min and is then ready for re-use.

7.4.2 Chemical absorption of H_2S

Several authors (Astarita and Gioia, 1964; Bland and Davidson, 1967; Kohl and Riesenfeld, 1985; Horikawa et al., 2001; Horikawa et al., 2004) have discussed processes involving the removal of H_2S. Many of these remove this pollutant only from the gaseous stream, but do not convert H_2S into a more stable or valuable product, or convert it into the elemental form sulphur (S). The conversion of H_2S into S or a valuable compound is an advantage of chemical absorption with respect to other methods. The process of chemical absorption of H_2S into iron-chelated solutions offers highly efficient H_2S removal, selective removal of H_2S and a low consumption of chemicals, because the iron-chelated solutions function as a pseudo-catalyst that can be regenerated (O'Brien, 1991).

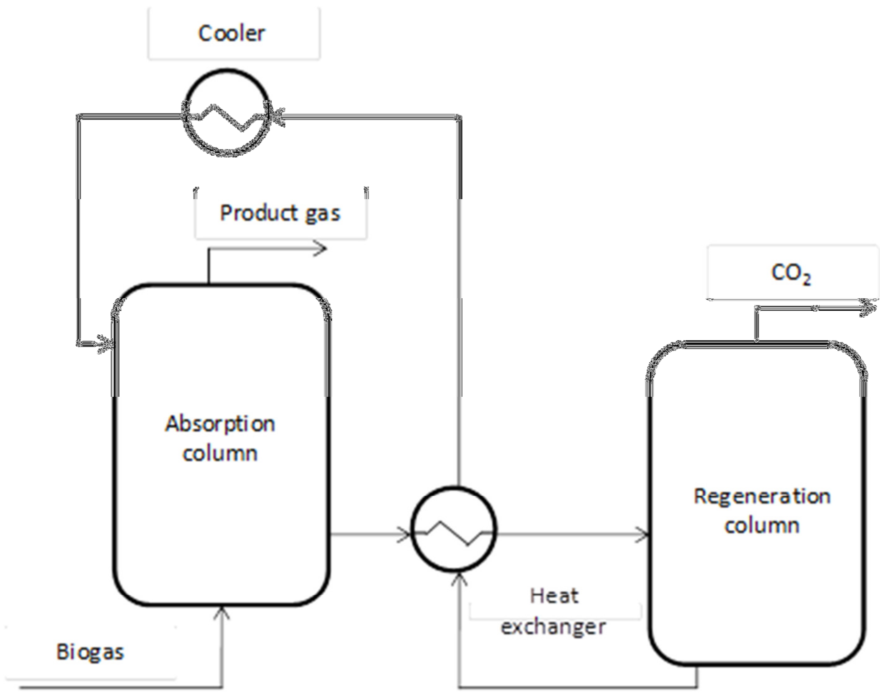

Figure 9. Flowsheet for chemical absorption process

The Gryaab biogas facility in Gothenburg (Sweden) treats 430000 Nm^3 $year^{-1}$ of thickened sludge from a local wastewater treatment plant along with grease trap waste and food waste using a single stage anaerobic process (Swedish Gas Centre, 2008b). The produced raw biogas (60000 MWh $year^{-1}$) is sold to Göteborg Energi for upgrading. Biogas is upgraded at the Arendal facility using Cooab (an amine based solvent) technology for CO_2 removal before it is regenerated for re-use. A small amount of propane is added to bring the energy content up to natural gas standard. The capacity of the plant is approximately 1600 Nm^3 $hour^{-1}$ and upgraded gas is distributed to the city gas pipeline network and to a network of local vehicle filling stations (Swedish Gas Centre, 2008b). More recently, upgrading plants utilising the Cooab process have been commissioned at Falkenberg in Sweden (800 Nm^3 $hour^{-1}$) and Stavenger in Norway (500 Nm^3 $hour^{-1}$) (Thulin, 2009).

7.5 Membrane separation

CH_4 and CO_2 can also be separated using membranes (Figure 10). Because of the difference in particle size or affinity, certain molecules pass through a membrane whilst others do not. The driving force behind this process is a difference in partial pressure between gases. The properties of this separation technique are highly dependent on the type of membrane used. Many different membranes are available, each with particular specifications (Ellig et al., 1980). Membranes can be grouped into two types: high pressure membranes which have gases present on each side of the membrane, and low pressure systems which have a liquid adsorbent on one side of the membrane wall. High concentrations of contaminants such as H_2S and moisture are generally reduced prior to separation of CH_4 and CO_2 in a membrane system.

High pressure membrane separation is normally undertaken at >20 bar, although some systems can operate at 8–10 bar (Persson and Wellinger, 2006). Biogas is generally upgraded in a multiple-stage process to yield a final CH_4 concentration of >96%. Waste gases from the first stages are recycled within the process to enhance CH_4 capture whilst waste gas from the final stage (which may contain 10–20% CH_4) is flared, used for heat production (Wellinger and Lindberg, 1999) or captured catalytically. This technology has been applied for some time to the upgrading of natural gas.

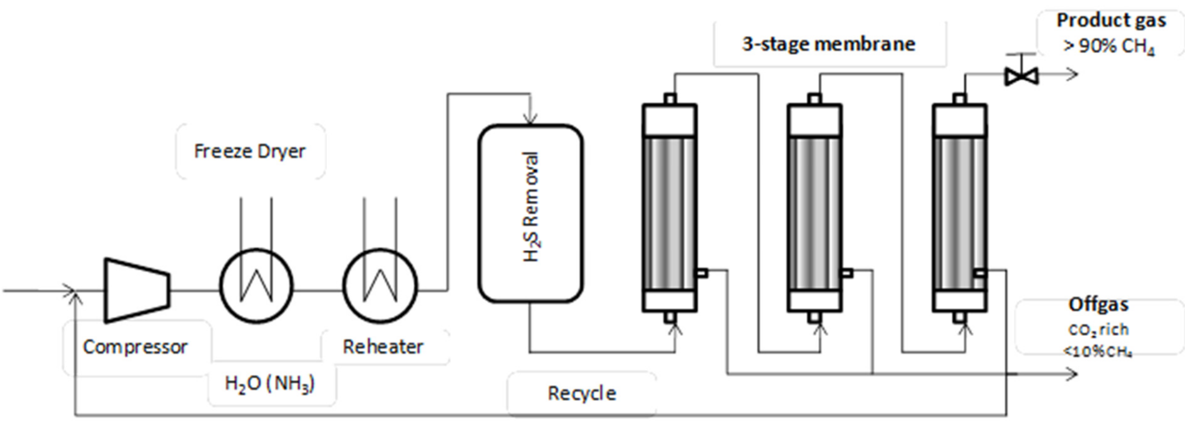

Figure 10. Flow sheet for membrane biogas purification process

Low pressure membrane systems work at pressures close to atmospheric. A micro-porous hydrophobic membrane separates the raw gas stream from a liquid phase absorbent. Absorbents such as NaOH (e.g. for H_2S separation) or heat regenerative amine solutions (e.g. for CO_2 separation) are used. CH_4 concentrations of >97% are possible and the process can yield high purity CO_2 that can be sold as a product (Chatterjee et al., 1997; Harasimowicz et al., 2007).

The advantages of membrane separation are that the processing equipment is compact and has low energy and maintenance requirements. The disadvantages of membrane separation are relatively low CH_4 yield and high membrane cost. According to De Hullu et al. (2008), the cost of the membrane method is 0.12 € Nm^{-3} biogas. Although this is low in comparison to other methods reviewed, difficulties with yield and purity as well as the potential for fouling membranes (requiring membrane replacement) raises operating costs and strongly impacts on process economics.

A novel membrane gas upgrading system has been demonstrated at a biogas plant in Bruck/Leitha in Lower Austria (Miltner et al., 2008). Hollow fibre membranes are used to separate methane from CO_2 with a pressure differential of around 8–9 bar across the membranes. Two stages of membrane separation are employed with permeate from the first stage being utilised in the biogas plant CHP engine; and permeate from the second stage, which contains a higher percentage of CH_4, being recycled back through the separation process. In this way, methane losses to atmosphere are limited. Upgraded biogas with a methane concentration of 98% is fed to the local gas grid. Whilst the process is capable of removing small concentrations of H_2S, pre-treatment to remove the majority of H_2S prior to membrane separation has been employed at the demonstration facility.

7.6 Cryogenic technique

Cryogenic technology relies on the principle that different constituents of a mixed gas stream have different boiling points. For instance, the boiling point of CH_4 is −160 °C and of CO_2 is −78 °C at atmospheric pressure. Therefore, by progressively cooling the raw gas under pressure, each of the constituents will condense to a liquid at a different temperature and thus can be separated (Fig. 11). Cooling is achieved by compression of the gas stream, cooling with heat exchangers followed by expansion, for example in an expansion turbine, to condense the target contaminant (e.g. CO_2) (Persson and Wellinger, 2006). High purity CO_2 is produced which can be sold as a product. A pilot cryogenic upgrading plant has been operational in the Netherlands since 2009; the only commercial plant is in Sweden (Persson and Wellinger, 2006).

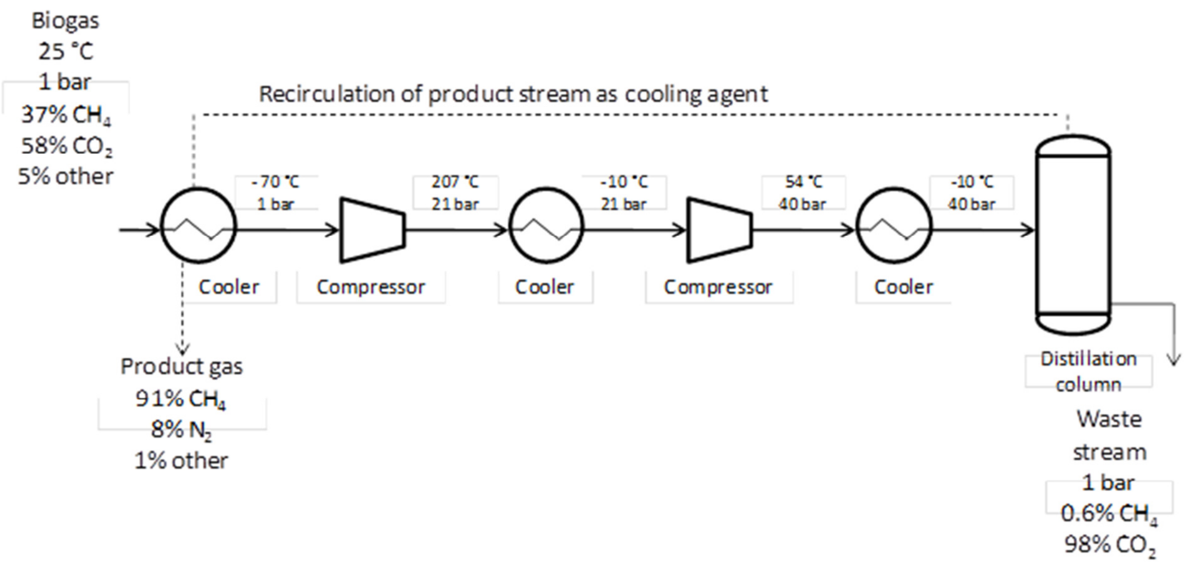

Figure 11. Flowsheet for cryogenic biogas purification process (Courtesy: ISET, 2008)

8 Economics of biogas upgrading in Europe

8.1 Economics of biogas upgrading in large-scale plants (>100 Nm^3 $hour^{-1}$)

The economic and technical performance of biogas upgrading units in Europe, especially for German and Swedish plants, was presented in a recent report by the ISET (2008) and Swedish Gas Centre (www.sgc.se) which is used in this report. Data from 11 of the Swedish upgrading plants with longest operation experience were included in the study (Jönsson, 2004). Some of the main conclusions are: The upgrading cost depends very much on the plant size. For small-scale units (<100 Nm^3 $hour^{-1}$), upgrading costs are between 0.03-0.04 € kWh^{-1} (NSCA, 2006). Upgrading plants in the range of 200-300 Nm^3 $hour^{-1}$ have costs of 0.01-0.016 € kWh^{-1} (NSCA, 2006; Rehnlund and Rahm, 2007). Compared to a current market price of natural gas of 0.03-0.04 € kWh^{-1} (situation Jan 2011), upgrading costs are high (http://www.energy.eu). The electricity demand for upgrading corresponds to 3-6 % of the total energy content in the upgraded gas.

The costs for biogas upgrading to biomethane for different upgrading technologies and capacities is presented in Figure 12. In general, biogas upgrading costs decrease with increase in capacity. At present, an input of 350 Nm^3 $hour^{-1}$ is the minimum for economical investment in upgrading units (ISET, 2008). For instance in Germany, the smallest upgrading units have a raw gas input of about 350 Nm^3 $hour^{-1}$ (IEA Bioengery, 2011). This could be different for different site conditions. Small-scale biogas upgrading unit depends on the capital cost of the biogas plant upgrading unit and also the cost of the raw material. There are many possibilities i.e., raw material is available free of cost, available at a nominal price or at commercial prices. One or two manufacturers of upgrading technologies are said to be developing units with an input of only 250 Nm^3 $hour^{-1}$ (ISET, 2008). There is a maximum and a minimum size of upgrading units for economic reasons. If the upgrading capacity of the units is too small, then the units become too expensive giving no returns on investment. Conversely, if the capacity of the units is too large, it may be impossible to contract all the necessary input feed for the biogas production.

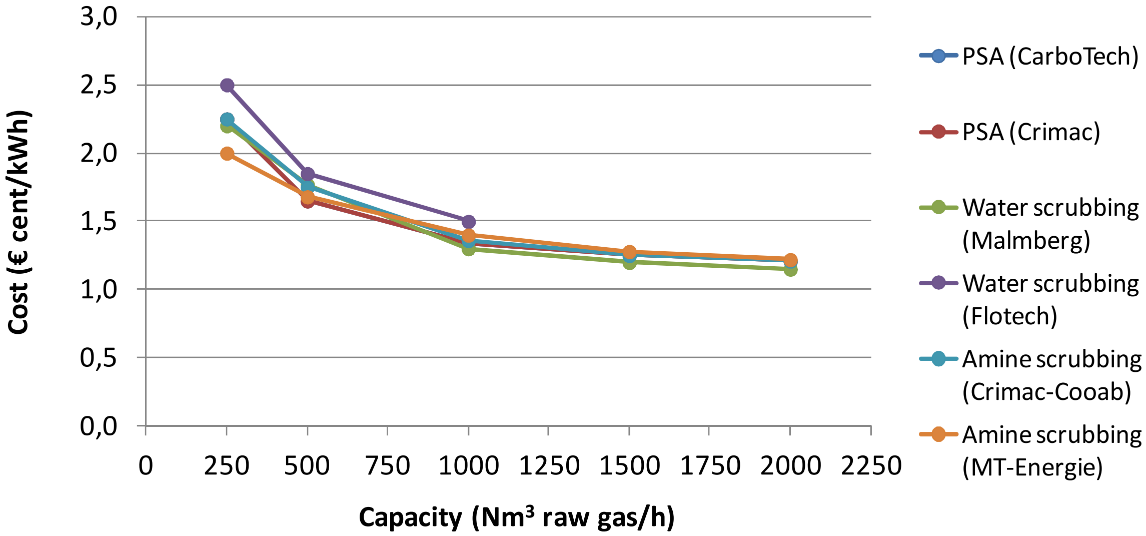

Figure 12. Costs for biogas upgrading to biomethane for different upgrading technologies and capacities (Source: (Persson and Wellinger, 2006).

Table 4 shows the costs per Nm^3 for production of biogas for vehicle use (upgraded and pressurised) from Swedish data (Rietz, 2005). The costs, excluding VAT, are estimated in the report as 1.8-5.0 SEK or 0.19-0.55 € $litre^{-1}$ of gasoline equivalent. The costs for the gas refuelling station and of delivery to the station from the production plant, are additional and may vary depending upon construction requirements, location, safety and other regulatory needs, capital amortisation etc. In the Swedish Gas Council report (Rietz, 2005), Swedish Biogas AB is quoted as estimating a cost range for the production of biogas used in vehicles, reflecting different production conditions, in the order of 3.50-4.50 SEK Nm^{-3} (or 0.38-0.49 € Nm^{-3}). This range also includes crop-based biogas. The higher feedstock cost when using crops is partially compensated for by lower treatment costs for upgrading in the biogas plant. The range of 3.50-4.50 SEK Nm^{-3} is considered sufficient to guarantee a price for the end customer that does not exceed the price of taxed gasoline in Sweden. The pre-tax market price for biogas used as a vehicle fuel in Sweden is claimed to be about 70 % of the total consumer price of gasoline (including tax). Hence, with the full tax rebated, biogas in Sweden can be competitive with gasoline or diesel fuels. The estimated cost range from this Swedish data is equivalent to 53-67 € kg^{-1} including compression costs. For use in vehicles, however, the biogas would also need to be delivered to the refilling station, with additional costs for transportation from the centralised anaerobic digestion (CAD) plant, and other operating costs at the filling station.

Table 4. Comparison of costs of biogas production and upgrading for vehicle fuel in Sweden (Adapted after Jönsson, 2004)

Process	Biogas (sewage sludge)		Biogas (organic waste)	
	SEK Nm^{-3}	€ Nm^{-3}	SEK Nm^{-3}	€ Nm^{-3}
Production	0-1.5	0-0.16	1.5-2.5	0.16-0.27
Upgrading	1-2	0.1-0.21	1-2	0.1-0.21
Compression	1	0.1	1	0.10
Total	2.0-4.5	0.21-0.49	2.0-4.5	0.38-0.60

Cost reduction in the upgrading technologies is possible by reduction of the complexity of the control system, adopting appropriate safety requirement, and keeping the methane content in upgraded biogas below 95%. This can be modified to suit the needs of different countries. To make small-scale technologies popular there is thus a need for low-cost robust and user friendly technologies for use in rural areas and remote places.

8.2 Economics of small-scale biogas upgrading (<100 Nm^3 $hour^{-1}$)

For small-scale plants, the most economical approach is to use the produced gas locally or as vehicle fuel. There is a minimum production rate to make the system economical viable. One Nm^3 of upgraded biogas is equivalent to about 1 litre of diesel and, therefore, worth about 0.70 € (natural gas price at the fuel station) to 1.2 € (diesel price). According to Lems and Dirkse (2010), the profit per Nm^3 of upgraded gas should be about 35-45 € cents to achieve a pay-back time of 5 years, without taking profits from the CHP unit in account. This means that the cost price for the biogas upgrading should be less than 0.2-0.3 € Nm^{-3}.

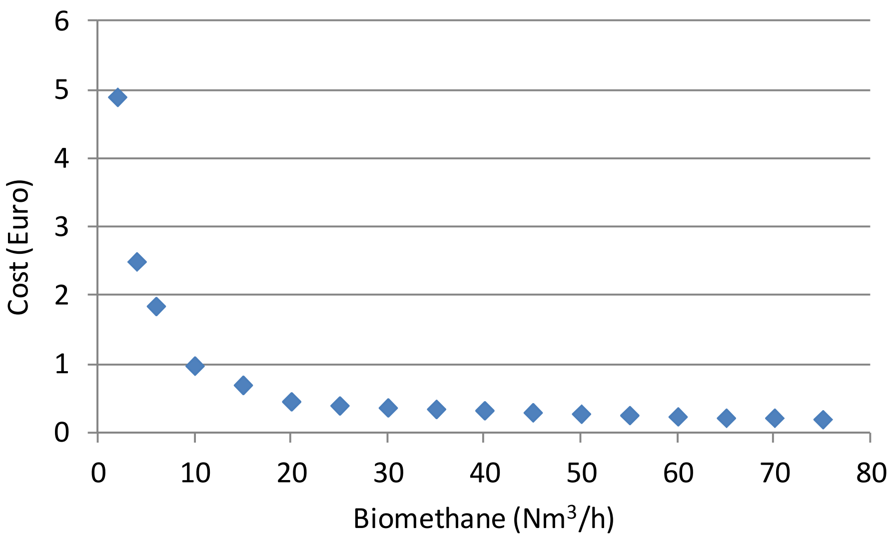

Figure 13. Product price in € Nm^{-3} of upgraded gas for various production flows (Courtesy: Lems and Dirkse, 2010),

Figure 13 shows the price in € Nm^{-3} of upgraded vehicle fuel. According to Lems and Dirkse (2010), at least 20 to 25 Nm^3 $hour^{-1}$ of upgraded gas must be produced to obtain a production price of approximately 0.2-0.3 € Nm^{-3}. When the investment only comprises the upgrading, and there is already a CHP on the location, then the payback time for the same situation is just 3-4 years. Moreover, due to depletion of fossil fuel it is likely that fuel prices will increase.

9 Comparison of potential upgrading technologies and operational scales with market needs

As noted in this report, there are several upgrading technologies on the market today, each with its own advantages and disadvantages. However, the choice of the optimal upgrading process is influenced by several factors viz., the biogas source, quantity and quality (e.g. landfill gas, manure digestion, energy crop digestion or sludge digestion), the desired final quality (gas grid injection or vehicle fuel use) and local circumstance like availability of heat, power and space. Most upgrading plants in Europe currently are based on large-scale biogas production sites, and are optimised for maximum methane and energy efficiency. This results in relatively high investment costs and a rather complex plant design and operation.

The large-scale upgrading plants rely for a large part on the benefits of scale and become more profitable at higher flows (Lems and Dirske, 2010). The potential number of small-scale units in Europe is higher, however, due to the rapid uptake of small-scale anaerobic digestion. For these locations the benefit should come not from economics of scale but from mass production. At these sites it may be more important to utilise all the biogas as an energy source than to produce upgraded gas. The company DMT Environmental Technology, Netherlands has re-engineered an upgrading plant targeted at small-scale production sites (Lems and Dirske, 2010). The final product is very basic and easy to reproduce as a standard (mass) product. In developing this plant, DMT Environmental Technology compared different parameters for both small-scale and large-scale biogas upgrading plants. The characteristics of the different upgrading techniques are compared in Table 5 together with their suitability for use at large and small scale. The techniques considered include pressurised water scrubbing (PWS), catalytic absorption (CA), pressure swing absorption (PSA), membrane separation (MS) and cryogenic liquefaction (CL) (de Hullu et al., 2008; Weidner, 2008). The results showed that pressurised water scrubbing is the most suitable process for most large-scale systems in Europe. This is because PWS is a moderately simple, very robust technology which can be easily regulated to handle big variations in flow and gas quality. Moreover, PWS has a high energy and methane efficiency and is moderately expensive. For small-scale plants, it is more important to have a cheap and very simple system. Variations in gas flow and methane efficiency are of less importance. Therefore membrane systems appeared to be ideal at a small scale, especially when combined with a CHP to provide increased flexibility of the system and high energy efficiency. It should be noted that in Germany regulations limit the methane slippage from these systems to 1 % up to 2011 and thereafter to 0.5 %. To receive a technology bonus under the German EEG regulations, a maximum methane slip of 0.5 % is allowed. Only the amine (MEA/DMEA) washing processes fulfil this threshold value without post-treatment of the off-gas. Thus to progress the development of small-scale gas upgrading units, a wider level of interaction is required between the technology providers and the beneficiaries and policy makers to ensure that profitable plants capable of meeting market requirements can be delivered.

Table 5. Comparison of demands for various upgrading techniques (Source: de Hullu et al., 2008; Weidner, 2008: Lems and Dirske, 2010).

Parameter	**PWS**	**C A**	**PS A**	**MS**	**C L**	**Large Scale**	**Small Scale**
Gas quality	High	High	High	High	High	High	High
Gas quantity v.	High	High	Medium	Low	Medium	High	Low
Investment	Medium	Medium+	High	Low	High	Medium	Low
Maintenance	Medium	Medium	Medium+	Low	High	Medium	Low
Operation	Medium	Complex	Complex	Easy	Complex	Medium	Easy
Compact	Medium	Medium	No	Yes	No	Medium	Yes
Methane eff.	High	High	Medium	Low	High	High	Low
Emissions	Low	Low	Medium	Medium	Low	Low	Medium
Waste streams	Continues	Continues+	Batch	Batch	Continues	Continues	Batch

Green: best match for small-scale plants *Yellow: best match for large-scale plants*

PWS - pressurised water scrubbing, CA - catalytic absorption, PSA - pressure swing absorption, MS - membrane separation, CL - cryogenic liquefaction.

10 Biogas production and utilisation in India

India has a vast potential of 6.38 x 10^{10} m^3 $year^{-1}$ of biogas produced from 980 million tonnes of cattle dung (MNES, 2009). According to the National Project on Biogas Development (NPBD) launched by the Government of India in 1981, there are about 3.65 million family-size biogas plants in operation in India (MNES, 2009). This is about 30 % of the total potential for 12 million family-type biogas plants. In addition, there are more than 3380 Community Biogas Plants (CBP), Institutional Biogas Plants (IBP) and Night-soil based Biogas Plants (NBP) installed all over the country (MNES, 2009). The produced biogas has mostly been used as fuel for cooking and running stationary engines. However, there is a great potential for enhancement in the utilisation of biogas as vehicle fuel especially in larger plants viz., IBPs in Goshalas, dairy farms or CBPs in villages. In urban areas, large quantities of biogas can also be produced in sewage treatment plants using anaerobic digestion. Okhala Sewage Treatment Plant, New Delhi is an example where more than 10 000 Nm^3 day^{-1} of biogas is produced.

In India, use of CNG as vehicle fuel is mandatory in many cities, including Delhi. As CNG technology is easily available in the country, biomethane can potentially be used for all applications where CNG is used. However, CO_2 removal and compression of the produced biomethane into cylinders is necessary for transport applications e.g. three wheelers, cars, pick-up vans etc and also for stationary applications with high consumption or at long distances from the biogas source.

Although biogas production in India is increasing, upgrading of biogas to biomethane has been very limited. These are no commercial upgrading units in India, and the biogas upgrading scenarios reported represent only laboratory-scale and pilot-level demonstration plants. Most of these upgrading units have been set up in the field with the support of Government as technology transfer and demonstration projects. At this scale (20 Nm^3 $hour^{-1}$) such upgrading units are not economically viable. Most of the work to date has been carried out at the Indian Institute of Technology (Vijay et al., 2006). Bhattacharya (1988) developed a water scrubbing system that produces 100% pure CH_4 but is dependent on factors like dimensions of scrubbing tower, gas pressure, and composition of raw biogas, water flow rates and purity of water used. Similarly, Vijay (1989) developed a packed bed type scrubbing system using locally available packing materials and reported that CO_2 removal was 30–40 % more by volume compared with the scrubbing systems without a packed bed. The quality of biomethane is also affected by the water flow rate, scrubber dimensions and the number of scrubbers. In a continuous counter-current type scrubber with gas flow rate of 1.8 Nm^3 $hour^{-1}$ at 0.48 bar pressure and water in flow rate of 0.465 m^3 $hour^{-1}$, CO_2 concentration was reduced from 30% at inlet to 2% at outlet by volume (Khapre, 1989). Dubey (2000) reported that the CO_2 absorption is influenced by the flow rates of gas and water than different diameters of scrubbers. The G.B. Pant University of Agriculture and Technology, Pantnagar, India developed a 6 m high scrubbing tower, packed up to 2.5 m height with spherical plastic balls of 25 mm diameter. The raw biogas compressed at 5.88 bar pressure was passed at a flow rate of 2 Nm^3 $hour^{-1}$ while water was circulating through the tower. A maximum of 87.6% of the CO_2 present could be removed from the raw biogas.

11 Conclusions

Biogas upgrading primarily comprises of the removal of CO_2, H_2S and other possible pollutants from the biogas. Removal of CO_2 will increase the CH_4 concentration and thus provide a higher calorific value. Currently, there are five biogas upgrading technologies that are commercially used in Europe. These include chemical absorption, high pressure water scrubbing, pressure swing adsorption, cryogenic process and membrane separation. Of the 137 biogas upgrading units in Europe, only 11 units are considered as small-scale units (<50 Nm^3 $hour^{-1}$). Approximately 10 plants are active in upgrading biogas for vehicular quality (97 % methane). Among the five upgrading technologies, high pressure water scrubbing is considered as the promising technology for small-scale biogas upgrading due to its low cost price, high purity and yield.

Most upgrading plants in Europe currently are focused on large-scale biogas production sites, and are optimised for maximum methane and energy efficiency. This results in relative high investment costs and a rather complex plant design and operation. However, the highest percentage of the total production of biogas comes from the many small-scale digesters producing small quantities of biogas (50-200 Nm^3 $hour^{-1}$). For these plants it is not feasible to upgrade the gas to natural gas quality and inject this upgraded biomethane into the natural gas grid or use it as commercial fuel at a gas station. The cost for quantity and quality control together with gas transport/injection makes it too expensive for small-scale applications. Other conditions may apply, however, when the gas is not used commercially but only locally within a small community or farm. Small-scale biogas upgrading can be made economically viable by reducing the main costs of upgrading (electricity and water costs), upgrading at low temperature (15-20 °C), use of low cost high pressure storage containers, and compressing to high pressures (250-270 bars) so as to reduce the electricity costs at filling station.

India has vast potential for biogas production especially from cattle dung. Although biogas production in India is increasing, upgrading of biogas to biomethane has been very limited. There are currently no commercial-scale biogas upgrading plants operating in India. Biogas upgrading initiatives reported to date are only laboratory and pilot-scale demonstration plants. Most of these upgrading units have been set up in the field with the support of the Government of India as technology transfer and demonstration projects. The largest scale of biogas upgrading unit in India is 20 Nm^3 $hour^{-1}$ and this is considered economically non-viable. The costs of upgrading could be reduced by reducing the costs of water through recycling wash water and incorporating less complex control systems, using low-cost fabricating materials, and mass production of the units.

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