The Technology and Economy of Farm-Scale, High-Solids Anaerobic Digestion of Plant Biomass

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Abstract

Anaerobic digestion is a microbially mediated process occurring in nature in the absence of oxygen and other non-carbonaceous electron acceptors. The majority of the carbon of the organic matter degraded in the process is transformed into carbon dioxide and methane. Most of the energy potential of the degraded material is conserved in the methane, thus providing a renewable energy carrier, which can be converted into heat and/or electricity, or upgraded for use as a vehicle fuel. The remaining undigested, recalcitrant lignocellulosics and mineralised nutrients constitute an excellent biofertiliser. Compared to using undigested organic material as fertiliser, the nutrient content of the digestate is more readily taken up by the plants. In addition, the lower levels of easily degradable carbon sources and nitrogen in the soil lead to reduced emission of greenhouse gases and nutrients to the air and water. The lignocellulosics of the digestate maintain the humic content of the soil, which is crucial for the long-term productivity of the soil. Anaerobic digestion of the organic waste fractions and agricultural residuals is a sustainable way to control and direct all the flows of recycled nutrients in society without risking excessive losses.

Anaerobic digestion would enable the energy potential of agricultural crop residues such as sugar beet tops and ley crops to be harnessed. Sweden is so sparsely populated that full utilisation of this potential (11 TWh/yr) by conventional centralised slurry-based technology is difficult. In addition, process disturbances in the form of crust formation make operation more costly and lower methane yields may result. It appears that simple but effective high-solids reactor systems have a better chance of being economically viable on farm-scale (50-500 kW).

The first part of this study shows that using straw beds improves the process performance in high-solids, anaerobic, stratified bed digesters by shortening the start-up phase of sequential fed-batch operations, and by enhancing the rate and extent of anaerobic digestion. After a non-feeding stabilisation period of the straw bed, the priming straw bed functions both as a particle filter and a microbial carrier. Methane yields from the sugar beet tops fed to pilot- and laboratory-scale equipment ranged between 0.33 and 0.39 m^3/kg volatile solids at average solids retention times of 11 to 39 days.

In the second part of this study, calculations on the economy of farm-scale digestion of a mixture of wheat straw and sugar beet tops were performed, assuming that the biogas was converted into heat or combined heat and electrical power, or upgraded to vehicle fuel. Among the three different reactor designs tested, the stratified bed digester was found to be the most competitive. However, the scale and utilisation rate of the equipment were too low to achieve reference case unit costs that were comparable to those of commercially available energy carriers. By increasing the scale (from 51 kW to 67 and 201 kW), replacing wheat straw by ley crops, and increasing the degree of utilisation of the equipment, the reference case unit costs were lowered to such an extent that they were on a par with most of the commercially available energy carriers (5.3 €ct/kWh_{heat}, 8.1 €ct/$kWh_{vehicle\ fuel}$). Both studies showed the great importance of full utilisation of the energy carriers produced, which might prove difficult on the farm-scale. Vehicle fuel is probably the best alternative, but the distribution system of biogas is currently restricted to certain areas. The incentive for buying biogas vehicles is reduced by the high engine conversion cost. Expanding the market by implementing some kind of ambitious, long-term subsidy programme is necessary for the wider implementation of anaerobic digestion of plant biomass in Sweden. A prime mover could be the organic farmers with no livestock, who would be able to improve their nitrogen management by removing and anaerobically treating the presently mulched or ploughed-in green manure of ley crops and other crop residuals.

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The papers

This thesis is based on the following papers, referred to by their Roman numerals in the text. The reprint of **Paper III** is published by kind permission of the journal concerned.

I. Svensson, L M, Björnsson, L, Mattiasson, B Enhancing Performance in Anaerobic, High-solids Stratified Bed Digesters by Straw Bed Implementation. *(submitted to Bioresource Technology)*

II. Svensson, L M, Björnsson, L, Mattiasson, B Straw Bed Priming Enhances the Methane Yield and Speeds up the Start-up of Anaerobic Digestion in Single-Stage, High-Solids reactors (*manuscript)*

III. Svensson, L M, Christensson, K, Björnsson, L Biogas production from crop residues on a farm-scale level: Is it economically feasible under conditions in Sweden? *(Biosystems and Bioprocess Engineering, in press, published on-line 20 September 2005)*

IV. Svensson, L M, Christensson, K, Björnsson, L Biogas production from crop residues on a farm-scale level: Scale, choice of substrate and utilisation rate most important parameters for financial feasibility. *(submitted to Biosystems and Bioprocess Engineering)*

V. Lantz, M, Svensson, L M, Björnsson, L, Börjesson, P The prospects of an expansion of biogas systems in Sweden – Incentives, barriers and potentials. *(manuscript)*

The thesis is concerned with the technological and economical aspects of anaerobic digestion of plant biomass, with emphasis on conditions in Sweden. The experimental work has been focused on single-stage high-solids digestion.

In **Papers I and II** the implementation of straw bed filtering in vertical column-type single-stage, high-solids, stratified bed digesters (1-SD) is investigated. In **Paper I** the results from extended fed-batch trials on laboratory-scale and pilot-scale are reported. The significance of the initial packing density of the straw was investigated. **Paper II** compare the performance between such reactors with and without a priming straw bed.

In **Papers III and IV** the economic efficiency on farm-scale of the 1-SD reactor design is investigated in two theoretical studies, based on pilot-scale experiences. The 1-SD reactor design is here a vertical modification of the horisontal design tested on a laboratory-scale. In **Paper III** the 1-SD design was compared with two other reactor designs (two-stage high-solids batch digestion and conventional semi-batchwise slurry digestion) on 50 kW scale, treating sugar beet tops and wheat straw. In **Paper IV** the significance of scale, choice of substrate and degree of utilisation of equipment was investigated for the 1-SD design.

In **Paper V** the current prospects for a wider implementation of anaerobic digestion in Sweden are reported, with respect to technical, economical and institutional parameters.

My contribution to the papers

Paper I: I did all of the experimental work, apart from a few sampling occasions. I wrote the paper.

Paper II: I did all of the experimental work, apart from a few sampling occasions. I wrote the paper.

Paper III: I managed and supervised the data collection. I did all the data evaluation. I wrote the paper.

Paper IV: I did all of the data collection and evaluation. I wrote the paper.

Paper V: I took an active part in the general discussions from the conception of the analysis to the final version of the paper. I wrote and edited parts of the paper.

1 Introduction

A (self-)sustainable system is defined as a closed system of inter-connected and self-regulating processes that has the ability to run continuously, without corrupting or depleting its resources in a way that risks the smooth operation of the system, for example by accumulating hazardous by-products. The ecosystem of the earth and its sun is an example of such a system. The arrival of the industrial era caused a number of serious disturbances in the earth's ecosystem such as, high levels of insulating gases such as carbon dioxide and methane in the atmosphere, persistent volatile compounds disrupting and reducing the UV filtering ozone layer, and the accumulation of recalcitrant xenobiotic compounds, some of which affect the biosphere. In addition, deforestation and unsustainable agriculture or animal rearing lead to irreversible losses of biodiversity and soil, the latter in the worst case leading to desertification.

Science is partly responsible for many of these adverse man-made threats against the earth's ecosystem, and during recent decades interest has been directed to the remediation of these effects (e.g. carbon dioxide sequestration, bioremediation, genetically modified plants for reforestation projects close to deserts). However, we need to completely rethink and reform technology and practices towards a fully sustainable society ("green" chemistry, renewable energy, recycling of materials, resource-efficient (leaner) production, life-cycle assessments, precision farming, organic farming, etc).

Anaerobic digestion has been in the service of human pollution control for more than a century, starting with the very first forms of reactor-based wastewater treatment[1]. This is a truly sustainable technology, merely speeding up the microbially aided degradation of organic material which occurs in nature when external electron acceptors such as oxygen and nitrate are absent. The end products are mainly carbon dioxide and methane, the latter potentially harmful as a greenhouse gas[2]. The methane produced constitutes a highly versatile energy carrier, which can be combusted in boilers or engines to supply heat, electricity or mechanical work (when used as vehicle fuel), or transformed into other energy carriers, such as hydrogen (fuel cell applications) or liquid alkanes (Fisher-Tropsch technology)[3, 4]. The rate of development and diversification of anaerobic digestion technology has increased since the oil crisis of the 1970s; the invention and development of more efficient wastewater treatment technologies being the most notable example[5-11], but the anaerobic treatment of solid waste is growing in importance, either in a diluted and homogenised form (referred to as slurry digestion), or without dilution (referred to as high-solids digestion, or dry digestion)[12-16] (**Papers I-IV**).

In the case of solid waste treatment, the main advantage of employing anaerobic digestion is the considerable volume reduction, most of the digestible carbon being transformed into gaseous compounds, a result of the low growth yields of anaerobic microorganisms[7]. In recent years, the energy aspect has grown in importance, improving the overall treatment economy. These two aspects are the most important advantages of anaerobic digestion compared with aerobic digestion, i.e. composting[7, 14]. The main advantage of composting is its low investment costs. In addition, it is a time-proven and established technology compared with anaerobic solids digestion[12, 16]. However, waste incineration usually has a market share that is higher than the other two treatment options[17] **(Paper V)**. The total treatment cost of incineration is not the lowest of the three[15, 18], but the modest need for pre-treatment and the flexibility of the technology in terms of suitable waste fractions, together with the higher volume reduction and energy production compared with anaerobic digestion, have made it a popular choice. Nevertheless, the incineration of complex and unsorted wastes is not a sustainable technology, since recyclable plant nutrients are mixed with heavy metals and other contaminants in the resulting ash[14]. Since the ash is landfilled, the net effect is that the nutrients are removed from the soil, being lost from the ecosystem for a considerable time. The ash resulting from pure biomass incineration is completely recyclable, but the nitrogen of the biomass is volatilised. Thus, to reach the goal of a sustainable society, it is very important to treat the organic waste fraction separately, by biologically based methods[14]. Composting has a drawback compared to anaerobic digestion in that aeration of the process causes undesirable stripping of nitrogen in the form of ammonia[19]. Decreasing the aeration to minimise this stripping may result in an increased production of the highly potent greenhouse gases nitrous oxide and methane[18, 20, 21]. In conclusion, the need for aeration makes the composting process less sustainable.

Anaerobic digestion, on the other hand, is performed in gas-tight vessels. The equilibrium concentration of ammonia in the biogas produced is very low[22]. High ammonia losses are only incurred when the digestate is exposed to the atmosphere for a prolonged period, which with good storage technology only happens during the spreading of the digestate on the fields[23-25]. New and improved spreading technology has the ability to decrease the losses to below 5% of the total nitrogen[23, 26].

The biogas potential of the organic waste fractions in the Swedish domestic and industrial sectors, including sewage sludge, is 3 TWh/yr[27]. In contrast, the potential of residual agricultural products, such as straw, animal manure and tops of potatoes and sugar beets, has been estimated in one survey to be 11 TWh/yr[27], and purpose-grown energy crops such as alfalfa, grass and clover may yield as much as 20 TWh/yr[28]. In comparison, the current Swedish consumption of petrol and diesel amounts to 70 TWh/yr (Swedish Statistics 2005). Current Swedish biogas production yields 1.4 TWh/yr, more than 90% of which is derived from wastewater treatment plants and landfills[29]. The low degree of utilisation of the Swedish biogas potential is based on purely economic issues – treating organic waste fractions brings profits, the energy production in the form of methane here being only an extra benefit, while acquiring agricultural products in the form of crop residues and energy crops incurs costs (**Papers III-V**). The profit is generated only by the energy production and the enhanced nitrogen management (**Paper III**). Environmental benefits, such as decreased emission of nitrogenous compounds to the air and water, reduced dependency on fossil fuels, and decreased greenhouse gas emission, are not fully valued. The only financial benefits implemented in Sweden today are those for renewable energy carriers, namely the green certificates for renewable electricity production (which amounted to 2.6 €ct/kWh during 2004[30]), and tax exemptions (no energy tax, no carbon dioxide tax) on renewable fuels, such as biogas-derived methane (**Papers III and V**). In Germany, on the other hand, the state provides an energy bonus of up to 21 €ct/kWh on biogas-derived electricity supplied to the grid[31]. In addition, the bonus only applies to farm-scale units, with extra benefits for digestion of energy crops.

Due to the small profit margins of anaerobic digestion, scaling up enhances the benefits of the process[32-34]. Centralised co-digestion of manure with the addition of 5-25% substrates with higher biogas yields, such as the organic fraction of household waste and food industry waste, is a concept that was established during the years 1988-2002 through the joint efforts of the Danish farmers, other market actors and the Danish state[32, 35, 36]. A small number of co-digestion plants have also been built in Sweden, most of them supported by investment grants. The profits of these plants are also reportedly marginal[22]. These Danish and Swedish co-digestion plants are on the scale of 1000-5000 kW. In Denmark, further scale-up has been shown to improve the economy, despite the increase in transport costs[32, 36].

Compared to Denmark, the situation in Sweden is aggravated by the longer transport distances. Since such a large proportion of the biogas potential lies in agriculture, full utilisation cannot be achieved without the development of economically feasible digestion technology on the farm-scale, here defined as 50-500 kW (**Papers III and V**). The concept of a sustainable society is likewise not achievable without the implementation of farm-scale anaerobic digestion, since nutrient recycling is such a vital part of the concept[20, 37], at least according to the official Swedish environmental quality objectives[38]. Another objective involves the expansion of organic farming, which requires the implementation of organic crop farming without livestock[39, 40], which in turn requires green manuring, i.e. the growth of nitrogen-fixing ley crops, such as clover[41, 42]. Currently, the yield and protein content of crops from such farms are lower due to the low efficiency of green manuring compared with mineral-based fertilisation[43]. If the repeatedly cut ley crops were collected and treated anaerobically, the retention and availability of the nitrogen would be increased due to reduced emission to air and water, and enhanced nitrogen mineralisation. Renewable energy would also be supplied[44-46]. There would be general socio-economic benefits through the decrease in pollution, as well as more direct benefits for organic crop farmers through a possible improvement of their economic situation. Augmenting the nitrogen efficiency of green manuring would increase the revenue of farmers, through freeing of land for profitable crops and an increase in the yield and protein content of crops. The price of the biogas produced and the total annual cost of the biogas digester will decide whether a net profit is actually achieved[43, 47](**Papers III and IV**).

The development of financially viable farm-scale digestion of residual agricultural biomass requires the introduction of new reactor designs that are less expensive than current technology, and with as low as possible maintenance requirements[48](**Papers III-V**). Although the maintenance and process control of slurry digestion is relatively simple, the costs involved in the handling and heating of the slurry favours the use of large centralised plants[32-34]. In the case of crop residues, the longer transport distances to these centralised plants might tip the economic balance, since higher costs for harvesting and storing and for size reduction and dilution are associated with crop residues, compared with liquid substrates such as liquid manure and food industry waste(**Paper III**). Purpose-grown energy crops are associated with even higher costs, since the operations of sowing and tending of the crops must also be financed[49](**Paper IV**). In addition, inherent process problems due the high water content of the slurry-based process, such as crust formation, are particularly pronounced in the case of dry or highly fibrous crop residues, such as wheat straw and ley crops[47, 50, 51]. Crust formation can be avoided by developing and introducing high-solids reactor designs. The volumetric efficiency increases, and handling and heating costs are reduced since no or very little extra water needs to be added[52-54].

2 Anaerobic digestion – A microbial multistep process

When organic matter is degraded in the presence of external electron acceptors such as oxygen, the carbon content is oxidised and the carbon is ultimately released as carbon dioxide, while the oxygen accept the released electrons, thus undergoing reduction. Oxygen is transformed into water, nitrate is transformed into nitrogen gas, and sulphates into hydrogen sulphide. The rate of reaction is determined by the different energy yields obtainable for each redox couple, utilisation of oxygen giving the highest yields[6, 55]. When all non-carbonaceous electron acceptors have been depleted, organic matter will instead be degraded anaerobically[56]. Under these conditions, the electron acceptor of choice is often the hydrogen atom removed from the organic matter during the first steps of degradation; molecular hydrogen being formed as an electron sink. At higher partial pressures of molecular hydrogen, this reaction is not energetically feasible[56]. The hydrogenotrophic methanogens deplete the growing pool of molecular hydrogen by hydrogenating carbon dioxide which, after splitting, ends up as methane and water. The electrons are thus transported further, ending up in the fully reduced methane. The net reaction thus means that the carbon of the organic matter is used partly as an energy source and partly as an electron acceptor. The ratio between the fully oxidised carbon of the carbon dioxide and the fully reduced carbon of the methane depends on the average oxidation state of the carbon in the organic matter. Carbohydrates, for example, will produce a 50/50 mixture, while proteins and fats have a higher proportion of methane than carbon dioxide[57].

2.1 The four main steps of anaerobic digestion

Anaerobic digestion involves an intricate interplay between several different microorganisms belonging to the *Bacteria* and *Archaea* kingdoms[58]. The degradation products of primary fermentation (steps I and II in Fig. 1) constitute the substrates of the later steps, such as secondary fermentation and methanogenesis (steps III and IV in Fig. 1). The degree of mutual dependence varies considerably, but in essence the chain of reaction steps leads to optimisation of the energy yield of each reaction concerned. The optimisation depends to a very high extent on the

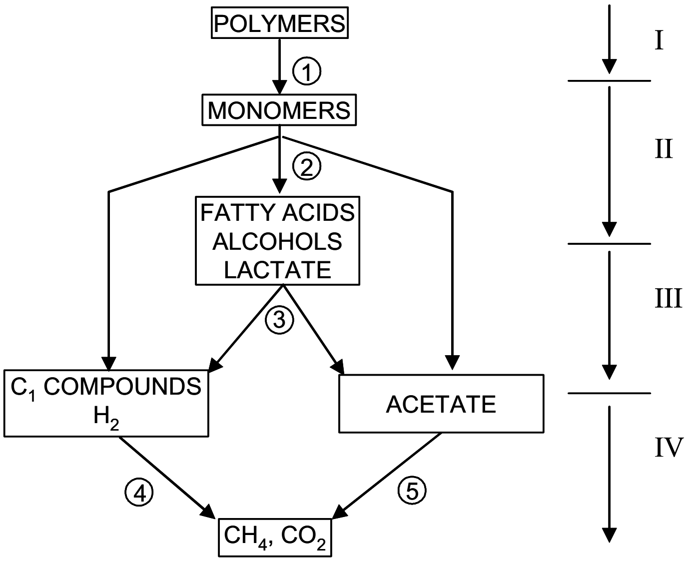

Fig. 1. Carbon and electron flow of the different reactions of anaerobic digestion. I: Hydrolysis; II: Acidogenesis; III: Acetogenesis; IV: Methanogenesis. Groups of microorganisms involved: 1: Primary fermenters; 2: Primary fermenters and anaerobic oxidisers; 3; secondary fermenting or acetogenic bacteria; 4: Hydrogenotrophic methanogens; 5: Aceticlastic methanogens. Fig. adapted from reference [56]

continuous depletion and minimisation of the pools of intermediate species; the end-products eventually being released as methane and carbon dioxide[56].

Hydrolysis involves depolymerisation of the organic material, which consists of carbohydrates, proteins and lipids, into the corresponding monomers of sugars, amino acids and fatty acids. Extracellular enzymes, either excreted or bound to the surface of the cell, perform the hydrolysis; the monomers thus become available to cell transport systems and further degradation[59, 60]. Hydrolysis is found to be the rate-limiting step in the anaerobic digestion of particulate organic matter as the access of the hydrolytic enzymes to the organic matter is governed by the specific area of the solid material[59, 61].

The ensuing acidogenesis (step II in Fig. 1) of the monomers is often the fastest step in anaerobic digestion, at least in liquid phase digestion of complex organic matter[61, 62]. The primary fermentative bacteria responsible for hydrolysis (1, 2), together with the anaerobic oxidisers (2), degrade the monomers into e.g. volatile fatty acids, lactate and alcohols, together with carbon dioxide and molecular hydrogen. If the molecular hydrogen pressure is kept low enough (< 10 Pa), molecular hydrogen will be preferred as the electron sink, and the reactions will consequently proceed by the two outer paths[56]. The flux through the middle path will never be completely zero, since branched and odd-numbered fatty acids that cannot be utilised directly by the methanogens end up there[56, 63, 64].

In the third step, referred to as acetogenesis (III in Fig. 1), the secondary fermenters (3) transform the accumulated electron sinks (e.g. propionate) into acetic acid and molecular hydrogen. The acetogens are extremely dependent on low levels of molecular hydrogen in order to gain enough free energy in the degradation reactions to allow growth[56, 57, 65]. Consequently, the acetogens have been found to form syntrophic co-cultures with the hydrogenotrophic methanogens[66].

Methanogenesis (Step IV in Fig. 1) is mainly performed by two groups of microorganisms belonging to the *Archae* kingdom, the aceticlastic (5) and the hydrogenotrophic (4) methanogens[58]. While the aceticlastic reactions can only be performed by a very small number of known species, the hydrogenotrophic reaction can be performed by almost all known methanogens[67]. The aceticlastic pathway provides much less energy than the hydrogenotrophic one, which is reflected in the very different growth rates of the two groups of microorganisms. The minimum doubling time of hydrogenotrophs is six hours, comparable to the values for the acidogenic, primary fermenters, while the aceticlastic group has a doubling time of 2.6 days[62]. However, stoichiometric calculations show that as much as 70% of the substrate flow goes via acetate[68, 69].

2.2 Environmental factors affecting anaerobic digestion

In a properly functioning anaerobic digester, the pH is around 7, since the slow-growing acetogens and methanogens have their optimum pH in that range[70]. If the pH decreases, the degree of volatile fatty acid (VFA) protonation increases. In this non-ionised form, the VFAs can penetrate the lipid cell membranes, disturbing the metabolism by turning the intracellular pH acidic[71]. A drop in pH might occur as the result of overloading of substrate, leading to an accumulation of VFAs that is so large that the buffering capacity of compounds with higher pKas, such as ammonium and carbonates, is consumed. The buffering capacity of anaerobic digesters is generally governed by the carbonate equilibrium[72, 73]. Carbonic acid has a pK_a of 6.3. Ammonium, on the other hand, has a pK_a of 9.3. The non-ionised free ammonia, prevalent at higher pH levels and high total concentrations of ammonium, can enter the lipid cell membranes freely, and disrupts the pH stability of the cells[74]. Anaerobic digestion of dry substrates with high levels of nitrogen, such as wilted ley crops(**Paper IV**), may thus inhibit the process, especially if complete liquid recirculation is employed[75](**Papers III and IV**). The addition of substrates poor in nitrogen or rich in water alleviates the problem[76, 77] (**Papers III and IV**). Possible toxicity problems due to increased levels of potassium would also be solved[75].

It is reported that the optimum carbon:nitrogen:phosphorus ratio is 100:3:1[78]. The amounts of these macro-nutrients and necessary micro-nutrients such as potassium, manganese and copper, are usually sufficiently high in most types of plant biomass, such as sugar beet tops and ley crops. The levels of nutrients can be balanced by mixing different types of substrates. Co-digestion often enhances the methane yield compared with the single substrates, demonstrating the importance of nutrients[51, 79].

Anaerobic digestion in the mesophilic temperature range (25-40 ºC) is the most common choice, since operation at thermophilic conditions (>45 ºC) has been considered unstable[68, 83]. Reports of higher conversion rates at higher temperatures[80-82] are contradicted by others stating that no benefit could be observed by increasing the temperature[68, 83]. However, commercially available high-solids reactor designs show good results at thermophilic conditions[14, 16, 84, 85]. In this study, all the reactor trials were carried out at 35 ºC (**Papers I-IV**).

3 Anaerobic reactors – Different designs and important concepts

In a single-stage process, all the different degradation steps take place in the same reactor vessel. If the reactor contents are homogeneously mixed and continuously fed and removed, such as in a continuously stirred-tank reactor (CSTR), all of the reactions involved in anaerobic digestion are equally prevalent over time, and evenly distributed in space; the overall rate being determined by the slowest reaction step[5]. If stirring is not employed, such as in an anaerobic baffled reactor[8], in which the reactor content moves as plug flow from the inlet to the outlet, spatial separation of the reactions will occur. The fermentative reactions dominate in the first part of the flow path, while the extent of acetogenesis and methanogenesis increases towards the end of the reactor. The gas production and the diffusion of solutes will provide a certain degree of mixing. If the material is fed in batchwise, such as in an anaerobic sequencing batch reactor[11], temporal separation of the aforementioned reactions will occur, the extent of which is governed by the feeding frequency and the proportion of reactor content replaced with each batch. With a high feeding frequency and a low exchange of reactor content, the temporal separation will be small and the degradation pattern will be very similar to the that of a CSTR. Therefore, this mode is often referred to as a semi-batchwise fed CSTR operation. At the other extreme, with a low feeding frequency and almost complete replacement of reactor content before each feeding, the term batch digestion is commonly used. A landfill containing municipal solid waste (MSW) is an extreme example of such a batch digestion, in which no mixing is possible. As a consequence, the reaction steps will be separated in both space and time. Acceleration of the reactions is possible by recycling the leachate produced to the top of the landfill[34, 86]. This percolation of liquid increases the mass transfer of solutes and moisture, evening out the differences between depleted and saturated zones[87].

An important parameter of anaerobic digestion is the retention time (RT). In the landfill example the solids retention time (SRT) is counted in terms of decades, while the more efficient CSTR has a hydraulic retention time (HRT) of 15 days or more, depending on the ease and extent of degradability of the substrate. In a fully mixed reactor such as the CSTR, the SRT and HRT are equivalent. The SRT and HRT can be decoupled by measures leading to the accumulation of particulate matter inside the reactor[7]. The ratio between microbial cell biomass and undigested substrate in the solids fraction depends on the digestibility of the substrate[12]. Attaching a clarifier to the outlet of a CSTR is one way of increasing the cell biomass density by recycling the thickened sludge of the clarifier to the inlet of the CSTR[88]. Attached growth, also called biofilm formation, is another way. This is achieved either by spontaneous granulation, such as in an upflow anaerobic sludge blanket reactor (UASB)[7, 10], or by the addition of a support or carrier material, such as in the downflow stationary fixed film reactor (DSFF)[9], on which the microorganisms adhere, eventually forming a layer, the biofilm. The carriers may either be separate entities or a monolithic block that fits inside the reactor. They may be made of plastic, glass, stone or metal, but organic material such as loofah sponge and straw have also been tested[54, 89-91]. Three parameters are important: high specific surface (m^2/m^3), low cost and low tendency for clogging.

Complete spatial separation of acid formation and methane formation is possible by implementing two-stage anaerobic digestion. This makes it possible to better control the process, allowing optimisation of the process conditions in accordance to the different needs of the microorganisms involved in the primary fermentation and the ensuing acetogenesis/methanogenesis[92-94]. Contradictory results have, however, been reported, stating that hydrolysis and acidogenesis of proteins and carbohydrates are not promoted by acidogenic conditions[95, 96]. The hydrogen sensitive syntrophy of the slow-growing acetogens and methanogenic hydrogenotrophs can be protected from the shock loading leading to increased levels of volatile fatty acids (VFAs) and molecular hydrogen by controlling the transfer rate between the two stages. Careful monitoring of the feed achieves the same goal in a single-stage operation[12]. If the final methanogenic stage employs biofilms, the resistance of the sensitive methanogens towards inhibitors such as free ammonia increases considerably. Weiland et al.[88] reported that two-stage digestion enabled a doubling of the maximum organic loading rate when digesting a certain mix of agro-industrial residues that produced a total ammoniacal nitrogen level of 5 kg/m^3. The disadvantage of two-stage operations is the poor energy economy and the increased investment cost[12, 13, 97].

4 High-solids anaerobic digestion – Different reactor systems

For many years, anaerobic digestion was limited to the treatment of waste water and slurries at a total solids (TS) content of 10-15% or below[13], with the exception of landfills. With the introduction of stricter landfill legislation[17] and increased uncertainty about the future energy prices[98], interest in anaerobic digestion increased, especially with respect to the mechanically or source sorted organic fraction of MSW (OFMSW). Initially, the conventional slurry technology dominated[15], in which the solids were comminuted and diluted. Impurities such as inert materials (plastic, sand, glass) increased the wear of the pumps and stirrers, and frequent removal of heavy inert materials was required. New, more elaborate reactor designs were introduced, which could take care of the floating scum layer, containing light inert materials and drier part of the organics[13]. The propagation of the scum layer was increased by foaming agents present in the plant biomass part of the OFMSW[12]. In addition, the higher TS content and its greater variation (20-50%) between the different types of OFMSW were more difficult to handle in conventional systems. There was thus considerable incentive for research and development of high-solids digestion of OFMSW, and today there are a number of commercially available high-solids digestion designs in Europe[85, 99, 100], with the wet and dry types of operation more or less evenly divided between the full-scale facilities[15, 16].

With respect to the optimal choice of digestion technology for a certain substrate, it can be said that liquid and slurry substrates are best suited for conventional slurry digestion, while solid substrates, especially highly fibrous plant biomass and heterogeneous waste such as OFMSW, are better suited for high-solids anaerobic digestion. It should be noted, as already mentioned in the Introduction, that anaerobic digestion by no means dominates the field of OFMSW treatment, since aerobic digestion, i.e. composting, has so much lower investment costs. If land prices are high, anaerobic digestion becomes more interesting, since the area required to apply the technology is usually considerably smaller than that required for composting[13].

High-solids reactor systems can be classified according to three parameters: the number of stages, the technology chosen to enhance mass transfer, and the frequency and manner of feeding and removal of material. Commercially available systems are focused on the treatment of OFMSW, and single-stage operations dominate, since two-stage systems have not proven to be more efficient[15, 16].

4.1 Single-stage digestion

If the highly viscous reactor content of a high-solids, single-stage process could be homogeneously mixed and continuously fed and removed, the different reactions would occur everywhere, simultaneously just as in a CSTR. This is not economically feasible in high-solids digesters as the energy consumption of the stirring would be unrealistically high, and the maintenance requirements due to wear would increase. The three commercially available continuously fed systems that dominate the market are of the plug-flow type[15]. The impellers of the Kompogas™ process[100] and the biogas injections of the Valorga™ process[99] homogenise and mix the paste of MSW (TS maintained at 23 and 30%, respectively) to a certain degree, but the plug-flow characteristics still dominate in both processes. The Dranco™ process[85] is a true plug-flow system; the reactor content moving from the top of the reactor to the outlet. In all three types of operation, the mixing and conveying of the highly viscous material is performed by screw conveyors, transport belts, piston pumps and other specially adapted pumps (Kompogas)[12]. This high level of technical sophistication in combination with the high degree of abrasion due to inert material in the substrate lead to high investments in the form of maintenance and reinvestment. Considerable scale-up and the profits derived from gate fees for OFMSW are necessary to make the operation economically viable. A less capital-intensive alternative, especially if land prices are not too high, is single-stage batch digestion, such as in the Biocel™ process[101]. The reactor footprint is ten times greater than that of the Dranco process, mainly due to the lower height of the reactor cells, but also due to the organic loading rate being half that of the Dranco process[13]. A high rate of inoculation and addition of structuring materials is necessary in order to shorten the solids retention time and avoiding clogging, respectively [101]. The advantage of the lower investment costs (40% lower than those of continuously run systems) [102] is somewhat offset by the 40% lower methane yield, the result of the less reliable mass transfer of leachate recycling. Channelling and partial clogging in the bed of OFMSW lead to the formation of stagnant zones, which are not in contact with the recycled flow[12].

4.2 Two-stage digestion

Single-stage batch digestion can be upgraded to a low-tech two-stage operation by simply exchanging leachate between recently started reactor cells and more mature reactor cells[103, 104]. The leachate exchange quickly increases the pH and decreases the high levels of VFAs in the recently started reactor cell, thus reducing the inhibitory effect on the methanogenic microorganisms. Soon a self-sustaining methanogenic activity develops, and the reactor cell is switched to single-stage operation, treating its own leachate. By then, the most mature reactor cell will have been emptied and filled with fresh material, and a new cycle begins; the most mature reactor cell still in operation taking over the role of being the methanogenic second stage. This sequential operation mode adds another important feature that is otherwise to the disadvantage of single-stage batch digestion; the evening out of the variable biogas production.

A more advanced option is to add a dedicated methanogenic reactor[12], treating all leachates rich in VFAs from the recently started reactor cells. A possible choice is the attached growth reactors described in section 3, which are able to treat high-strength leachates at high loading rates. The VFA turnover does not necessarily need to be complete, since the leachate recycling prevents the losses of VFAs.

The commercial deployment of high-solids, two-stage systems is low in Europe today. Regarding the anaerobic treatment of OFMSW, 10% of the existing large-scale facilities are of the two-stage type in Europe, including wet treatment systems[15]. Considering the more simple sequential batch digestion technology, a number of entrepreneurs exist[105].

4.3 A hybrid approach – The high-solids, single-stage, stratified bed digester

The simplicity and lower investment costs of sequential batch digestion may be combined with the higher rate and extent of methanisation and volumetric efficiency of continuous single-stage digestion in a hybrid design known as the single-stage stratified bed digester. The design was conceived and first tested on laboratory-scale and household-scale in the work by Chanakya et al.[50, 106-109]. As in the case of the Dranco process, the fixed bed consists of the biomass which is being fed into the system. An illustration of the reactor design is shown in Fig. 2. Since mass transfer is achieved by leachate recycling, the process is best suited for wet and semi-dry biomass, such as most types of plant biomass. At the top, the material fed in most recently starts to hydrolyse and acidify. The solutes trickle down further into the bed, which becomes more and more methanogenic in character, since the material is closer and closer to being fully digested. Stratification thus develops, separating the different steps of the anaerobic process in terms of their depth within the biomass bed. This stratification within the bed resembles the spatial separation of a continuous plug-flow process, or even a two-stage process, since the leachate

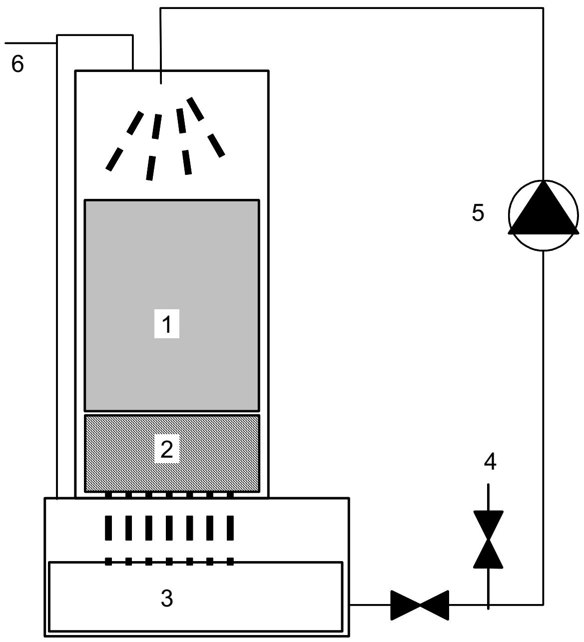

Fig. 2. Outline of the high-solids, single-stage stratified bed digester design, here with the addition of a priming straw bed. 1: Plant biomass; 2: Straw; 3: Leachate; 4: Feed inlet; 5: Recirculation of leachate; 6: Biogas outlet.

recycling transports the VFAs produced in the substrate-rich higher regions downwards to the substrate-poor lower regions, rich in acetogenic and methanogenic activity. The bed rests on a metal grid, and the leachate produced is collected and recycled intermittently. The process is inoculated by adding a portion of a digested bed to the bottom of the new reactor, and by adding liquid inoculum, preferably low in particulate matter in order to avoid clogging. No material is removed in the bottom, the feeding operation being of the fed-batch type, in which the active volume increases with each batch feeding up to a maximum level. Digestion is allowed to continue for a certain period of time, with leachate recycling, and then the reactor is terminated, and a new cycle begins.

Fed-batch processes lie between batch and continuous operations with regard to technical complexity. Three factors improve the volumetric efficiency of fed-batch operations compared with batch digestions. First, the fed material decreases in volume with digestion, mostly because of liquid drainage. Second, the methane formation has a much shorter lag-phase, effectively decreasing the optimal SRT. The third and last aspect is the reduced need of inoculation, avoiding use of the reactor space for unproductive inoculum. Thus, the volumetric efficiency of the process is better than that of batch digestion(**Paper III**). Nevertheless, the recurrent restarting of the process may be just as time-consuming as in batch digestion, and it involves risk of loosing the methanogenic activity of the solid inoculum placed in the bottom of the reactor. Starting up an inadequately inoculated anaerobic process is often both time-consuming and difficult, since it involves the inter-play of four different reaction steps in a biological process mediated by an even higher number of different species of *Bacteria* and *Archaea*. Increasing the proportion of inoculum added will ensure efficient start-up, but will decrease the volumetric efficiency of the process. Minimising the proportion of inoculum addition while ensuring and maximising its inoculating effect on the process would thus be of great value in the total economics of the reactor system.

The optimal kind of inoculating material at the bottom would be one acting both as a particulate filter and as a support for the biofilm-forming microorganisms. This starting bed material functions as a “primer” for the growing bed, composed of the more easily degradable plant biomass which is being fed into the reactor. This primer material should be rigid in structure and have a low biodegradability in order to maximise the period of continuous operation of the reactor. The primer could be confined, in order to contain it during the emptying of the reactor at the end of each cycle of operation. Straw has been found to function well as a carrier material for biofilm processes in different anoxic and anaerobic applications involving liquid feeds[54, 90, 110-113] (**Papers I and II**).

4.4 Straw bed implementation in stratified bed digesters

Paper I reports the results of the introduction of such a priming straw bed in single-stage stratified bed digesters on laboratory- and pilot-scales. Upon inoculation, easily degradable organic material in the straw beds was mobilised, resulting in elevated levels of VFAs and moderately high gas production rates. The pre-digestion period without feeding allowed microbial and structural stabilisation to occur. Feeding with 7 kg volatile solids (VS)/m3 batch loads of ensiled sugar beet leaves twice weekly could be sustained, and the total methane yield was in the range of 0.31-0.33 m3/kg VS at an average SRT of 20 days, suggesting that the introduction of a priming straw bed enhanced the performance of the process. In comparison, Chanakya's end loading rate of 0.8 kg VS/m^3·d needed to be decreased by a factor of two during a four-week start-up[50], while in the study of **Paper I** a direct onset of the chosen loading rate of 2 kg VS/m^3·d was possible, as long as the priming straw bed had been pre-digested for a certain period of time. In **Paper II**, the initially tested pre-digestion period of six to eight weeks (**Paper I**) was reduced to four weeks without problems. The results of the trials described in **Papers I and**

Table 1. Summary of the results of the experiments presented in **Papers I** and **II**.

	Batch load size (kg VS/kg straw)	Average SRT (days)	Methane yield (m3/kg VS_{added})
Lab (**Paper I**)	0.14	22	0.36
Pilot[a] (**Paper I**)	0.23	20	0.33
Lab+1 (**Paper II**)	0.10	25	0.37
Lab+2 (**Paper II**)	0.20	25	0.37
Lab+3[b] (**Paper II**)	0.30	25	0.30
Lab+4 (**Paper II**)	0.40	-[c]	-[c]
Lab-1 (**Paper II**)	n.a.	30	0.25
Lab-2[d] (**Paper II**)	n.a.	30	0.30
Lab-3[d] (**Paper II**)	n.a.	30	0.31
Lab-4 (**Paper II**)	n.a.	30	0.32
Sugar beet tops, fresh / ensiled [114]	n.a.	40	0.36 / 0.38

Notes: n.a.=not applicable; [a]best pilot trial out of two; [b]yield lowered by leakage; [c]no results, turned acidic; [d]average of duplicate trials.

II are summarised in table 1.

The conclusion drawn in **Paper I** is that the introduction of a priming straw bed speeds up and ensures the start-up of a single-stage stratified bed digester, shortening the feeding escalation phase of the start-up considerably. However, the time spent on the unproductive pre-digestion of the straw may reduce the benefits achieved.

The aim of **Paper II** was to investigate the usefulness of straw bed priming by making a direct comparison of the two different start-up procedures outlined above in single-stage stratified bed digesters: a conventional one, involving no straw bed priming, fed from day 1 with easily degradable plant biomass, in this case fresh sugar beet leaves, and an alternative one in which the priming straw bed was pre-digested for four weeks before feeding of sugar beet leaves commenced. The twice-weekly feeding was adjusted to give the same level of accumulated sugar beet leaves added in both types of systems by week five. The final feeding in week six doubled the accumulated amount of VS fed in all reactors. The methane produced was corrected by subtraction of control values, see **Paper II** for details. The pattern of the methane yields (see Table 2 and **Paper II**) lead to the general hypothesis that straw bed priming had increased both the extent and the rate of anaerobic digestion of the sugar beet leaves added. The hypothesis was strengthened by the analysis of the VFAs, see **Paper II** for details.

The batch loads in the first set of experiments (**Paper I**) corresponded to 0.15-0.25 kg VS/kg wheat straw, while those used in the second (**Paper II**) ranged from 0.10 to 0.40 kg VS/kg straw (see Table 2). It may thus be concluded that the maximum start-up batch load size lies somewhere between 0.30 and 0.40 kg VS/kg straw, Lab+3 and Lab+4, respectively. The potential performance in these two experiments might have been hampered by the straw beds eventually being soaked in liquid, see Section 4.5.

The methane yields achieved in the straw bed primed trials Lab+1 and Lab+2 of **Paper II** are high for such short average SRTs, 0.33-0.39 m^3/kg VS_{added} in 11-39 days. Zubr[114] reported a methane yield of 0.36 m^3/kg VS_{added} (40 days) for fresh sugar beet tops in a 3 litre slurry batch trial. Could co-digestive effects between the wheat straw and the sugar beet leaves explain the difference? The co-digestion would enhance not only the yield of the leaves, but also the straw, thus introducing a positive error in the calculation of the sugar beet leaves yield[51, 79]. This notion is rebutted by the fact that the methane yields are equal in size, even though the contribution of the straw to the total VS load of each reactor is so different; 69 and 48%. In a slurry batch trial (**Paper III**, Table 6), where the straw contributed approximately 55% of the total VS in co-digestion, the co-digestive effect was calculated to be 8%, increasing the methane yield of the sugar beet tops from the expected 0.24 $m^3/kg\ VS_{added}$ to 0.26[115].

4.5 Optimum characteristics of and conditions for straw beds

How long could such a priming straw bed be operational? Laboratory-scale results (**Paper I**) suggest that a working life in excess of 300 days might be possible. However, it was also found that sudden and high compaction of the straw bed could jeopardise the functioning of the biofilm. Intermittent pumping, with the bed being flooded and drained at intervals, triggered bed compaction (**Paper I**). Introduction of a second metal grid which shielded the straw decreased the bed compaction to almost zero, and feeding was performed at a straw bed age of 450 d (Svensson 2004, unpublished data). It was shown that an initial straw bed density in the range of 80-100 $kg \cdot m^{-3}$ was optimal(**Paper I**). Lower densities led to problems associated with extensive compaction of the bed and a higher risk of clogging in the bottom of the bed[116]. Higher densities also gave problems due to clogging, mostly in the upper half of the straw bed, and a higher risk of process failure during the pre-digestion of the straw bed (**Paper I**). The risks of process failure during pre-digestion and startup can be decreased by increasing the wetting ratio (kg inoculum$\cdot kg^{-1}$ straw). A ratio in the range of 5-10 was deemed to be optimal.

More important than avoiding compaction of the straw bed is to keeping it drained. The results presented in **Paper II** indicate that flooding of the straw bed may have been deleterious to the methanogens. During the liquid immersion the stagnant liquid layer decrease in thickness, effectively increasing the VFA concentration in close proximity to the methanogens. Liquid immersion could be said to correspond to a very high leachate recycling rate, and it has been shown that solid-state batch digestion is less prone to failure by keeping the initial leachate recycling rate low[87]. In slurry-based digestion systems, it has been shown that a lower degree of mixing makes the digestion process more robust, allowing for higher loading rates[117]. New experiments and modelling have shown that the low degree of mixing leads to an increase in the spatial separation between seed and substrate, which is crucial for the successful start-up of a batch digestion process[118, 119]. New theories in high-solids digestion imply that the seed material must be of a specific size in order to survive and propagate into the regions rich in substrate[120, 121]. These findings provide a probable explanation of why high-solids batch digestion start-ups are protected from process failure by keeping the initial leachate recycling rate low[87]. In addition, they also shed some light on the reasons behind the fact that the start-up performance of a single-stage stratified bed digester is improved by introducing a priming straw bed(**Paper I and II**).

Upon feeding, the permeability of the bed always decreased, but the lower flow rate was consistent with no complete blockages occurring at any time during feeding. On the laboratory-scale, the leachate recycling during feeding was typically sustained at average superficial flow velocities ranging from 1 to 2 m/d. Even after severe compaction (to 20% of the original volume) one bed permitted a flow of 1 m/d. In a pilot-scale set-up, daily averages just before feeding ranged typically from 0.5 to 1.5 m/d, whereas directly after feeding they were often higher, typically 1-2 m/d (**Paper I**). The significance of reliable recirculation is well illustrated by a slower increase in methane yield when recycling is aborted (**Paper I**). Chanakya et al.[107] used flows around 0.1 m/d, and claimed that flows as low as 0.02 m/d were sufficient to sustain anaerobic digestion. Nevertheless, a higher leachate recycling capacity of the bed should provide for more efficient mass transfer. As reported in the literature, the recirculation of either untreated leachate[34, 86] or methanogenically stabilised leachate[122-124] accelerates the degradation and reduces the problems associated with stagnant zones. Also, if the permeability is higher, the plant biomass bed will drain more quickly(**Paper I**). This is an important parameter in the control of foaming, see below.

4.6 Mass transfer – Pros and cons of free liquid

Mass transfer of solutes takes place by two routes: either by diffusion within segments of free liquid or moist solids, or by convection of these segments, brought about by moving impeller blades, thermal gradients or the formation and buoyancy of gas bubbles[125]. Convection involves macroscopic movements, while diffusion occurs on the microscopic level. The cell metabolism depletes the levels of VFAs in close proximity to the cells, creating a motive force for the surrounding VFAs to diffuse in that direction, a concentration gradient thus forming in the stagnant layer surrounding the cells. Liquid convection decreases the thickness of the stagnant layer surrounding the cells. In addition, diffusion rates are higher in free liquids than in moist solids. If the immersion in liquid is constant, such as in a CSTR, it is very important not to overload the reactor, since the increased flux of VFAs and molecular hydrogen is brought into contact with the slow-growing acetogens and methanogens so quickly[12]. In high-solids reactors employing leachate recycling this is not so important, since changes in the recycling rate can control the extent of liquid immersion[87]. However, reliance on leachate recycling is a potential risk factor when trying to maximise the loading rate, because of the related thinning of the stagnant layer. High-solids digestion is actually not always so high in solids; in-reactor levels of TS in reactors during plant biomass digestion of sugar beet leaves may be as low as 15% (Svensson 2004, unpublished data).

Another disadvantage of free liquid is the phenomenon of foaming. The fermentative degradation of easily degradable biomass is initially very high, leading to hydrogen and carbon dioxide production peaks. The greater flux of VFAs is immediately followed by an increase in the production of methane. Each batch load of feed causes a peak in biogas production. In a CSTR foaming may be so violent and enduring that the reactor has to be opened for several days in order to release the foam. The lower proportion of free liquid in high-solids systems reduces the extent of the problem, but the bed still expands and foaming agents present in or produced by the degradation aggravate the situation[12]. The expansion of the bed decreases the volumetric efficiency of the reactor, since a larger head space is required in order to keep the gas outlet unobstructed by the peaks in foaming. Implementation of intermittent recycling of leachate leads to intermittent drainage, which lowers the free liquid content of the bed, making it harder for the foam to form and propagate[116](**Paper I**). Adding smaller batch loads of feed at a higher frequency evens out the gas production, enabling an increase in the loading rate at the same rate of foaming. Increased costs, either in the form of higher investments and maintenance costs for automated feeding technology, or increased feed-related labour costs, are to the disadvantage of this foaming control method. Another way is to add a bulking agent such as straw, which breaks up channels in the paste of easily degradable plant biomass, facilitating the escape of the biogas and increasing the drainage capacity of the bed. The lower methane yield of the bulking agent is the main drawback of this method, but the risk of leachate flowing along preferential paths – channelling – increases, leading to the development of stagnant, less-digested zones[13, 101].

The only foolproof way of avoiding both foaming and the formation of stagnant zones is to increase the TS in the reactor to such an extent that the content of free liquid is significantly reduced or even completely eliminated. The convective, macroscopic mass transfer between acidogenic and methanogenic regions rich and lean in substrate, respectively, thus has to be managed by solids mixing. Gas formation will still contribute, but to a smaller extent. Removing or minimising the free liquid content has the positive effect of increasing the size of the stagnant layer surrounding the cells, thus protecting the more vulnerable microorganisms from the transient effects of feeding shock loads[13]. The commercially available types of high-solids mixing (see Section 4.1) show that gas injection yields adequate mixing, since no recycling of digestate is necessary in the Valorga biogas plants[13, 99]. Both the Kompogas and the Dranco process rely heavily on digestate recycling for proper inoculation and mixing[12, 85, 100]. The actual mixing takes place either inside the reactor by slow-moving impeller blades, such as is the case in the Kompogas process, or outside of it, through mixing during screw conveying, such as in the Dranco process. All of these three designs have been developed with the aim of treating mechanically or source-sorted OFMSW, sometimes in the form of pure plant biomass, by the treatment of a combination of source-sorted vegetable, fruit and garden waste. Obviously, no technical or biological aspects stand in the way of the implementation of these three designs in the anaerobic digestion of agricultural plant biomass, such as sugar beet leaves, straw and dedicated energy crops in the form of fresh or wilted ley crops. Economical constraints, on the other hand, today hinder such an implementation, see next section. In essence, mass transfer is managed in a less expensive way by employing recycling and exchange of leachate in systems of sequentially run fed-batch reactor cells(**Papers III and IV**). Disadvantages associated with the simplicity of the design are potentially decreased methane yields if channelling occurs easily, and worse volumetric efficiency due to foaming, the latter effectively increasing the reactor investment costs through the increased space requirement.

5 Economical and technical aspects of anaerobic digestion of agriculturally derived biomass

In this chapter the technical and economical aspects of anaerobic digestion of agriculturally derived biomass are discussed in general terms. This discussion is followed by the presentation of a study on the economical feasibility of farm-scale anaerobic digestion of plant biomass under conditions in Sweden. Farm-scale is defined as 50-500 kW power output, based on the total energy content of the methane produced (9.81 kWh/m^3[126]). Farm-scale digestion is advantageous for various reasons:

- A larger part of the biogas potential can be utilised than is possible with centralised anaerobic digestion plants, at least in a rather sparsely populated country such as Sweden[27](**Paper III**).
- The acceptance and successful development of new technology can be facilitated by starting on a smaller scale. Danish wind power[127, 128], which became a genuine success story, is an example of this.
- It facilitates the certification and acceptance of the digestate as a biofertiliser in which plant nutrients are conserved[129]. The spread of plant diseases also becomes less of a problem[130].

5.1 Agricultural feedstock

As was mentioned in the Introduction, the biogas potential of Swedish agriculture is much larger than that originating from industrial and household waste fractions. In addition, it is presently virtually unexploited, the current use amounting to only 0.01 TWh/yr[29]. These residual products of agriculture include solid and liquid animal manure, with a biogas potential estimated to range between 2.9 and 3.5 TWh/yr[27, 28]. The current potential of residual crop products is more than double that, 8 TWh/yr. The major contributor to the current biogas potential of Sweden is straw, amounting to 7 TWh/yr. Tops and leaves of sugar beets and potatoes has a potential of 1 TWh/yr. In addition, Nordberg (1998) adds the cultivation of ley crops, consisting of mixtures of grass and clover, on 170,000 ha as a current potential, yielding an extra 3.2 TWh/yr. Of the 3 million hectares of farm land in Sweden, only half is used for food production today. Ley crops is presently grown on 900,000 hectares (Statistics Sweden, 2005), both as cattle feed and as a green manuring crop that is ploughed in during the autumn. The nitrogen of removed and anaerobically treated ley crops would be preserved to a higher degree compared to conventional greeen manuring, while simultaneously extracting the otherwise lost energy of the crop in the form of methane. Assuming a harvest of 25 tons/ha (wet weight), each 100,000 ha of ley crops could provide 2.3 TWh/yr[113](see Table 2, **Paper IV**). Ley crops could, for example, be cultivated on the land presently used for export crops, which bring very low profits for the farmer, together with the set-aside land, in all corresponding to 500,000-600,000 ha. This would then yield another 11-14 TWh/yr. The energy scenario for 2020 of the Federation of Swedish Farmers[28] estimates a range of 10-20 TWh/yr for the same land area. If this scenario seems unrealistic, it is worthwhile to compare it with the current situation in Germany, where biogas-derived electricity from farm-scale digestion utilising only energy crops is strongly supported[31]. A current prognosis states that the current 300,000 ha of energy crop cultivation will increase to 900,000 by 2010[141].

5.2 Economical and technical feasibility of conventional slurry digestion of residual agricultural products

Conventional slurry-based anaerobic digestion has been widely employed for treating pumpable agricultural residues such as liquid manure[79, 131-133]. The co-digestion of pumpable or dilute substrates with high biogas potential, such as food industry waste and by-products, has proven to make operations more cost-effective[51, 79, 134]. Even so, the economic situation is far from stable, since the profit margins are so small[121, 135]. Problems of this sort have led to many countries offering state-subsidised programmes that include such vital tools as tax exemptions, investment grants and green certificates or fixed tariffs for “green” electricity[3, 36, 136, 137]. In so doing, society puts a price tag on the indirect environmental benefits of utilising renewable energy sources, of preventing the pollution of drinking water by extensive animal rearing, and of minimising the eutrophication of lakes, rivers and inland seas[32, 138]. Still, these benefits may not be sufficient to broaden the use and acceptance of anaerobic treatment of agricultural residuals. The fact that only 3% of Danish manure production is anaerobically treated in twenty centralised co-digestion plants shows that even an ambitious development programme, involving investment grants of up to 40% and a price bonus of 3.6 €ct/kWh on renewable electricity as vital incentives, faces problems when it has to adjust to strict economics[35, 139]. No more centralised plants have been erected since 1998, mainly because of radical changes in the electricity policy in 1999, leading to uncertainties regarding the future profitability of "green" electricity generation[136]. A recent economic evaluation showed that only six out of the eleven facilities investigated showed acceptable economic results[36]. Further scale-up has been shown to improve the economy, despite the increase in transport costs, which currently stands for 25% of the operational costs[32, 36]. Nevertheless, the increased investment needs and smaller and more uncertain subsidy programmes discourage potential investors[139].

Solid substrates must be comminuted and diluted in order to be treated, which incurs extra costs. Since the profit margins are already small, such costs might be difficult to cover[121]. Even if solid substrates come free of charge or bring in revenue (e.g. municipal solid waste) it could be difficult to make ends meet[135]. Although the maintenance and process control of slurry digestion is relatively simple, the costs involved in the handling and heating of the slurry favours the use of large centralised plants[32-34]. The contribution of the transport costs to the total increases. For crop residues and purpose-grown energy crops, the combined need of collection or purchase, size reduction and transport of the substrate make the economic gains involved marginal. In addition, to be effective, slurry digestion requires that process problems such as foaming and crust formation, inherent in the high water content of the process when certain feedstocks are employed, are dealt with adequately[12, 47, 50, 51]. The problem of crust formation is particularly pronounced in the case of dry or highly fibrous crop residues, such as straw and ley crops[47]. Although in pilot-scale studies it has been found that a reduction in particle size and an increase in TS content (> 10%) could solve such problems[140], the continuous stirring and the marked size reduction that are needed can result in fairly high costs. In Germany, these problems have been overcome by implementing a generous subsidy programme. The German state guarantees a minimum price of up to 21.3 €ct/kWh for farm-scale biogas-derived electricity if the installed electrical power output is lower than 150 kW_{el}[31, 47]. A special bonus of 5.8

€ct/kWh for electricity generated from pure energy crops has boosted the interest in plant biomass digestion.

The Swedish market for farm-scale digesters is limited. Each reactor has a unique construction, the benefits of serial production only pertaining to the auxiliary equipment, such as pumps and gas furnaces. The cost of the reactor vessel with insulation, including installation, may fall in the range of €500-600/m^3 (stainless steel, 106-1200 m^3 total volume), the effect of scaling thus not being so significant in terms of cost reductions. Using and equipping such a stainless reactor for the semi-batchwise CSTR treatment of liquid manure will render a total reactor investment costs of €600-1,200/m^3, the scaling effect for auxiliary equipment thus being quite strong[142]. Choosing to buy a turn-key facility, where the buyer assigns a single contractor for the complete installation, often with guaranteed replacements and repairs, will further increase the costs. In Germany, the boom in the building of farm-scale digesters has increased interest and competition among existing and new contractors, resulting in reduced prices, broader ranges of products, and refinement of the technology. A recently installed 500 m^3 farm-scale stainless steel digester, acquired as a turn-key facility from Germany, had a price tag of €222,200, corresponding to €444/m^3[47]. Guaranteed repairs and replacements were part of the deal. A 590 m^3 digester, acquired and contracted by the buyer in person, could in Sweden cost as much as €755/m^3, probably with no guaranteed repairs or maintenance[142].

Lack of experience has been stated as the most significant obstacle in widening the implementation of anaerobic treatment technology[6]. The generous farm-scale biogas programme in Germany is turning biogas technology into an everyday farming practice. The disadvantage is the total reliance on the guaranteed electricity price. Without it, the economics of the digesters would not be acceptable. The heat supplied has until now not been utilised efficiently, due to the focus and economic significance of the electricity. The new drive encompasses incentives in the form of a higher guaranteed electricity price if the heat supplied is more effectively utilised[31, 47].

In Sweden, the concept of farm-scale digestion has for a long time been focused on slurry digestion of cow and pig manure[143]. The main reason for not digesting other agricultural feedstocks is mainly economical. The manure comes free of charge and gains a higher fertilisation value through the enhanced mineralisation of nutrients brought about by the anaerobic treatment, with a maintenance requirement of only two hours a week[142]. In addition, odour emission during spreading will be smaller[36]. Energy carriers such as heat and electricity are supplied at a known price for a very long period of time. Another important reason is technical: the conventional stirred slurry digester works very well with this type of liquid substrate. Still, the implementation of anaerobic manure treatment on farm-scale is more of a curiosity in Sweden. The profit margins are small, since no specific benefits are available for farm-scale facilities (**Paper V**), thus leading to a situation where the market actors are either unwilling to spend time and money to make things happen or completely ignorant about the possibility, since so little information is available. In addition, Swedish legislation regarding manure handling is not as strict as in Denmark, and the extent of animal rearing is not as intensive in Sweden. A recent Swedish study of co-generation of heat and electrical power on farm-scale from manure-derived biogas showed that the extent of utilisation of the heat supplied is the major factor governing whether the installation of a biogas plant is economically favourable or not[142].

Currently, approximately one farm-scale facility is built per year in Sweden[143]. The reasons for investing is stated as being associated to issues of energy and nutrient management. Organic farming is a common denominator among these prime movers of Swedish farm-scale digestion. Not only manure, but also ley crops are of interest for these farmers[143]. However, the use of other agricultural feedstocks than liquid manure in slurry digestion may prove difficult; straw-rich horse manure and ley crops have been shown to lead to problems associated with crust formation, which cannot be overcome by the stirrer without great effort[47, 144]. However, successful development and refinement of pre-treatment and feeding technologies is ongoing in Germany due to the increased demand from farmers who digest energy crops such as fodder maize.

5.3 Methods of biogas conversion and market value of the energy carriers produced

The energy of the biogas can be converted and utilised in a number of different ways. All the methods discussed below aim to utilise the energy content of the methane by converting it into other energy carriers such as heat and electricity, or by merely enriching the methane content of the gas, by the removal of the other constituents of the biogas, essentially the moisture, the hydrogen sulphide and, above all, the carbon dioxide. From an economical point of view, the method of conversion that maximises the profits should be chosen. From socio-economic and environmental perspectives, the choice is more debatable. Higher profitability of the end product almost invariably causes higher investment costs. From a farm-scale point of view, it is important to keep costs down, especially investment costs. Capital-intensive applications often have a higher degree of scale-sensitivity, narrowing the range of scale that is economically acceptable on farm-scale by increasing the minimum size that is financially feasible. Unless stated otherwise, all prices given below are excluding value-added tax (VAT) but include other regulatory taxes.

Combustion of the biogas is the least costly form of conversion, with regard to both investment and operational costs, and the value of the supplied heat is potentially the lowest. Purification of the gas is restricted to partial water removal, which occurs spontaneously when the gas cools down and the formed condensate collects in the water traps of the gas pipe system. High levels of hydrogen sulphide must be reduced in order to avoid excessive corrosion, but with regard to plant biomass this is rarely necessary, since the sulphur content of crops is so low. Regulatory taxes increase the price of heat in Sweden considerably if the energy carrier is of fossil origin. However, farmers are exempt from these taxes or they are markedly reduced. The average retail price for district heating in Sweden in 2003 was 5.5 €ct/kWh[145], but this kind of heating is rarely available to farmers. In a normal oil-fuelled boiler (with 90% efficiency) heat can be supplied at an operational cost of 10.4 (including VAT) and 5.3 €ct/kWh (excluding energy tax (100%) and carbon dioxide tax (79%)) for the household and farming use, respectively[146, 147]. Electrically heated boilers may supply heat at an operational cost of 10.6 (including VAT) and 5.8 €ct/kWh (energy tax reduced to 0.06 €ct/kWh) for the farmer's household and occupational use, respectively[142]. A grain-fuelled furnace can supply heat at a total cost of 4.9 €ct/kWh (90% efficiency, 6% real interest rate)[148].

Combined heat and power processes (CHP) involve the simultaneous generation of both heat and electrical power. Combustion of biogas in a water-cooled gas engine, gas turbine or Stirling engine leads to efficiencies that can be higher than 90%[149]. If the condensation heat of the water produced during reaction is also trapped, the heat yield may increase to levels above 100%[150], when using the lower heat value. The electricity efficiency of CHPs suitable on farm-scale lies in the range of 0.25-0.35[142] for the above mentioned systems. Farm-scale, dual-fuel diesel engines have yields as high as 0.34, while comparable single-fuel systems have a yield of 0.30 but with twice the investment cost[151]. In the dual-fuel engines 10% of the fuel is diesel, used for ignition purposes[142, 152]. Dual-fuel engines are very common in Germany, where the electricity brings a very high profit, while the heat is regarded as a by-product, which can never be fully utilised. Even with less advantageous bonus systems, such as the Swedish system of green electricity certificates, the value of the supplied electricity is much higher than that of heat. A special circumstance of the Swedish system is that the bonus applies to all renewable electricity generated, irrespective of the source/final customer. In Germany, only the production funnelled to the grid is entitled to the bonus. Since internal use of generated electricity is free of tax in Sweden, the value of this electricity is 5.9 €ct/kWh, excluding the bonus (2.6 €ct/kWh). Selling the electricity to the grid brings in 3.7 €ct/kWh, excluding the bonus[142].

The third and most advanced technology involves upgrading the quality of the energy carrier methane, by removing as much of the other constituents of the biogas as possible. A number of technologies are available, based on different principles of selective removal. In many of these processes water or hydrogen sulphide interfere with the process, requiring a preceding removal step for the optimal performance of the process. Three of the most common purification techniques are described below[153].

- Pressure swing adsorption (PSA) utilises the physical adsorption of carbon dioxide under high pressure to solid carriers such as zeolites. Regeneration through the release of the carbon dioxide and the subsequent recovery of the smaller amounts of methane adsorbed take place when the pressure is lowered, finally close to vacuum. A certain amount of methane is always lost in the process.

- In water or Selexol™ scrubbing the carbon dioxide is selectively absorbed in the liquid. If pressure is applied, more methane dissolves in the liquid, requiring a methane recovery step. Selexol is the brand name of a water solution of di-ethyl ether derivates of poly ethylene glycol, another common brand is Genosorb™. These solutions absorb three times as much carbon dioxide as compared to water. A certain amount of methane is always lost in the process.
- Certain liquid chemicals, such as ethyl amines, react selectively with the carbon dioxide. Regeneration is performed by heating the liquid with steam, and the carbon dioxide is released as gas. The selectivity and the efficiency of the process are very high, but the heat supplied must be recovered profitably in order for the process to be financially viable.

There are two Swedish standards for gaseous vehicle fuels, one for engines not equipped with lambda regulation, and one for engines equipped with it[153]. Lambda regulation allows a wider range of methane content, 95-99% by volume, while no regulation requires a more narrower range, 96-98%. In Sweden, the highest retail price of compressed natural gas/biogas (CNG/CBG) in July 2005 was 9.3 €ct/kWh, if one calculates with a methane content of 97%[154]. The average retail price of petrol in May 2005 was 10.5 €ct/kWh[155]. Prices can vary locally, but the trend for vehicle fuel prices in general is upwards; the rise in fossil fuel prices allowing the price of gaseous fuels to follow. Farmer use mainly diesel, buying it in bulk at a lower price than the retail price, which might be as high as 10.7 €ct/kWh[154]. The diesel used in farm machinery, such as harvesters, is exempt from 77% of the carbon dioxide tax[146], making the price much lower than that for trucks and passenger vehicles, 5.7 and 8.0 €ct/kWh, respectively[155].

Distribution of the upgraded biogas is a problem, if it is not possible to sell it as a vehicle fuel directly at the site of production. An efficient distribution alternative is to inject the upgraded biogas into the natural gas grid, as is presently done by a few Swedish facilities[156]. Injection requires a lower degree of compression than that used for gas at the filling stations. The gas grid owners require that the energy value of the gas be increased by the addition of propane to accept the biogas.

5.4 Economical feasibility of farm-scale anaerobic digestion of plant biomass under Swedish conditions

One way of ensuring the financial viability of farm-scale digestion of agricultural crop residues and energy crops is the introduction of new reactor designs that are less expensive than currently available ones, and with as low as possible maintenance requirements, allowing operation to be managed by the farmer alone. In southern Sweden the Agrigas project[54, 115, 157] has been working with agricultural crop residues, mostly sugar beet leaves, wheat straw and ley crops, since the year 2000. Within the project, managed by the Department of Biotechnology at Lund University, a variety of different reactor systems have been tested on pilot-scale, with the aim of developing and introducing new farm-scale reactor concepts. One important objective is to test the performance of different high-solids reactor designs, and compare them with the performance of conventional slurry digestion. Two theoretical studies, based on pilot-scale experiences, have been carried out to explore the economical feasibility of farm-scale anaerobic digestion of plant biomass under Swedish conditions. The first compared three different reactor designs (**Paper III**), while the second compared different scales and substrate mixtures for the best performing candidate in the first study (**Paper IV**). Experimental data both from laboratory- and pilot-scale studies, together with operational observations of pilot-scale trials, represent the basis for the full-scale calculations conducted in both the studies. The methane in the biogas is converted in any of three different ways: as ordinary heat (H), as combined heat and electrical power (CHP), or as upgraded vehicle fuel (VF). Full utilisation of the products is assumed.

An important requirement for the successful implementation of anaerobic digestion on farm-scale is to keep the costs down. It is thus important to identify the main categories of costs, and the extent to which it is possible to reduce them. Operational costs may be categorised as the costs pertaining to labour, substrate, digestate, maintenance, heating and handling. The category *labour* is defined in these two studies as all the work that is related to the running of the anaerobic digestion facility. Labour costs depend on how the farmers value their own work; cost analysis shows that conventional farming would not be economical if farmers did not put the value their own work very low[158]. In the calculations that follows the reference case cost of labour was set in the medium range (€22/h), which is somewhat lower than the current average level of income. Lower values have also been reported (€16/h[47]).

Substrate costs include the total cost of harvesting, transportation and storage. The cost of wheat straw and sugar beet tops is €44.4/ton (dry weight). The cost of wheat straw is in reality probably lower, but for the sake of simplicity it has been set at the same value as the cost of sugar beet tops[159]. The ley crops cost is higher, €55.5/ton (dry weight)[49]. The cost of sowing and tending the crop is not included, since the aim of the studies is to examine the effect of introducing anaerobic digestion on an organic farm growing ley crops for green manuring purposes. Investment costs for storage facilities may be excluded or included. The assumption is that the model farm recently converted from conventional cattle rearing (dairy or beef) to organic crop farming, making it possible to exclude investment costs as facilities were already in place, such as bunker silos and liquid manure tanks. At higher scales, such as in the case of the 201 kW scenario (**Paper IV**), investment costs for these two types of facility were included to cover the extended storage needs, adding approximately 100, 60 and 30% to the total investment cost of the H, CHP and VF biogas conversion alternative, respectively. It will probably not be possible to decrease the substrate cost further, with the exception of the wheat straw cost, since the estimates are based on an optimised substrate handling chain.

It is assumed that spreading of solid and liquid fractions of *digestate* is contracted out, solids spreading being three times more costly than the liquid spreading (wet ton basis). The costs can be considered to be optimised. *Maintenance* costs include all aspects of maintenance, and are calculated as a percentage of the cost of machinery, here chosen to be 5%. A more conservative estimate would have yielded a higher figure, for example 10%. *Heating* of the reactor is either supplied by auxiliary heating (grain-fuelled furnace) or by combustion of the produced biogas in a furnace or an engine. The choice should be based on cost efficiency. In the first study (**Paper III**) auxiliary heating was employed, while in the second study (P**aper IV**) biogas incineration was assumed to cover the heating needs of the process. The category of *handling* incorporates all non-labour costs associated with running the anaerobic digestion facility, such as electricity, transport and sometimes contracted work (container hauling). These costs are related to the choice of reactor and biogas conversion technology.

Investment costs can be divided into machinery and reactor costs, the latter including buildings and all non-machinery equipment. The real interest rate was set at 4%, and the depreciation periods were 10 and 20 years, for machines and reactors, respectively. The yearly cost was calculated as an annuity. As was discussed in Section 5.2, the costs of machinery and other auxiliaries seem to be more strongly affected by scaling than the reactor cost. In addition, the operational costs, apart from the chosen value of the labour, are difficult to minimise further without increasing the scale. The best way to improve the financial viability of farm-scale anaerobic digestion, especially in the lower part of the range defined (50-100 kW), is thus to construct and build very inexpensive reactors.

Regarding biogas conversion, the investment cost of the heat (H) alternative of the studies was not considered as an optional auxiliary for the other two conversion alternatives, a gas furnace was thus included as a reactor auxiliary in all the different scenarios. The combined heat and electrical power (CHP) investment costs are scaled to fit the methane production, assuming an average utilisation rate of 95%. In contrast, the vehicle fuel upgrading (VF) investment costs are fixed, irrespective of the methane production. A small-scale recirculating water scrubber that is still under development was used in the calculations on two scales (51 and 67 kW)[160]. The maximum treatment capacity is 12 m^3 biogas/h, corresponding to 71 kW (60% methane). The company speculated that it may be possible to triple the capacity (36 m^3 biogas/h, 212 kW) while only doubling the investment costs. This, together with an assumed decrease in the electricity requirement for the purification process (from the original 0.106 $kWh_{el}/kWh_{methane}$ to 0.100) was used to calculate the VF upgrading costs of the 201 kW scenario (**Paper IV**). It was later found that the estimates were too optimistic, and the company said that a much smaller scale saving should be expected. This has been taken into consideration in the results presented below, a VF investment cost of the 201 kW scenario of €333,000 instead of the original €250,000.

Besides the electricity, the nitrogen content of the digestate has also been assigned a value, which in the reference case was set at 1.8€/kg[49, 130, 161], This value is twice as high as the value of conventional mineral-based nitrogen[162], which reflects the higher value of organic fertilisers. The amount of recycled nitrogen was calculated by subtraction, in the form of the calculated net contribution of recycled total ammonia nitrogen ($TAN_{recycled,net}$). This was defined as the net benefit of implementing removal and anaerobic treatment of ley crops and sugar beet tops compared with traditional green manuring. For a detailed description of the calculations and assumptions, see **Paper III**.

5.4.1 Comparison of different reactor designs

Reactor designs were compared in the first study (**Paper III**) to investigate the cost-efficiency of high-solids, farm-scale reactors. The reactor investment costs and the overall running costs of two high-solids, anaerobic digestion technologies, batchwise two-stage digestion (2-SD) and fed-batch single-stage digestion (1-SD), were compared with those of conventional slurry digestion (CSD) in set-ups that were simplified so as to increase the economic feasibility of farm-scale operation. The scale was approximately 50 kW. Substrates were assumed to be an ensiled mixture of wheat straw and sugar beet tops, 7:93, wet weight. The sugar beet tops, treated in a 35 °C process involving full liquid recirculation, corresponded to full utilisation of the sugar beet tops from a 150 ha model farm in southern Sweden. All of the ley crops produced and most of the wheat straw were assumed to be disposed of as green manuring. The 1-SD reactor design is a vertical modification of the horisontal column type single-stage stratified bed digester described in Section 4.3-4.5.

In Fig. 3, the three farm-scale reactor designs are depicted in varying degrees of detail. In **Paper III**, a commercial turnkey facility was chosen for the 2-SD design[163]. It consists of eight separate reactor cells, each consisting of a modified 20-foot container. Seven of these are for treatment of the substrate, while the eighth one serves as a methanogenic stage. The roof consists of an easily removable lid that makes it easy to fill and empty the cells by employing a hook lift mounted on a truck. The SRT was 40 d. The 1-SD reactor is also module-based but, since it is not a commercially available design, the buyer is assumed to do much of the construction. The average SRT was 27 d. Building the CSD reactor requires both contracting and a great deal of the farmer's own work. The reactor is based on the use of prefabricated wall elements[164]. Dewatering and reuse of the leachate which is produced reduces the liquid storage compartment and water processing needs. The HRT was 20 d.

The main result of the first study was that the 1-SD design was the most competitive of the three designs tested. The reference unit costs of the CSD design was at the most 20% higher than those of the 1-SD design, but the process problems inherent in its high water content remain as a serious doubt. Scaling up is also more problematic, since stirring will obviously need to be more powerful and sophisticated than that offered by the directable cutting pump used. Although the 1-SD design has not yet been tested on full-scale, uncertainties regarding its volumetric capacity do not appear to affect its economic performance appreciably[165]. Buying a third module, effectively increasing the reactor volume by 50%, would only increase the annuity of the investment costs by 5-12%. In any case, the results show the great importance of keeping the investment costs of reactors as low as possible. The poorer economy of the 2-SD design can mainly be

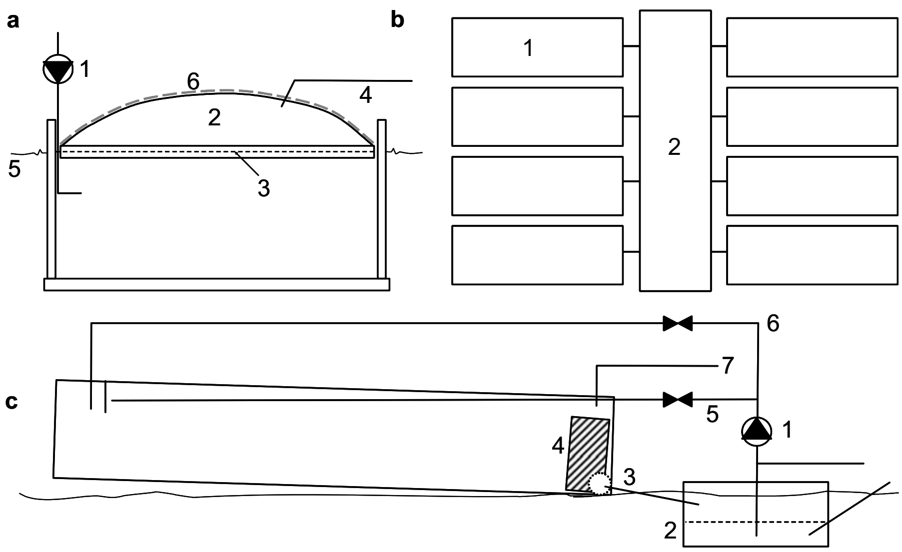

Fig. 3 The three farm-scale reactor designs. (a) Side-view cross-section of the slurry reactor. (1) Pump; (2) Floating gas lid; (3) Liquid level; (4) Gas outlet; (5) Ground level; (6) Rubber top of lid insulated with foamed PE. (b) Top-view of the 2-SD design, basic outline. (1) 20-foot container reactor module; (2) 40-foot container housing auxiliary equipment. (C) Side-view cross-section of one of two modules (40-foot containers) of the 1-SD design. (1) Pump; (2) Reservoir; (3) Drainage; (4) Straw filter; 5) Leachate recycling inlet; (6) Feed slurry inlet; (7) Gas outlet.

attributed to its lower methane yield and its higher operating and reactor investment costs. Nevertheless, even the lowest reference case unit costs of the energy carriers supplied were higher than or similar to the prices of commercially available alternatives. A sensitivity analysis was also carried out, showing that changes in the degree of utilisation of the biogas, methane yield and the operational costs caused the highest changes, in a decreasing order of sensitivity.

5.4.2 Effects of scale-up, substrate choice and degree of utilisation

The second study (**Paper IV**) was based on the results of the first study. First, the availability of the process was increased from 300 to 350 d/yr. Using the 67 kW scenario the benefits of a higher methane yield and a higher nitrogen content of the substrate digested were explored, by completely replacing the wheat straw in the 51 kW scenario with ley crops. The 201 kW scenario was used to investigate the benefits of scaling up the reactor set-up and the biogas upgrading unit, but also incorporated the effect of a moderate increase in the methane yield and nitrogen

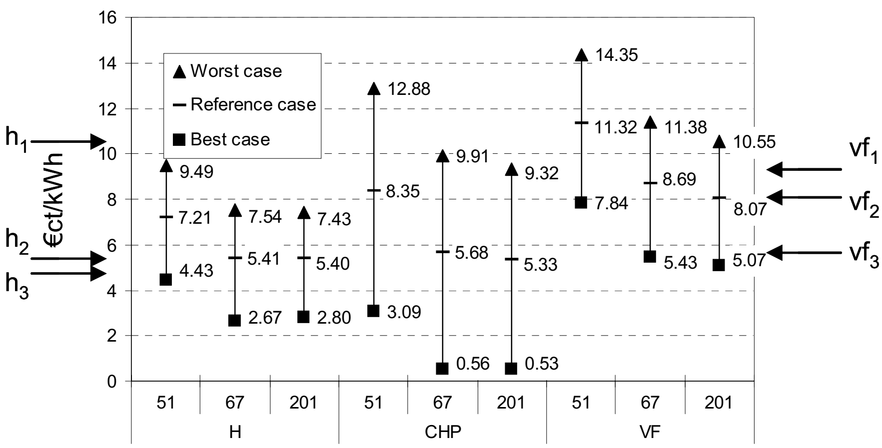

Fig. 4. Reference case unit costs obtained in the second study (**Paper IV**). The bars represent the accumulated effects of a sensitivity analysis, presented as a worst and a best case. The effect of the increased investment cost of the VF equipment in the 201 kW scenario can be seen by comparing this figure with Fig. 3 in **Paper IV**. The cost of commercially available energy carriers are indicated on the sides of the graph. Heat (left side): h_1=oil, household use; h_2=oil, subsidised; h_3=grain. Vehicle fuel (right side): vf_1=CNG/CBG; vf_2=diesel; vf_3=diesel,subsidised.

content, by replacing some of the wheat straw with ley crops. In both the 67 and 201 kW scenarios the degree of utilisation of the biogas upgrading equipment were increased compared to the one of the 51 kW scenario.

The results, in the form of unit cost of the heat or upgraded methane supplied, are shown in Fig. 4. The bars represent the unit cost of the accumulated effects of a sensitivity analysis, presented as the worst and best case. The unit cost was calculated by subtracting the indirect profits from the total cost, and then normalising the resulting net costs by dividing by the total amount of energy carrier supplied.

Since several parameters were changed at the same time between the different scenarios, the results must be interpreted with care. Attention was given to the following three parameters: the replacement of wheat straw with ley crops, the relative importance of investment costs, and the degree of utilisation of the VF equipment.

Regarding scenarios assuming the H and CHP biogas conversion alternatives, the considerable improvement between the 51 and 67 kW scenario implies that replacing wheat straw with ley crops improves the economy, by increasing the methane yield and the amount of nitrogen recycled. The higher substrate costs and labour cost were not high enough to counteract the improvement. The higher degree of VS degradation in the 67 kW scenario makes it possible to use the same reactor system, although the loading rate is somewhat higher than in the 51 kW scenario (see Table 3 in **Paper IV** for values). No other parameters were changed. Regarding the 201 kW scenario, the investments increased considerably due to the extra storage needs. The increase in the investment cost annuity is almost twice as high in the H conversion alternative, while it is approximately 50% higher in the CHP conversion alternative. In addition, the wheat straw is not completely replaced by ley crops, giving an intermediate value of the methane yield compared with the other two scenarios. All in all, these negative factors counteract the positive scale effects in the 201kW/H combination; the reference unit cost being the same as that of the 67kW/H combination. The decrease in the specific investment, maintenance and operation costs of the CHP conversion alternative leads to a more significant scale effect in the 201kW/CHP combination (see Table 1, **Paper IV**), thus lowering its unit cost compared with the 67kW/CHP combination.

Regarding the VF scenarios, the same reasoning as for the CHP alternative can be applied, with the additional effect of the increased degree of utilisation of the VF equipment in the 67 and 201 kW scenarios. The unit cost of the vehicle fuel upgrading is 4.55, 3.60 and 3.00 €ct/kWh for the 51, 67 and 201 kW scenarios, respectively. The first improvement in the unit cost can be derived from the increased utilisation of the VF upgrading equipment, the degree of utilisation in the 51 kW scenario being only 64%; the second gain is scale-dependent, the specific investment, maintenance and operational costs being lower for the scaled-up VF equipment in the 201 kW scenario. The degree of utilisation of the VF equipment is the same as in the 67 kW scenario, 86%. The difference between this actual VF availability and the estimated availability of 95% is the result of the internal use of biogas for heating the reactor. At 95% availability the VF unit cost would become somewhat lower, 3.39 and 2.87 €ct/kWh for the 71 and 212 kW VF equipment, respectively. With respect to investment requirements, it is interesting to see how much lower the reference case unit cost would have been with the originally lower price of the VF upgrading unit: 7.54 €ct/kWh (see Fig. 3, **Paper IV**). The effect of completely replacing all wheat straw with ley crops in the 201 kW scenarios is that the 10% increase in methane yield only leads to a decrease of approximately 3-4% in the unit cost. The conclusion is that the addition of small amounts of wheat straw do not endanger the financial viability to any significant degree. The addition of wheat straw affords structure to the digested bed, improving contact between the solids and the recycled leachate.

There is considerable uncertainty about the pricing and recycling rate of the total ammoniacal nitrogen supplied. If the higher estimates are correct, the economic impact is far from insignificant. The highest indirect profit for each conversion technique range from 2.1 to 3.7 €ct/kWh. In addition, if the increase in crop yield and crop protein content are borne in mind, higher revenues can be expected. On-going field trials indicate that a 100 ha farm with a five-year crop rotation could increase its profits by €9,200/yr by implementing anaerobic treatment of the ley crops and sugar beet tops, instead of ploughing them in as green manure[43]. The buyer of the German turn-key reactor referred to in Section 5.2 is an organic farmer, and this aspect is just as important for him as the generation of energy[144].

5.4.3 Financial prospects of farm-scale, high-solids digestion

The commercial values of different energy carriers, as discussed previously in Section 5.3, are given in the graph in Fig. 4. The reference unit costs of the study compare quite favourably, in most cases, with the exception of the subsidised diesel. A likely scenario in this case is that the farmer would continue to use diesel in his own vehicles, and try to sell the upgraded biogas at the market price. The price indicated is the highest reported in Sweden, and selling at a profit is possible down to the price of diesel bought in bulk. With optimisation of the process and cost reductions, the profit margin could be further increased. Using biogas to meet the process heating needs is uneconomical in the reference case for all three biogas conversion alternatives.

As the best case indicates, the heat unit costs in the CHP alternative in the 67 and 201 kW scenarios have the potential to be significantly lower than the unit costs in the H alternatives. With even better economical performance, the indirect profits may actually become higher than the total costs, effectively making the heat production free. The break-even point for the reference case of the 201 kW/CHP combination is an electricity price of 18.6 €ct/kWh. This explains why German farmers are able to maintain a good economy without full utilisation of the surplus heat. From a practical standpoint, the CHP alternative is thus probably the most attractive conversion alternative under current Swedish conditions, not only because it delivers electricity at a predictable price, and possibly in the future a lower price than commercial sources, but also because the lower amount of heat supplied facilitates its utilisation. The electricity can be fully utilised by selling the surplus to the grid.

The sensitivity analyses of both studies show that full utilisation of the energy carriers produced is the most vital factor for the financial feasibility of the process (data not shown for the first study). A 20% decrease results in a 25% increase in the unit costs. If the electricity conversion is assumed to be affected to the same extent, the decrease is even further exacerbated; the CHP_{heat} unit cost increasing by 36-41%. The conclusion is thus that full utilisation of both equipment and products is essential for the sound economics of farm-scale anaerobic digestion. The second most sensitive parameter is the operational cost, which dominates the costs in all nine combinations studied; the share of the operational costs ranging from 80-60% (**Paper IV**).

The first study (**Paper III**) revealed another factor important for success: volumetrically efficient and well-performing reactors, which are still inexpensive. The simple batch operation of the competitively priced 2-SD system saves money in terms of labour and machine investments, but this is offset by its lower yield of methane and its higher operating and reactor costs, through a larger volume being needed to accommodate the bulky untreated substrate and the construction as a whole being more expensive. The CSD design has the least expensive reactor, but greater electricity and labour requirements. Together with higher machine and heating costs, this makes it less competitive than the 1-SD design. In Table 2 the cost-efficiencies of the five reactor set-ups investigated employing the H biogas conversion alternative are compared with the two earlier discussed slurry digester set-ups. The table shows how the 1-SD investment costs are lower than or equal to the earlier discussed German turn-key facility, from a volumetric standpoint. The increased volumetric efficiency of high-solids digestion is made clear when the investment costs are normalised with respect to the power output.

Table 2. Comparison of cost efficiency.

Reactor type	1-SD[a]	CSD[a]	2-SD[a]	1-SD[b]	1-SD[b]	1-SD[b,c]	CSD[d]	CSD[e]
Total volume (m^3)	150	199	319	150	449	449	500	590
Power output (kW)	51.1	51.1	47.4	67.1	201.3	201.3	111.1	-
Reactor cost (€/m^3)	149	115	335	149	149	149	-	557
Investment costs (€/m^3)	456	381	458	456	696	352	444	756
Investment costs (€/kW)	1332	1478	3080	1015	1551	785	2000	-

[a]**Paper III**; [b]**Paper IV**; [c]Excluding extra storage investments; [d][47]; [e][142]

5.5 Biogas potential vs. degree of biogas utilisation

Full utilisation of the biogas potential on a national level is not possible without the implementation of economically viable anaerobic digestion on a lower, decentralised scale, such as farm-scale digestion. However, it is difficult to find uses for all the energy produced on the farm-scale, in particular heat. Biogas production is economically optimised when the operation is run year-round, but the need for heat peaks in the winter and during harvest periods, when certain crops need to be dried, while it is very low in the summer[142].

5.5.1 Vehicle fuel utilisation – possible solutions to current barriers

The situation is the same regarding vehicle fuel: The fuel is produced continuously, but the demand on the farm is highest in the spring and in the autumn, when work in the fields is most intense. Selling gaseous vehicle fuel on such a small scale is difficult as there is no widely available distribution system. As a consequence of this, the number of potential customers in the form of biogas vehicle owners is often low, especially in the countryside. This is a problem of the small market: few buyers, few sellers. As there are no biogas filling stations, there is no incentive for buyers. But if there are no biogas car owners, there is no incentive for the filling stations. An option that has been discussed is to "jump-start" the market by opening biogas filling stations in areas far away from biogas production, and to distribute the biogas to the stations by truck[166]. The problem is that this requires high investments, with very small and risky initial profits. The question is whether the state would consider it worthwhile and cost-efficient to subsidise such an expansion. At any rate, it would certainly open up the market for farm-scale digestion, at least at the higher end of the range (200-500 kW), due to the benefits of scale in the currently available biogas upgrading equipment. The approximate optimum unit cost of a 75 m^3 biogas/h recirculating water scrubber put into service in 2000 was found to be 2.1 €ct/kWh, while two larger units brought into service in 2000 had optimum costs of approximately 1 €ct/kWh[153]. A 6% real interest rate and an electricity price of 5.6 €ct/kWh was assumed in all cases. The development and introduction of less scale-sensitive and cost-efficient biogas upgrading techniques would increase the incentive for the expansion and more even distribution of biogas production and consumption.

A promising small-scale upgrading technique is enzymatically assisted recirculating water scrubbing at atmospheric pressure. Laboratory-scale batch tests have verified the original hypothesis that the enzyme speeds up the transfer of gaseous carbon dioxide to the water phase, but work remains to be done on the production of the enzyme in a bacterial host and laboratory-scale optimisation[167]. Current gas scrubbing technology often employs high pressures to remove the carbon dioxide, and this requires expensive technical equipment, and an additional methane recovery step, since some methane also dissolves at high pressure. Avoiding this expensive high-pressure equipment would significantly improve the upgrading economics.

Another promising and technically more mature technology is to strip the carbon dioxide dissolved in the process liquid by recirculating it outside the reactor against a counter-current of air. The process is called internal methane enrichment, and a recent Swedish study showed that the prospects are good, especially from an economical point of view, since the cost of such a facility is only a third of that of traditional gas upgrading equipment[168]. The drawback is that all the methane in the recirculated sludge is lost, making it difficult to achieve high concentrations of methane in the biogas without risking quite large losses in the outgoing air. Pilot-scale trials achieved 87% methane, contaminated with 2% nitrogen at a loss rate of 8%. Nonetheless, modelling shows that it should be possible to attain a 95% methane content while keeping the losses below 2%, even with sludge. Thus, the lower limit of one of the two Swedish standards for biogas for vehicle fuel use could be attained. If the methane content of the process liquid varies with its particulate and microbial content, it may very well be that air-stripping of the leachates resulting from high-solids digestion will lead to higher levels of methane enrichment without risking too high methane losses.

However, it is actually possible to run Otto gas engines at lower methane contents[169]. The reason why lower methane contents can be used is that the carbon dioxide in the biogas can be regarded as exhaust gas recirculation. However, the higher heat capacity of carbon dioxide makes operational control more difficult, and the effect on the levels of NO_x emissions remains to be investigated. It is also vital that the methane content and the carbon dioxide contents in the gas are known. The gas only needs to be dried and particles removed to be acceptable. The content of hydrogen sulphide does not cause corrosive damage inside the engine[169]. Nevertheless, the life expectancy of the exhaust system will probably be reduced by the sulphur compounds in the exhaust, and these compounds also add to particle emissions. The lower energy density of the biogas fuel tank is the main reason why this alternative has not been investigated further. However, the short distance between the fields and a biogas filling station at the farm would reduce the disadvantage of having to fill up the tank more frequently, making it possible for the farmer to use the biogas in his machinery. Conversion of diesel engines to the dual-fuel type engines mentioned above is possibly less costly than converting them to pure biogas engines [191, 192]. Since the investment costs would be much lower in this case, it would be possible for the farmer to acquire a CHP facility as well, making his options for biogas conversion more adaptable to his needs.

5.5.2 Future solutions of the storage issue

The primary cause of the problems associated with full utilisation of the energy carriers produced is the lack of economically viable long-term storage solutions. Gases are voluminous by nature, and liquefaction requires high pressure and low temperatures. This is too costly and technically sophisticated to be a realistic solution. High-pressure storage is also too costly for more than short- to medium-term storage. Continuous turnover is therefore absolutely necessary with the anaerobic digestion systems of today. Inexpensive means of transportation are therefore vital. Injection into the gas grid is one option, but for smaller producers the investments required for biogas upgrading equipment and the gas grid connection may present an obstacle. Building pipelines to transport the raw, untreated biogas to a centralised large-scale upgrading unit may be worth considering. The Swedish gas grid is still being developed, and currently runs only from southern Sweden, along the west coast. The consumer pipelines run to more densely populated areas and heat-intensive industries. The gas grid must thus be greatly expanded if it is to be used by small-scale biogas producers. In contrast to the gas grid, the electricity grid is already in place. However, CHP electricity efficiencies are still too low to allow the full utilisation of the heat generated in farm-scale digestion plants. As discussed in Section 5.3, the electricity efficiencies for small-scale plants are in the range of 0.25-0.35.

A promising future CHP candidate with better performance is fuel cell technology[3, 170]. The technology is not scale-sensitive, and the electricity efficiencies are higher. The current obstacles to the implementation are the low cost-efficiency, and the fact the techniques yielding higher electricity outputs are operated at elevated temperatures requiring more technically sophisticated cooling systems. Also, not only the water and the hydrogen sulphide, but also the carbon dioxide in the gas must be removed since they destroy the catalyst of the fuel cell[3]. Refinement and development of the existing gas engines may be more realistic, in the form of "homogeneous engines"[171, 172]. A recently promoted solution is the conversion of the gas to liquid fuels, in the form of long-chain paraffins[4, 173, 174]. The Fischer-Tropsch process was industrialised and used on a large-scale by the Germans during the Second World War. They gasified coal to produce syngas, the main constituents being carbon oxide and hydrogen. The same operation is possible with biogas, without having to remove the carbon dioxide. The major problem associated with the process is that it produces waste heat at high temperatures, and paraffin production yields not only liquids, but also waxes, which require further refinement to be useful as fuels. The technology is rather sophisticated and capital-intensive, ruling out the possibility of farm-scale implementation, at least in the medium term.

Full utilisation of the energy value of the biogas produced in many of the disposal technologies mentioned above is prevented by the production of surplus heat. Heat in the form of hot water at normal pressure is a low-quality energy carrier in the sense that its energetic use is restricted to heating, and without proper insulation it dissipates quickly. In more densely populated areas district heating on different scales is an option. Some of the Swedish and Danish centralised co-digestion plants are suppliers of district heating[36]. However, establishing new heating schemes takes time and money, since people already have solutions to their heating needs. Newly built areas can be designed to use a centralised heating solution, and farm-scale digestion might be an option in smaller, peripheral areas where the expansion of the existing network is not cost-efficient. However, the competition from other tax-exempted biofuels, such as grain, straw and wood pellets, is stiff, and the constant production feature is to the disadvantage of biogas. Long-term storage of heat in underground aquifers would make it possible to achieve full utilisation of the heat produced by using the surplus heat generated in the summer period during the more heat-demanding winter period[175]. The investments required are still rather high, restricting the use to anaerobic digestion facilities of larger scale than farm scale.

6 The role and prospects of anaerobic digestion in the sustainable society

Cycling is the key factor in the successful implementation of the sustainable society. Microorganisms play a major role in the biogeochemical cycling of nutrients in the ecosphere. The microbially mediated shuttling of carbon between the biotic and abiotic parts of the ecosphere is central to the cycling of all nutrients[6, 20, 176]. An important role of anaerobic digestion in the sustainable society would be to solve the problem of losses and uncontrolled spreading of plant nutrients, above all the macronutrients nitrogen, phosphorus and potassium. Since organic material is degraded in the process, the nutrients are mineralised, which facilitates their uptake by growing crops when the digestate is spread on the fields as a biofertiliser. The methane production is an extra bonus, which helps balance not only the economy but also the environmental impact of the operation, by counteracting for example the extra needs of vehicle fuel and electricity. Being renewable, the energy contained in the methane fit very well into the concept of a sustainable society, if fully utilised and spent in the most optimal way. However, the largest impact would come from the lowering of the emissions of the greenhouse gases methane and nitrous oxide, standing for 60% of the total global warming potential of Swedish agriculture. Two thirds of this figure would be directly effected by the implementation of anaerobic digestion[48].

6.1 Recycling of nutrients

In the world today, the recycling of nutrients in the most energetically efficient and environmentally friendly way is not a prioritised issue, since energy costs are relatively low and environmental costs, with a few exceptions, still have no price tag at all. The broken cycle of nutrients between the densely populated cities and the crop-producing fields in the countryside is a good example[20]. Municipal solid waste is largely either landfilled or incinerated[17]. The small proportion that is biologically treated is often mixed with other household waste, making it more difficult to find a buyer for the end-product, i.e. bio-solids for use as a fertiliser, among farmers. Human urine and faeces are diluted and mixed with other waste streams, and treated together in wastewater treatment plants. In general, treatment is often restricted to decreasing the carbon content of the water, and in most parts of the world the nutrients are simply released to the sea or other waterways, ultimately leading to eutrophication. In Sweden it is common to remove as much nitrogen as possible by biological processes; the nitrogen ultimately being released as inert nitrogen gas. Nevertheless, around 40% of the nitrogen reaching the treatment plant is released in the treated water. Phosphorus is contained either chemically or biologically and is mostly found in the solid remnant of the treatment, in the form of sludge, where 10% of the nitrogen is also immobilised. The sludge, although anaerobically stabilised, is difficult to dispose of as a fertiliser due to its mixed origin. In Sweden in 1999 one third of this sludge was recycled as a fertiliser in agriculture[177]. Wastewater treatment is very costly, with estimates of nitrogen (and phosphorus) removal costs ranging from €8-20 /kg N[178, 179].

The end-result of this broken cycle is that the nutrients either accumulate in the wrong part of the ecosphere, or are returned at great effort to the abiotic part of the ecosphere. These nutrient losses would not have been sustainable without a constant transfer of nutrients from the abiotic to the biotic part of the ecosphere. Anthropogenic transfer of phosphorus originates from mining of minerals. Estimates show that at the current rate of consumption, cheap reserves in USA will be depleted within about 30 years[180]. Fertilisation with mineral-based nitrogen, fixed from the nitrogen in the air in a very energy-intensive process, has increased in Sweden from below 20 kg/ha in the 1940s to current levels of 80 kg/ha[177]. On a global scale, the fixation rate of nitrogen has doubled since the pre-industrial era[181-183]. If the organic materials were source-sorted and anaerobically digested, it would be possible to return a higher proportion of the plant nutrients removed from the fields in the form of foodstuffs, thus closing the broken cycle of nutrients between agriculture and consumers[20, 37]. Ultimately, such a recycling scheme would enable a radical decrease in the requirement for mineral-based fertilisation, enabling a net decrease in the global fixation rate of nitrogen and simultaneously reducing the eutrophication of seas, lakes and rivers.

Nutrient losses also occur in the fields. The monocultures of modern agriculture are actually rather unnatural. The soil lays bare and uncultured under periods of high precipitation, and they are efficiently drained by underground piping. Crop residues left in the field and animal manure spread to it are degraded by a combination of aerobic and anaerobic processes, depending on the soil type, weather conditions and the delay before the soil improvers are ploughed in. Agricultural soils have always lost nutrients to the air and water, and these total losses were not substantially lower in older times. Nevertheless, the total leaching losses in Swedish agriculture in 1995 were approximately 66,800 tons N/yr, i.e. 67% higher than the figure in 1951. Approximately 40% of this leached nitrogen is retained before it reaches its ultimate recipient, the sea. Ammonia losses amount to 47,000 tons N/yr, creating local acidification and overfertilisation when it precipitates[177].

Denitrification processes are promoted by anoxic soil conditions and increased soil levels of nitrate. Both of these circumstances are more prevalent in the autumn and winter, especially in the south of Sweden, when plant uptake is very low. A minor part of the volatilised nitrogen ends up as nitrous oxide, and the rate has been shown to increase with the proportion of easily degradable carbon sources[48, 184]. Nitrous oxide has a very high global warming potential (296 times higher than carbon dioxide), and is also detrimental to the ozone layer[2, 20, 185]. Estimates of Swedish emissions range from 1-5 kg/ha[177]. A current estimate of the total emission of greenhouse gases from agriculture shows that they contribute 12% to the total global warming potential of Sweden. Nitrous oxide accounts for 40% of this figure[48]. Calculating the total balance of the nitrogen transferred to and from the fields of Sweden shows that 36% of the nitrogen is taken up and removed from the fields in the form of crops, while as much as 40-60%, depending on the amount of nitrogen retained in the soil, may be lost to air and water[177]. Another study reports nitrogen efficiencies as low as 20-30% in Europe[37].

Increased implementation of anaerobic digestion on farm-scale could alleviate this situation. The removal and subsequent anaerobic treatment of crop residues and green manure in the form of grass and clover would decrease the soil levels of nitrate during the autumn and early winter, when the potential for leaching and denitrification is at its highest[42, 46]. During digestion, the nutrients are mineralised, and are freed when the degradable part of the organic material is removed in the form of methane and carbon dioxide. The non-digestible parts, mostly lignin and lignocellulosics, remain as a solid digestate. The liquid part of the digestate, containing most of the soluble nutrients, such as nitrogen and potassium, would be spread during the spring and summer when the demand and uptake of nutrients by crops is high. The higher potential for losses of ammonia are compensated for by the lower viscosity of the digestate, as penetration of the soil is much faster[26]. Optimised spreading technology may decrease the loss of total nitrogen from the digestate to as little as 1-5%[23]. The solid part of the digestate, containing most of the phosphorus and very little of the nitrogen, would be spread during the autumn. The same advantages would be obtained with the anaerobic treatment of solid and liquid manure, avoiding the current problems of a high proportion of the ammonia in solid manure being lost during spreading. In addition, odour would be decreased.

Thus, appropriate implementation of anaerobic digestion would improve the nutrient management of farms and of society as a whole, by containing and recycling the nutrients with minimum losses. The energetically wasteful production of fertilisers could be reduced significantly, decreasing the direct environmental impact of their production. Nevertheless, a complete end to the practice of mineral-based fertilisation will be difficult to achieve, since the inevitable decrease in crop yields would cause the profit margins of many farmers to disappear. Although the importance of mineral-based fertilisers has sometimes been exaggerated, it contributes 10-30% to Swedish crop yields[177]. The most important nutrient contributing to this increase is nitrogen.

Organic crop farmers avoid the use of mineral-based fertilisers, relying instead on animal manure, other organically based fertilisers and the biological nitrogen-fixation of leguminous crops – green manuring. The yield and nitrogen content of the crops of conventional farms are usually higher than those achieved by organic crop farmers[43]. This is particularly the case for organic farmers who have no livestock, who are completely dependent on green manuring for their nitrogen management. The current practice of mulching, in which the ley mixture of grasses and clovers is cut and left in the field 2-4 times/yr before it is collected, does not seem to exploit the full nitrogen-fixation capacity of the ley. More than 80% of the nitrogen fixed in the mulched material has been shown to be leached out and re-adsorbed by the growing ley, or lost to air and water[186]. In addition, after termination of the ley in the autumn, the soil levels of mineralised nitrogen increase drastically, while the nitrogen uptake of the autumn-sown crop is simultaneously very low. Consequently, the risks of leaching are very high[46]. It has been reported that approximately one third of the nitrogen fixed above-ground could be lost by leaching during the winter[42].

Augmenting the nitrogen efficiency of green manuring by introducing a biogas process would increase the revenue of organic farmers, through increased yield and protein content of the crops[43, 47]. As a result of the removal of the cut ley crops, the levels of mineralised nitrogen in the soil would probably also become lower, reducing the degree of nitrogen leaching[42, 46]. Low soil inorganic nitrogen levels have been reported to enhance the growth of legumes such as clover, whereas grasses dominate if the soil inorganic nitrogen levels are high[198]. It is thus likely that removal of the cut material would enhance the extent of nitrogen fixation compared to leaving the material in the fields, especially in older swards[199]. In addition, it would not be necessary to terminate the ley crops on a yearly basis, since spreading the digestate of the removed material would replace the fertilising effect of traditional green manuring rotation. All in all, the specific losses of nitrogen, expressed either per ha or per kg crop produced, would be greatly reduced. Field trials showed that a 100 ha organic farm with a five-year crop rotation could increase its profits by €9,200/yr by implementing anaerobic treatment of ley crops and sugar beet tops, instead of ploughing them in as green manure[43]. In addition, cultivation of ley crops offsets the detrimental effects of monocultured cereals, such as soil packing and reduced levels of humic substances, thus restoring the productivity of the soil[158]. A final point is that the higher prices of organic crop products may actually make organic farming more profitable than conventional farming, both with and without subsidies. Without subsidies, conventional farming would show negative results if the compensation for land leasing and for the farmer's own labour costs were not reduced[158]. With the implementation of anaerobic digestion, the profits from organic farming could perhaps increase even further. This will depend on the utilisation rate and potential value of the biogas produced[43].

6.2 The role of renewable energy in the implementation of farm-scale digestion

At the beginning of this chapter, it was claimed that one of the most important contributions of anaerobic digestion in attaining the goal of a truly sustainable society is the improved nutrient management. The reason for this is simple: it is a sustainable way to control and direct all the flows of recycled nutrients in society without risking excessive losses. The energy aspect is, however, still very important. Without the potential revenue from methane as a renewable energy carrier, it would be much more difficult to convince farmers to start treating their crop residues and ley crops anaerobically. The costs of the digestion facility must be covered, and the presence of the energy carriers on the open market is an excellent instrument for the state to promote and support the wider implementation of anaerobic digestion. Despite the efforts mentioned above to decrease their magnitude, agriculture will always have effects on the environment. With full utilisation of the energy carriers produced, the total environmental influence of agriculture could be decreased, since the methane could replace fossil fuels. The environmental benefits of this renewable source of methane are maximised when it is used as vehicle fuel, under the assumption that full utilisation is reached[187]. Methane has been classified in the premium environmental class of renewable vehicle fuels – the only fuel in this category so far. Not only are the emissions low during methane combustion, but also during production. The energy and land-use efficiency are very high compared with other agriculturally derived fuels, such as rapeseed methyl ester and ethanol[188, 189]. The main drawbacks for the wider implementation of biogas as vehicle fuel are:

- the high cost of expanding the gas distribution network,
- the poorer production economy of current technology when using energy crops as raw material,
- the lack of economically viable small-scale biogas upgrading equipment and
- the high cost of vehicle engine conversion.

The cost of an Otto engine conversion lies in the range of €3,000-5,000, typically increasing the price of a standard car by 15-20%. For diesel engines in heavy trucks and buses the cost is much higher, €22,000-55,000, as production series are still small[190]. It is interesting to note that a potentially much less costly alternative is dual-fuel gas engines, where a minimum of 10% diesel is used for ignition purposes[142, 152]. In other countries, many road transport companies have converted their trucks in this fashion, in order to profit from the lower natural gas prices[191]. A Swedish pilot project has recently reported about the retrofitting of a heavy diesel vehicle[192].

The results presented in this thesis show that anaerobic digestion is indeed economically feasible, the prices paid for the energy carriers produced being approximately equal to or sometimes even lower than those of commercially available alternatives(**Paper IV**). Nevertheless, the problems of achieving full utilisation of the biogas produced year-round reduces the prospects of a viable economy, especially in farm-scale applications. As in the case of centralised co-digestion plants in Denmark, further development, scale-up and commercialisation of the farm-scale and dry digestion technology in Sweden require funding of research, demonstration plants and information, and some other type of benefit directed specifically at the end-user, in this case the farmer(**Paper V**). Organic farmers with no livestock could become prime movers, due to the additional benefit in their case of enhanced nutrient management. Fixed interest loans and investment grants would reduce the risk of trying out innovative technology in an emerging market. It has been shown that the investment costs in such a market decrease radically with an increase in the number of installations. Reductions in the investment costs of emerging technologies, such as the reactor technology and the biogas upgrading equipment, can be estimated by employing the concept of technical learning, expressed in the form of learning or teaming curves. The teaming rate expresses the constant percentage improvement in an emerging technology for each doubling of the technology's cumulative installed capacity[193]. A conservative teaming rate in this case is 5%. If the sugar beet tops in southern Sweden could be fully utilised together with ley crops according to the 67 kW scenario, 486 installations of 201 kW could be supported. Starting at 10 installations, the cost could be reduced by 25%. If a teaming rate of 10% is assumed, the investment costs would decrease 44%. The reduction in investment costs resulting from the twenty centralised co-digestion plants erected in Denmark resulted in a teaming rate of at least 12%[194, 195].

The advantages of the full-scale implementation of anaerobic digestion in general, and farm-scale digestion in particular, is that the environmental effects on our climate, air and water would be reduced, limited resources such as oil would be used less, and the biodiversity of plants and animals in the cultured landscape would be maintained, the latter as the result of the extensive introduction of organic farming[196]. The implementation of anaerobic digestion would thus contribute to fulfilling nine out of the fifteen environmental quality objectives that the Swedish parliament has decided upon, such as a reduced impact on climate, clean air and a varied agricultural landscape[38]. The Danish and German biogas programmes show that it is possible to help an emerging market to overcome the economical barriers of not yet fully optimised technology and lack of practical experience. The socio-economic gains, in terms of environmental benefits, new jobs and the creation of a new business segment with potential for export incomes, may in the future show that the subsidies were actually more like an investment.

By following the Danish and German examples, and not being afraid of trying out new technology, the Swedish state has the opportunity to proceed further along the path towards the self-appointed goal of becoming a more sustainable society[197].

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9 Populärvetenskaplig sammanfattning

Den ekologiska odlingen har mycket gemensamt med forna tiders växtodling, där mängden gödsel begränsade hur mycket åker man kunde bruka. Den förr i tiden så viktiga kossan kan dock ersättas med biogasreaktorn, som förutom gödsel och bättre miljö även ger en bonus i form av energirik biogas. Eftersom konventionell rötningsteknik inte är optimerad för jordbrukets växtrester bedrivs nu forskning på Avdelningen för Bioteknik på Lunds universitet för att få fram enkla men ändå innovativa fastbäddsreaktorer som har potential att fungera ekonomiskt på gårdsnivå.

Den mänskliga delen av världens befolkning ackumulerar avfall, både ytterst påtagligt genom växande sopberg, och mer osynligt genom växthuseffekt och föroreningar i luft och vatten. Behövs ett nytt synsätt? Borde vi som grönavågarna förespråkar ”var och en ta ansvar för vår egen skit”? Eller kan vi genom politiska styrmedel och marknadens självbevarelsedrift få fram ett högteknologiskt kretsloppssamhälle? Sanningen ligger troligen någonstans där emellan; ny teknik behövs, men inget händer utan personligt engagemang och insikten om att vi alla bidrar till och är en del av denna vår jord.

Min egen forskning inom biogasområdet drivs av denna insikt. Genom att använda halm som bo för de biogasbildande mikroberna kan jag och mina kollegor ta fram fastbäddsreaktorer som kan ta hand om jordbrukets växtrester på gårdsnivå. Syftet är att göra vårt jordklots bönder mindre beroende av konstgödsel. Den av människor styrda kvävefixeringen är lika stor som den naturliga. Genom att återföra växtnäringen till jordbruket kan denna onaturligt stora kvävefixering minskas. Det finns farhågor om att den växande mängden reaktivt kväve som vi släpper lös i jordens biosfär inte bara leder till övergödning, utan även ökad växthuseffekt.

Kväve på fel ställe = miljöbelastning

Dagens svenska lantbruk är mycket specialiserat, antingen odlar man växter, eller också håller man djur. Dessutom domineras en trakt ofta av antingen det ena eller det andra. Hur gör då ekologiska växtodlare som inte har tillgång till djurgödsel för att klara sitt gödselbehov? Jo, man odlar vart tredje till fjärde år luftkvävefixerande växter, som plöjs ner som så kallad gröngödsling på hösten. Kväve är det växtnäringsämne som begränsar skördarna mest. Ett problem är de stora kväveförlusterna: 30-60 % av det kväve som tillförs marken i form av gödsling går förlorat. Detta gäller både konventionella och ekologiska odlare. Om konstgödslingen ska upphöra måste dessa förluster minimeras. Nerplöjningen av vall eller andra skörderester leder till utsläpp av miljöstörande ämnen både till luft och vatten. Syrefria processer i jorden leder till utsläpp av växthusgaserna metan och lustgas. Under vintern växer höstgrödor långsamt, eller också lämnas åkern obrukad, så mycket av den frigjorda växtnäringen hinner sköljas ut ur jorden innan den tas upp av något växande. Följden blir övergödning av vattendrag och kustnära hav, och en försämrad kvävehushållning för lantbrukaren, oavsett om lantbruket drivs ekologiskt eller konventionellt.

Artificiella kor

Den ekologiska odlaren drabbas hårdare av kväveförlusten, på grund av svårigheterna med att hitta gödsel godkänt för ekologisk odling. Om den ekologiska odlingen ska kunna bli större i Sverige måste gödselfrågan lösas, men djurhållning är inget realistiskt alternativ för dagens specialiserade växtodlingsbönder.

Vad som skulle behövas är en artificiell ko, som under vintersäsongen kan ta hand om växtrester och vallgrödor, för att sedan framåt vårkanten leverera den färdiga gödseln. Givetvis får den här plåtkossan Rosa gärna samtidigt producera något slags mervärde utöver gödseln, så att även de konventionella odlarna blir intresserade.

Bättre miljö och fri energi som bonus!

Plåtkossan Rosa finns redan, i form av en biogasreaktor, som helt enkelt är en stor tät behållare där vi under anaeroba, det vill säga syrefria, förhållanden kan få till stånd en naturlig, mikrobiologiskt betingad nedbrytningsprocess. Vi matar den med vilket organiskt material som helst, vilket till största delen bryts ner och förgasas.

Denna rötningsprocess kan grovt delas upp i två steg. I det första bryts materialet ner till korta fettsyror som till exempel ättiksyra och smörsyra, det så kallade syrasteget. I det andra steget, kallat metansteget, bryts syrorna ner till lika delar metan och koldioxid. Det organiska material som de anaeroba mikroberna inte kan rå på blir kvar i form av en rötrest. Dessa svårnerbrytbara ämnen, som till exempel cellulosa och lignin, har jordförbättrande egenskaper. I denna rest anrikas också alla näringsämnen som till exempel kväve och fosfor i en form som är lättupptaglig för växterna.

Plåtkossan Rosa tar alltså elegant hand om vår växtodlings problem, i form av miljöfarliga utsläpp och styrning av den kvävefixerande vallens och växtresternas gödseleffekt. Som bonus får vi energirik biogas. Genom förbränning kan vi få vattenburen värme, men bäst ekonomi blir det om man kan använda biogasen som fordonsbränsle, eftersom biogas är ett skattebefriat drivmedel. Bondens traktor kan alltså bli både miljövänlig och billigare i drift!

Bonden behöver ny typ av biogasreaktor

Givetvis låter det här för bra för att vara sant. Trots att rötningen har använts i människans tjänst för rötning av avfallsprodukter ända sedan slutet av 1800-talet så domineras den fortfarande av sin ursprungliga tillämpning, vattenrening. I konventionella biogasreaktorer måste växtresterna blandas upp med vatten, eftersom rötningen sker i vätskefas. De långa transporterna till och från dessa ofta centraliserade anläggningar, plus hantering av de genom utspädning stora volymerna rötrest, gör det ofta olönsamt för bonden att röta sina växtrester.

Vad bonden behöver är en ny typ av biogasreaktor som kan behandla växtresterna som de är, så att vätskemängderna som behöver hanteras hålls nere. Utöver det måste reaktorn vara lönsam i mindre skala, så att den kan anläggas nära källan, det vill säga bondens åkrar. På så vis minskas transportkostnaderna, och bonden får möjlighet att själv sköta driften. Anläggningen måste vara billig att bygga och driva, och ha ett litet behov av tillsyn och skötsel.

Enklare reaktor möjlig vid torrötning

Ett svar på bondens krav är rötning vid en högre torrhalt, i en fast bädd utan omrörning. Bädden är uppbyggd av det växtmaterial som ska rötas, och lakvatten som ansamlas i botten pumpas då och då upp till toppen. Rundpumpningen motsvarar omrörningen i en vätskefasreaktor, och är nödvändig för att stabilisera och hålla igång rötningen. En nackdel med fastbäddsrötning är att bädden lätt sätter igen. Den försämrade vätsketransporten kan i värsta fall ”döda” reaktorn.

Den största nackdelen med rötning i fast bädd är den långsamma uppstartsperioden; upptrappningen av matningen måste dras ut över en längre tid. Orsaken står att finna i det komplicerade samspelet mellan rötningens olika nedbrytningssteg. Rötningen inleds av det första stegets syrabildning. Om materialet är lättnedbrytbart kan detta gå rätt fort, så fort att det andra stegets mikrober inte hinner med att äta upp syrorna, vilka då ansamlas. Detta är mycket lätt hänt, eftersom metanstegets mikrober växer långsammare än det första stegets. Problemet är att de höga syrakoncentrationerna och det sura pH:t inhiberar metanstegets mikrober, som trivs bäst vid pH 7–8. Mikroberna slutar producera biogas, och bädden blir sur. Reaktorn är i praktiken ”död”. Man försöker undvika detta genom att tillsätta rötslam med hög metanbildande aktivitet, och man kan också tillsätta pH-höjande ämnen som till exempel kalk. Slammet och kalken tar dock upp plats i reaktorn och kostar extra pengar, så det blir lätt olönsamt.

Halm skyddar mikroberna

I min forskning har jag för att komma runt det här prövat att börja rötningen med ett mer svårnerbrytbart växtmaterial, som till exempel halm. Rötningen går långsammare, så tillsatsen av rötslam behöver inte vara så stor, och ingen kalk behövs. Halmens inre är full av hålrum, där mikroberna helt enkelt bosätter sig och förökar sig. Därinne klarar de mycket lättare av sjunkande pH och höga syrakoncentrationer.

Bosättningsprocessen kräver 3–4 veckor utan matning, men när matningen väl börjar kan den trappas upp mycket snabbt, på grund av den rötade halmens stora kapacitet. Dessutom fungerar halmen i botten av reaktorn som ett filter, så att problemen med igensättning av bädden minskar. I artikel I och II beskrivs halmbäddsreaktorn mer ingående.

Ekonomin viktig faktor

En mycket viktig faktor för att Sveriges lantbrukare ska bli intresserade av att satsa på rötning av sin gödsel och sina växtrester är att det är ekonomiskt lönsamt. I artikel III och IV undersöktes det närmare hur stor lönsamheten för rötning av växtrester skulle kunna vara på gårdsskala för en ekologisk växtodlare som just konverterat från djurhållning. Av tre olika reaktorutformningar visade sig den ovan beskrivna reaktorn ha bäst ekonomi. Ekonomin förbättrades genom att röta kväve- och energirika material, och en uppskalning av processen var också fördelaktig, speciellt om biogasen uppgraderades till fordonsgas. En minskad avsättning av gasen visade sig vara det som kraftigast påverkade ekonomin.

Omogen marknad kräver stöd

Produktion och användning av biogas är dåligt utbyggd i Sverige i dag. Det finns en biogaspotential på 10-30 TWh som mestadels grundar sig på växtrester och energigrödor från lantbruket, men dagens produktion är bara på 1,4 TWh, och inget av den produktionen kommer från den jordbruksrelaterade biogaspotentialen. Staten har genom sin skattebefrielse av biogas bidragit till en ökad satsning på biogas som fordonsbränsle. Denna avsättning skulle för biogasproduktion i gårdsskala vara den mest lönande, men problemen med distribution av biogasen är ett stort hinder. Det är mycket svårt att få bönder att satsa på ny teknik om det inte är lönsamt för dem.

En väg runt detta kan vara att satsa på de ekologiska växtodlingsbönderna. De har ett större intresse av rötningstekniken, eftersom det kan förbättra deras kvävehushållning, och därmed förbättra deras inkomster genom ökade skördar och ökad proteinhalt i brödsäden. Bidrag till byggandet av både konventionella och mer innovativa rötningsreaktorer skulle kunna bidra till en större och mognare marknad för biogas i Sverige. I artikel V beskrivs detta närmare.