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Abstract

In various literatures, the technical potential of biogas in Sweden has been investigated, but less effort has been spent on investigating the economic potential. This study investigates the economic potential for upgraded biogas produced by anaerobic digestion with the purpose of using it as vehicle fuel. Costs that have been considered covers the investment cost for a large scale, central biogas plant, price or compensation for feedstocks used, transportation costs for the feedstocks and costs associated with hygienisation. Feedstocks included in the study are wastes from agriculture, food wastes from households, restaurants and shops, wastes from industry, sludge from sewage treatment works and energy crops. The result is divided into two scenarios; the first includes all current wastes and residues from society, while the second also includes energy crops grown on 10 percent of the Swedish arable land. The curves show that biosludge from paper and pulp industry and slaughterhouse sludge results in a negative production cost, thanks to the compensation for waste handling received by the biogas plant. Biogas produced from whey and waste milk and energy crops is the most expensive. If prices of petrol and biogas are assumed to remain constant at current levels, then upgraded biogas would have to be produced at a maximum cost of about 0.37 SEK/kWh in the best case. With such a constraint, the resulting biogas potential would correspond to a yearly production of 5.2 TWh. Since it reflects the best case scenario, the real biogas potential is probably lower, unless governmental financial support is given or regulations favouring biogas production are implemented.

Keywords: biogas, economic potential, feedstocks, vehicle fuel, upgraded.

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1 Introduction

Biogas is considered a good vehicle fuel from a sustainability perspective since it is renewable and contributes to the reduction of greenhouse gas emissions. At present, only a small amount of the personal cars in Sweden use biogas as transportation fuels. However, it has been expressed in literature (Åhman, 2010; Börjesson & Mattiasson, 2007) that biogas has a large scale future potential as an alternative to fossil vehicle fuels and companies are presently investing to realise the potential.

There are, however, several reasons to further investigate the idea of biogas as a major transportation fuel of the future in Sweden. Even though the technical potential of biogas is large, the economic potential may be smaller. The costs associated with biogas production are directly dependent on what feedstocks that are used for the production of biogas. Additionally, determining what is considered economically feasible not only depends on costs, but also on what income from selling biogas that can be expected, which in turn is linked to petrol prices.

To know the economic potential of biogas and what influences it is essential in the assessment of what support that is reasonable to provide and for the industry to know how to invest. Overestimations could result in inaccurate venturing, while underestimations could mean missed opportunities, both for society and industry.

The aim of the thesis is to draw a cost/supply curve for upgraded biogas produced by anaerobic digestion, showing how the cost depends on what feedstocks that are used, in order to make it possible to make a reasonable estimation of the economic potential for biogas for transportation in Sweden.

2 Methodology and assumptions

The types of costs, feedstocks and properties that have been taken into consideration and what assumptions that have been made about those are presented in this section.

2.1 Cost perspective

The cost assessment has been made from a large scale, central biogas plant owner perspective. That means the plant collects feedstocks from selected suppliers. Owners of farm based biogas plants uses feedstocks they themselves have produced, resulting in a different economic situation, thus the cost estimations made in this study are generally not applicable for such plants. Additionally, focus in this report is on upgraded biogas and it is rare (at least in Sweden) that farm based biogas plants upgrade their biogas since it requires considerable investments.

2.2 Investment costs

Large scale biogas plants can be divided into two types, those that mainly make use of liquid feedstocks and those that make use of more solid feedstocks (mainly household waste). Investment costs of the former type are significantly lower than for the latter type because of differences in equipment.

Svenska Renhållningsverksföreningen (2005) performed an extensive study about biogas plants in Sweden, where investment costs were investigated among other topics. In the study, both existing biogas plants as well as biogas plants not yet constructed or started where included. Answers received from large scale biogas plants about the investment costs are summarised in table 1, where R1 and R2 refers to biogas plants using liquid feedstocks and more solid feedstocks respectivelly. The investment cost include equipment and buildings for pretreatment, digestion (reactor) and storage. Upgrading facilitis are not included.

Table 1 Investment costs in relation to treated amount of feedstock at existing and planned biogas plants. (Svenska Renhållningsverksföreningen, 2005)

Type of biogas plant	Min SEK/(tonne feedstock/year)	Mean SEK/(tonne feedstock/year)	Max SEK/(tonne feedstock/year)
R1	850	1 280	1 600
R2, existing		6 000	
R2, planned	2 200	4 500	8 600

The study by Svenska Renhållningsverksföreningen (2005) also looked into the biogas yield from the considered plants in relation to the amount of feedstock used. A mean value of 80 m_n^3 CH_4/tonne feedstock was then achieved.

To allocate the investment cost to the produced biogas in a plant, these two properties together with the energy content of methane (9.81 kWh/m_n^3 CH_4) have been combined. The mean value of 1 280 SEK/(tonne feedstock/year) have been used for biogas plants of type R1, while 5 000 SEK/(tonne feedstock/year) have been used for biogas plants of type R2. This results in investment costs of 1.63 SEK/(kWh/year) and 6.37 SEK/(kWh/year) for R1 and R2 respectively.

The investment is depreciated during the lifetime of the plant resulting in an annual cost for the biogas plant. With an interest rate of 6 percent and the depreciation time set to 20 years, annuity costs have been calculated. For R1 and R2 respectively, the annuity costs allocated to the produced energy become 0.14 SEK/kWh and 0.56 SEK/kWh.

Biogas plants of type R1 mainly use liquid feedstocks but also use smaller amounts of household waste and other easily pretreated (but solid) feedstocks. R2 plants use household waste as their main feedstock and sometimes other half solid feedstocks. Thus for food waste the investment cost of an R2 type biogas plant is used, while for other feedstocks the investment cost of an R1 type biogas plant is used.

To enable the biogas to be used as a vehicle fuel, it must be upgraded, i.e. the methane and CO_2 must be separated. The most common upgrading technique is water scrubbing and the investment cost for such equipment is displayed in figure 1.

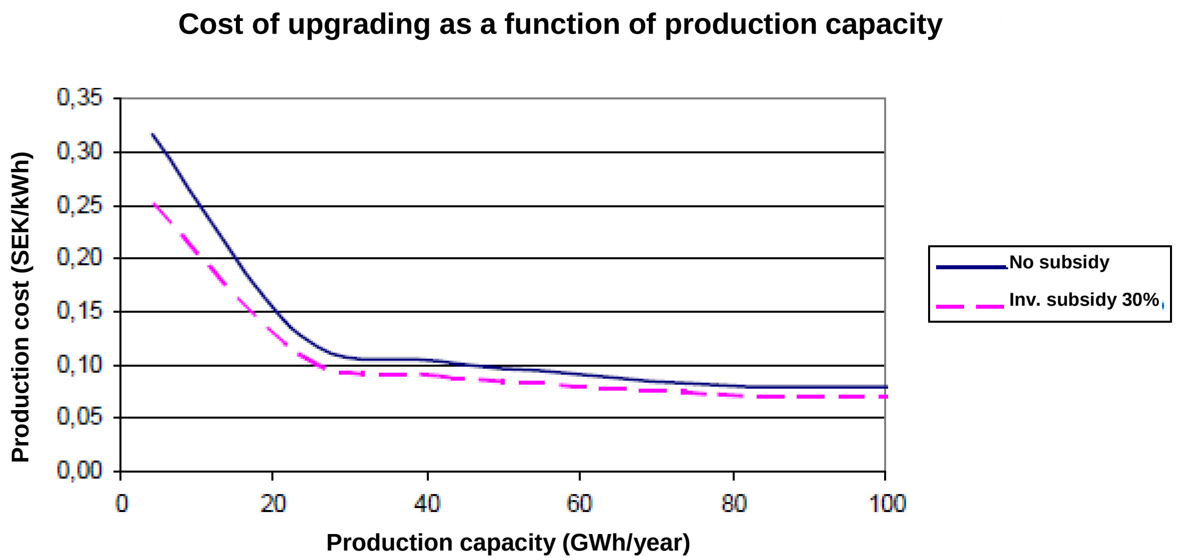

Figure 1 Costs of upgrading as a function of production capacity. (Grontmij AB, 2009)

In this study a reasonably large scale biogas is considered to have a production capacity of at least 40-50 GWh/year. Based on figure 1 an upgrading cost of 0.10 SEK/kWh is assumed for future calculations.

2.3 Feedstock properties

There is a wide range of organic feedstocks used for digestion and all of them possess different properties. This section presents properties that have been considered when calculating costs and potentials.

In this report, total mass is referred to, though data sources have sometimes stated their values in units related to mass of dry matter (DM). These values have been converted to total "wet" mass to simplify reading. A complete chart with both DM and total mass and the DM amount for each feedstock can be found in Appendix A.

Realistic availability

A lot of biomass that could be digested is produced every year, though naturally there are always losses of different kinds. The realistic availability tells the amount of feedstock that can be considered to be used for commercial biogas digestion. It is presented in mass available per year.

The latest estimation of the biogas potential in Sweden was made by Linné et al. (2008) and that report has been used as a solid basis to start from when evaluating different feedstocks. Figures about availability have been taken from it exclusively, except for the case when energy crops are included. Availability of energy crops has been taken from an older potential estimation by Linné & Ekstrandh (2006).

Average methane yield

The amount of methane that is produced from a certain amount of feedstock. Methane is measured by volume (m^3_n) and the feedstock in tonnes.

Dry matter content

Most feedstocks contain a lot of water which in itself does not contribute to the production of biogas. Since some estimations of feedstock availability have been made in mass of DM, the DM content is needed to achieve the total mass of the feedstock. It is also used to determine if a feedstock is considered liquid or solid (<12 percent is mostly considered liquid). DM content is measured in mass DM/mass, but often written in percent.

Average yield and DM content have in most cases been achieved from Carlsson & Uldal (2009). This sometimes leads to slightly different potential estimations for the feedstocks compared to those made by Linné et al. (2008), but the overall potential remains the same.

2.4 Feedstock costs

The feedstock costs have been split up into separate parts which together comprise the total cost.

Costs of transportation

The feedstocks need to be transported from wherever they are produced to the biogas plant. Liquid and solid feedstocks require different handling, implying different costs. Agreements with the feedstock provider sometimes include transportation.

The most common way of transportation is using lorries either with a platform/container (solid feedstock) or a tank (liquid feedstock). For short distances, a tractor with a wagon could also be used, but lorries get cheaper starting at a distance of about 1-2 km (Johansson & Nilsson, 2007). Another transportation solution could be the use of a pipeline for liquid feedstock. This is rather uncommon and requires high capacity and good geographical conditions to be economically feasible (Johansson & Nilsson, 2007).

In this study, it is assumed that all transportation is carried out with lorries, since the use of tractors and pipelines are uncommon. When calculating the cost of transportation for different feedstocks, the distance between the source and the biogas plant is doubled, since the lorry must go both ways (to the source and back to the plant) in order to complete the delivery.

To calculate the costs, more information is needed about the lorry, such as its capacity, how long it takes to load and unload, average speed and of course the hiring cost. Literature (Grontmij AB, 2009; Johansson & Nilsson, 2007; Linné & Ekstrandh, 2006) and a contractor[1] have been consulted, and the properties in table 2 are estimations of an "average" lorry.

Table 2 Properties of a general lorry from contractor. [a]Performed twice per load.

Type of feedstock	Type of lorry	Capacity tonne	Time to load/unload[a] hour	Average speed km/h	Hiring cost SEK/h
Liquid	Tank	35	0.5	60	800
Solid	Platform/container	40	0.6	60	675

In order to draw the cost/supply curves, another assumption about the transportation must be made. Since transport distances vary, so does the cost of the feedstock. How the transport distances vary is hard to tell, and might differ considerably between different feedstocks. It is assumed that the transportation distances vary linearly.

Price/compensation

Some feedstock are bought (e.g. energy crops), some are "borrowed" for free (e.g. manure) and some even generate income to the plant (e.g. waste). The unit used most often is SEK per tonne.

Facilities that take care of waste get economic compensation for the service, also known as gate fees. Some feedstocks have a variance in gate fees that implies bigger changes in the total cost than the variance of transportation distance. For these feedstocks, the gate fees are assumed to vary linearly, while each bearing the cost of its estimated average transportation distance.

Costs associated with gathering of feedstock

Depending on what agreements that have been made between the biogas plant and its feedstock providers, gathering the feedstock might be undertaken by the plant itself. Such actions naturally imply costs.

Hygienisation

Handling of waste with animal origin is regulated by *Animaliska biproduktförordningen* (*Animal by-product regulation*) (EG) no 1774/2002. It consists of a breakup of animal wastes into three categories; each with certain requirements on handling of the waste.

The consequence of the regulation is that some feedstocks (those with animal origin) are required to be heated to 70° C and kept at that temperature for one hour, before digestion. More information about the regulation can be found in Carlsson & Uldal (2009) and Energimyndigheten (2010a), or in the regulation itself. There are exceptions and special cases, but those have not been considered in this study. Grontmij AB (2009) estimates the cost of hygienisation to be 0.03 SEK/kWh.

[1] Stefan Bengtsson. Personal communication April 2010. Josab Maskin AB.

2.5 Feedstocks

In this section the feedstocks that can be used for biogas production by anaerobic digestion are examined. Feedstocks with a low potential (<50 GWh/year) have not been included.

2.5.1 Wastes from agriculture

Growing crops and keeping animals generate a wide range of wastes suitable for digestion. Properties for all types of agriculture wastes are summarised in table 3.

Manure

The biggest source of organic waste within agriculture is animal excrement. Farmers use it as fertilisers on their fields, since it contains plant nutrients. The manure could instead be used for biogas production and afterwards the digestate could be used as fertiliser. The digestion process even increases the amount of available nitrogen that plants can recover (ammonium-nitrogen), thus resulting in a more efficient fertiliser (Carlsson & Uldal, 2009; Börjesson & Berglund, 2003; Börjesson & Berglund, 2007).

Manure is divided into several categories, each with its own properties. Different literatures define their categories in different ways, so in some cases there have not been perfect matches when trying to couple data. To tackle this problem some categories have been merged to form new ones that fit better, resulting in a distinction between liquid manure and solid manure for cattle and pig, while manure from other animals are all considered to be solid.

Centralised biogas plants using manure as a feedstock borrow it from the local farmers. In return, the farmers get a corresponding amount of digestate to use as fertiliser (Berglund, 2006; Sävsjö Biogas AB, 2006; Lantz & Börjesson, 2010; Grontmij AB, 2009). The manure is thus considered to be a free feedstock. The cost for transportation is allocated to the biogas plant. The distance between the biogas plant and the farms is estimated to range between 2 and 30 km. Additionally, manure requires hygienisation.

Potato and sugar beet tops

When harvesting sugar beets the leaves and petioles are left on the ground with the intent that the nutrients in it will be absorbed by the soil. Before harvesting potatoes, the tops are removed mechanically, chemically or thermally. The tops from both these plants could instead be collected and used for biogas production through digestion. The majority of the biogas potential comes from sugar beet tops, and there are harvesters that can collect the tops while harvesting the beets. Though not common in Sweden, they are highly available in Germany.

It has been assumed that the feedstock is free, though the biogas plant carries the economic burden of collecting and transporting it. The cost of collecting tops is brought up in various literature (Hansson & Christensson, 2006; Hansson & Christensson, 2005; Malmöhus läns hushållningssällskap, 1996; Lantbrukarnas Riksförbund, 2008), and has been set to 0.45 SEK/kg DM, corresponding to 0.16 SEK/kWh. The distance between the biogas plant and the farms is estimated to range between 2 and 50 km.

Table 3 Properties of agriculture wastes. [a]Derived from Linné et al., 2008. [b]Carlsson & Uldal, 2009.

Feedstock	Availability[a] ktonne/yr	Average yield[b] m^3_n CH_4/tonne	Potential GWh/yr
Cattle liquid manure	6 656	14	914
Cattle solid manure	1 532	60	902
Pig liquid manure	3 142	17	524
Pig solid manure	297	40	117
Poultry manure	239	79	185
Horse manure	708	41	284
Sheep manure	145	60	85
Sugar beet and potato tops	1 054	48	492

Straw from grain and oil

A large amount of straw is produced within agriculture. Straw is extensively used as fodder and bedding for animals, or at some places used as fuel for heating (Nordberg, 2006). It can be used for digestion, but requires considerable pretreatment (grinding into fine particles) or longer processing time to reach an acceptable biogas yield and can also cause mechanical problems within the reactor (Carlsson & Uldal, 2009; Linné et al., 2008). Because of these circumstances no biogas plant uses straw at present and thus it will not be considered in this study.

2.5.2 Food wastes from households, restaurants and shops

A lot of the waste generated in households and other facilities is of organic nature, making it interesting for biogas production. 133 municipalities collect and treat organic waste separately instead of treating it like regular waste that gets incinerated (Avfall Sverige, 2009). Swedish environmental goals states that at least 35% of all organic waste should be treated biologically in 2010.

Since the composition in the food waste varies, so does its properties, which should be kept in mind when looking at the figures in table 4.

Table 4 Properties of food waste from households, restaurants, shops and organic waste from gardens. [a]Derived from Linné et al., 2008. [b]Carlsson & Uldal, 2009.

Feedstock	Availability[a] ktonne/yr	Average yield[b] m^3_n CH_4/tonne	Potential GWh/yr
Food waste	663	118	767

Facilities that take care of waste get economic compensation for the service, also known as gate fees. It is hard to determine an average level of the gate fees, since one plant can have different agreements with different municipalities and details about the agreements are often considered business secrets. Avfall Sverige (2009) states that the gate fees for biologic treatment range between 400-800 SEK/tonne, but also includes compost plants. Naturvårdsverket (2005b) asked biogas plants about their gate fees for different types of wastes, but only got a few responses. Also, gate fees vary with time and those listed are probably not fully accurate any longer. Within this study several plants were contacted to estimate an average, but in most cases were refused any information or only got vague numbers.

The conclusion from this is that an average value would not give an appropriate picture of reality. Instead, a minimum gate fee of 500 SEK/tonne and a maximum gate fee of 800 SEK/tonne were used.

It is assumed that the gathering of waste is taken care of by the municipality, though the plant is charged for the cost of transporting the feedstock to the plant. An average transportation distance to the biogas plant of 20 km is assumed. Additionally, food waste requires hygienisation.

2.5.3 Wastes from industry

Industry also produces organic wastes, especially food industry. An advantage of process waste is that it is often relatively homogeneous (compared to household waste) and produced on a regular basis. The availability, naturally, varies a lot geographically, depending on where different industries are situated. Waste properties are presented in table 5.

Biosludge from paper and pulp industry

When producing paper and pulp, one of the residues obtained is called biosludge. At present, the biosludge is incinerated, composted, spread on land, recycled or taken care of through other means.

The size of the compensation received for biosludge is based on the estimated cost of getting rid of the biosludge by other means than digestion (Truong et al., 2010); 80 SEK/tonne. There is no cost of gathering the sludge, and the distance between the biogas plant and the paper and pulp plant is estimated to range between 5 and 20 km.

Residues from grain mills

Milling grains results in residues in the form of shells and screenings. At present it is used as a biofuel in incineration plants, but it could be used for biogas digestion as well (Linné et al., 2008; Nilsson & Bernesson, 2008).

Since the residues are currently used as fuel, they are of economic value for the mill. 0.15 SEK/kWh is an estimation of that value, which then gives the price of 600 SEK/tonne (Nilsson & Bernesson, 2008). There is no cost of gathering the mill residues, and the distance between the biogas plant and the mill is estimated to range between 5 and 20 km.

Residues from dairies

Dairies not only produce milk, cheese and yoghurt, in addition there is whey, waste milk and sludge.

The gate fee for the dairy sludge is, just as for food waste, hard to estimate. With the information from Naturvårdsverket (2005b) and the contacted biogas plants, the gate fee is assumed to vary between 100 SEK/tonne and 300 SEK/tonne. The transportation distance to the biogas plant is then assumed to be 20 km on average.

Whey & waste milk are at present used as animal fodder. The price is 0.08-0.11 SEK/litre, which corresponds to 80-110 SEK/tonne (1 kg≈1 litre). Transport is included and the price varies with distance (the maximum distance is 6 km).[2] Additionally, hygienisation is required.

Residues from slaughterhouses

Slaughterhouse residues originate from parts not desirable in meat products. Just as for household waste, an average gate fee for slaughterhouse waste is hard to determine because of geographical variations in competition and the fact that plants are not willing to share too much information about their agreements. The gate fee has been set to vary between 0 SEK/tonne and 300 SEK/tonne. Slaughterhouse waste is a sought-after feedstock by biogas plants and competition has great influence on the gate fee. One of the contacted biogas plants stated that it actually pays for the slaughterhouse waste (though no figure was given, thus the minimum gate fee is set to 0 SEK/tonne).

The gate fee for the slaughterhouse sludge is assumed to vary between 100 SEK/tonne and 300 SEK/tonne, just as for dairy sludge.

For all slaughterhouse residues, the average distance between slaughterhouse and biogas plant is set to 20 km. Additionally, hygienisation is required.

Table 5 Properties of waste from industry. [a]Derived from Linné et al., 2008. [b]Truong et al., 2010. [c]Carlsson & Uldal, 2009., slaughterhouse waste average yield is the average between stomach/intestine content and soft parts.

Feedstock	Availability[a]	Average yield	Potential
	ktonne/yr	m^3_n CH_4/tonne	GWh/yr
Biosludge	1 014	12[b]	122
Mill waste	57	272[a]	152
Dairy sludge	140	45[c]	62
Whey & waste milk	970	18[a]	175
Slaughterhouse sludge	54	61[c]	32
Slaughterhouse waste	40	128[c]	50

2.5.4 Sludge from sewage treatment works

At present, sewage plants with digesters are the biggest producers of biogas in Sweden (Energimyndigheten, 2010b). Despite that, existing processes can be further optimised and there are still a lot of plants that do not digest their sludge (Linné et al., 2008). In table 6 the properties of sewage sludge are shown.

Table 6 Properties of sewage sludge. [a]Derived from Linné et al., 2008.

Feedstock	Availability[a]	Average yield[a]	Potential
	ktonne/yr	m^3_n CH_4/tonne	GWh/yr
Sewage sludge	1 805	39	691

By implementing digestion on a sewage treatment works, sludge reduction is achieved alongside biogas production. This was the reason sewage treatment works came up with the

[2] Per Fallgren. Personal communication May 2010. Arla.

idea of implementing digestion in the first place (Linné et al., 2008). Economically this means that less sludge has to be taken care of by other means, resulting in less cost. In Swedish sewage treatment works, the average achieved sludge reduction from digestion is 40 percent of DM content (Linné et al., 2008). How the remaining sludge is treated varies between the sewage treatment works and different treatments imply different costs (Svenskt Vatten, 2010a; Svenskt Vatten, 2010b). From a survey about sludge treatment and costs associated with it at sewage treatment works throughout Sweden it can be concluded that the average cost of depositing sewage sludge is slightly above 200 SEK/tonne (Weglin, 2004). In this study it is thus assumed that a saving of 200 SEK/tonne is made for each tonne not needed to be treated.

Generally, since the biogas production is carried out at the sewage treatment works itself, no transportation is needed. Some sewage treatment works are too small to have their own digestion facility. Instead, the sludge will have to be transported to another sewage treatment work that has a digestion facility. The maximum distance for such transports has been set to 50 km.

2.5.5 Energy crops

There is a possibility to grow crops with the sole purpose of being used as digestion feedstocks, known as energy crops.

Until 2008, farmers within EU were subject to the set-aside regulation, meaning they were only allowed to use 90-95 percent of their acreage to grow food. The remaining area could be laid fallow, or used to produce energy crops. Therefore, potential estimations made before 2008 often assumes that 10 percent of the total agriculture land could be used for energy crops (to boost the overall potential estimation).

Even without the set-aside, it is still possible to use land to grow energy crops. At present it is not very common, but could be in the future if the incentives for farmers change.

It is assumed that 10 percent of the Swedish arable land (~270 000 ha) evenly distributed across the nation could be used for energy crops. Sugar beets and maize have high energy yields per cultivated area, but are only suitable to be grown in southern Sweden while grain and ley can be grown in the entire nation. Farmers also need to consider crop rotational effects when determining what energy crop to grow. With that in mind, Linné et al. (2005) assumes the land share for each crop to be distributed according to table 7.

Table 7 Area distribution, harvest and properties for energy crops. [a]Linné et al., 2005

Feedstock	Share[a]	Cultivated area	Average harvest[a]	Availability	Average yield[a]	Potential
	%	ha	tonne DM/(ha*year)	ktonne/yr	m^3_n CH_4/tonne	GWh/yr
Ley crops	40	108 000	7.5	2 455	87	2 090
Maize	20	54 000	10	1 800	95	1 679
Grain	30	81 000	6	565	329	1 821
Sugar beets	10	27 000	14.6	1 188	95	1 125
Sugar beet tops	Included in the figures for sugar beets above			572	48	267

Following is a closer look at the individual energy crops.

Ley crops

Ley crops consist of a mix of grass and clover, commonly used as animal fodder. In organic farming, ley is an important nitrogen source. Additionally, the soil structure benefits from the cultivation of ley crops.

The central biogas plant in Västerås uses ley crops as feedstock to large extent. The farmers and the biogas plant have different responsibilities within their agreement; the farmer takes care of sowing and makes sure that the ley grows successfully while the biogas plant provides the farmer with seeds and takes care of the harvest, transportation and ensiling. The biogas plant pays the farmer 0.20 SEK/kg DM. The costs of gathering (harvesting etc.) and transportation (including field transportation, the distance to biogas plant is within 15 km) is estimated to be 0.62 SEK/kg DM (Hallén, 2003). These estimations have been used to calculate the cost of ley crops as a biogas feedstock. Additionally, the assumed maximum distance to the biogas plant is increased to 50 km.

Maize

Maize ensilage is used as animal fodder, but is also a suitable for digestion. It is widely used by biogas plants in Germany. The price for maize ensilage varies both over time and geographical location. It has been assumed to be 1.1 SEK/kg DM in this study, considering what is stated in different literature (Tell, 2010; Swensson & Lidström, 2008; Hellberg, 2009; Swensson, 2009). There is no cost of gathering (it is included in the price for the feedstock). The distance between the biogas plant and the farmer is assumed to range between 2 km and 50 km.

Grain

Grain, in particular wheat, is a commonly grown crop that is suitable for digestion. The Swedish price index for wheat is 1.136 SEK/kg, which has been used in the calculations for the costs of grain (Statens Jordbruksverk, 2010:03). The distance between the biogas plant and the farmer is assumed to range between 2 km and 50 km.

Sugar beets

Sugar beets, including the tops, are useful as a biogas feedstock. Just as for grain, there is a price index for sugar beets. The price for sugar beets is set to 0.276 SEK/kg (Statens Jordbruksverk, 2010:03). Costs for the sugar beet tops were covered earlier in the report. The distance between the biogas plant and the farmer is assumed to range between 2 km and 50 km.

3 Results

Since assumptions of energy crop availability are not based on physical availability (but on speculation on what could be possible), two scenarios are formed; the first in which only wastes of different kinds are used, and the second where the assumptions of energy crops are realised as well.

By sorting the feedstocks' costs and plotting them according to each feedstock's biogas potential, figure 2 and figure 3 are achieved. Table 8 lists the data from which the curves have been drawn.

Table 8 Feedstock potentials and costs.

Feedstock	Potential	Minimum cost	Maximum cost
	GWh/year	SEK/kWh	SEK/kWh
Cattle liquid manure	914	0.44	0.52
Cattle solid manure	902	0.31	0.32
Pig liquid manure	524	0.41	0.48
Pig solid manure	117	0.32	0.34
Poultry manure	185	0.30	0.31
Horse manure	284	0.32	0.34
Sheep manure	85	0.31	0.32
Sugar beet and potato tops	492	0.45	0.48
Food waste	767	0.02	0.28
Biosludge (paper and pulp industry)	122	-0.22	-0.17
Mill waste	152	0.47	0.47
Dairy sludge	62	0.29	0.32
Whey and waste milk	175	0.71	0.88
Slaughterhouse sludge	32	-0.18	0.15
Slaughterhouse waste	50	0.06	0.29
Sewage sludge	691	0.03	0.14
Ley crops	2 090	0.56	0.57
Maize ensilage	1 679	0.62	0.63
Grain	1 821	0.35	0.36
Sugar beet	1 125	0.62	0.64
Sugar beet tops	267	0.45	0.48

In 2008, the energy usage in Sweden by passenger and goods transportation was 51 and 22 TWh/year respectively (Energimyndigheten, 2010c). As can be seen in figure 2, the first scenario (only wastes) could cover about 6 TWh/year. In the second scenario (including energy crops as well), slightly above 12 TWh/year could be produced, see figure 3. In 2008, the total amount of biogas produced in Sweden corresponded to 1.359 TWh (Energimyndigheten, 2010c).

The production cost of biogas can be compared to the current fuel price of petrol and biogas. The constituents of the petrol price are displayed in table 9.

Table 9 Costs and taxes for petrol. [a]Average for 2009 (Svenska Petroleum Institutet, 2010). [b]Taxes for 2010. [c]25 percent.

Constituents of the petrol price	Cost	
	SEK/litre	SEK/kWh
Production cost and gross marginal[a]	4.40	0.48
Energy tax[b]	3.06	0.34
CO_2 tax[b]	2.44	0.27
Value-added tax[c]	2.48	0.27
Total	**12.38**	**1.36**

For biogas there is no energy or CO_2 tax. The price of vehicle fuel gas (including both natural gas and biogas) is about 20 percent below the price of petrol (FordonsGas Sverige, 2010; Energimyndigheten, 2010a). To maintain that cost relation, the price of biogas should be around 1.09 SEK/kWh (≈9.90 SEK/litre petrol equivalent), corresponding to 0.87 SEK/kWh (≈7.92 SEK//litre petrol equivalent) without VAT. If the production cost (displayed in figure 2 and figure 3) is then subtracted, what is left is supposed to cover any additional costs in the biogas value chain (e.g. distribution of the gas) as well as the profit for the producer.

The cheapest feedstocks have a negative cost, implying that a biogas plant would make profit just by taking care of the feedstocks (and not attempting to sell the biogas). This is accomplished through the gate fees the biogas plant receives for the feedstocks.

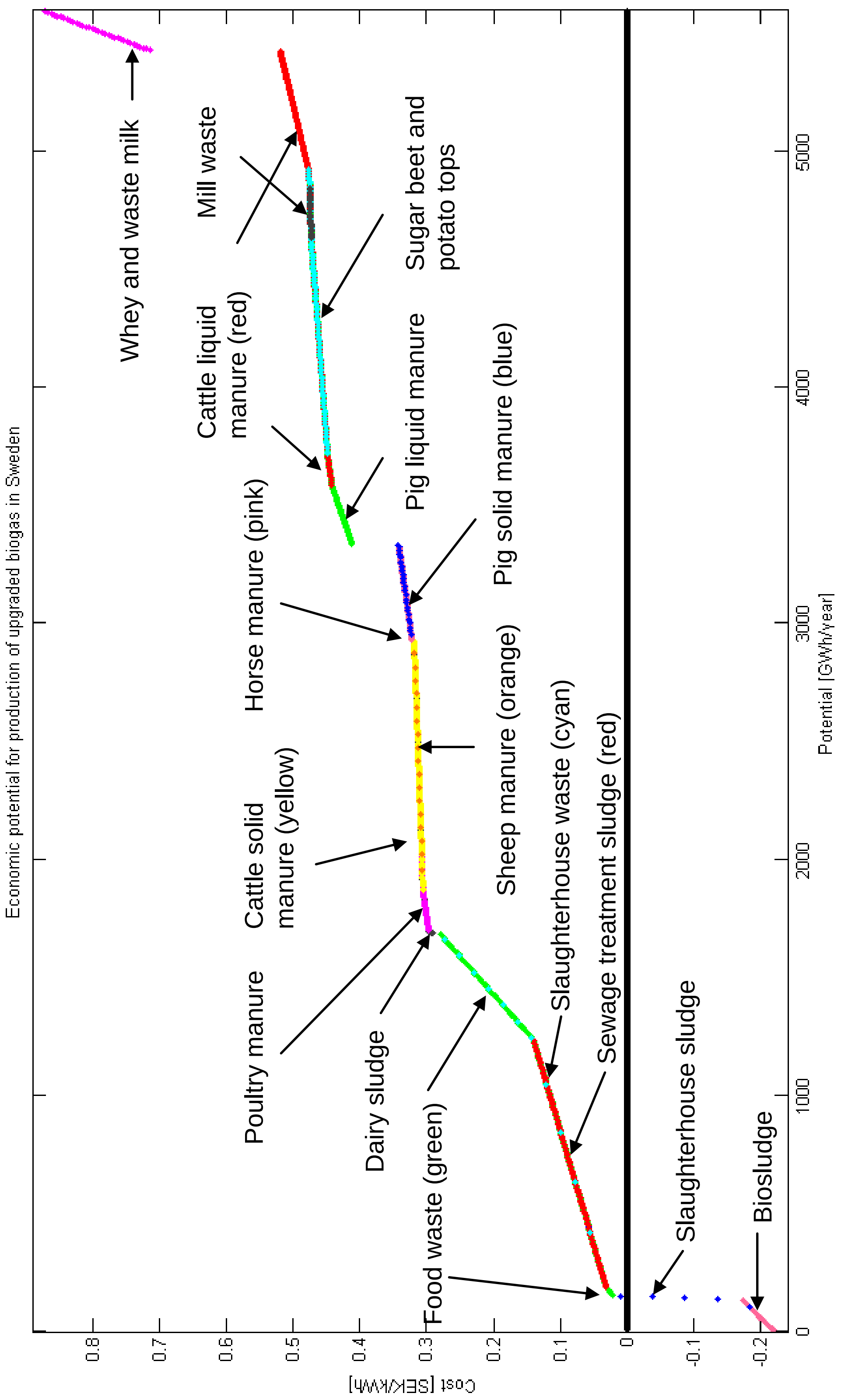

Figure 2 The economic potential for production of biogas in Sweden, without energy crops.

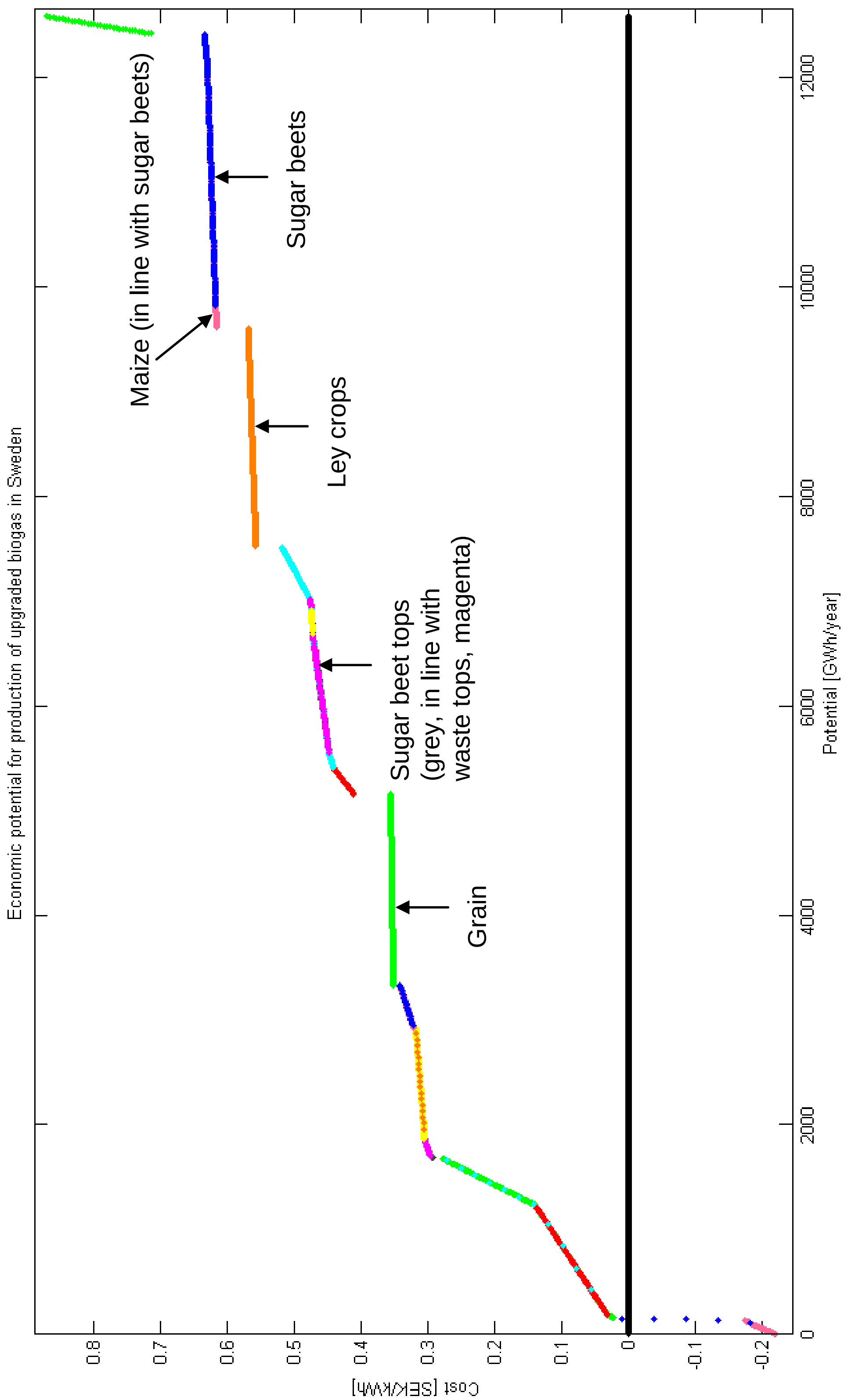

Figure 3 The economic potential for production of biogas in Sweden, with energy crops.

4 Discussion and conclusions

Regarding the results, comparisons, uncertainties and the relation between biogas and petrol are explained and discussed in this section.

4.1 Similar estimations of feedstock costs

In search for data, estimations of feedstock costs with various kinds of assumptions have been identified. At two occasions, cost/supply graphs similar to those presented in the previous section were found.

In her doctoral dissertation, Berglund (2006) presents a graph with similar axes, see figure 4. The graph presents the price/compensation for feedstocks rather than the total costs (including costs derived from investment, transportation, hygienisation etc.), and thus differ somewhat from the figures in the previous section. Additionally, the axes have no units but the graph as a whole provides a good visualisation of the price/compensation properties of feedstocks compared to each other.

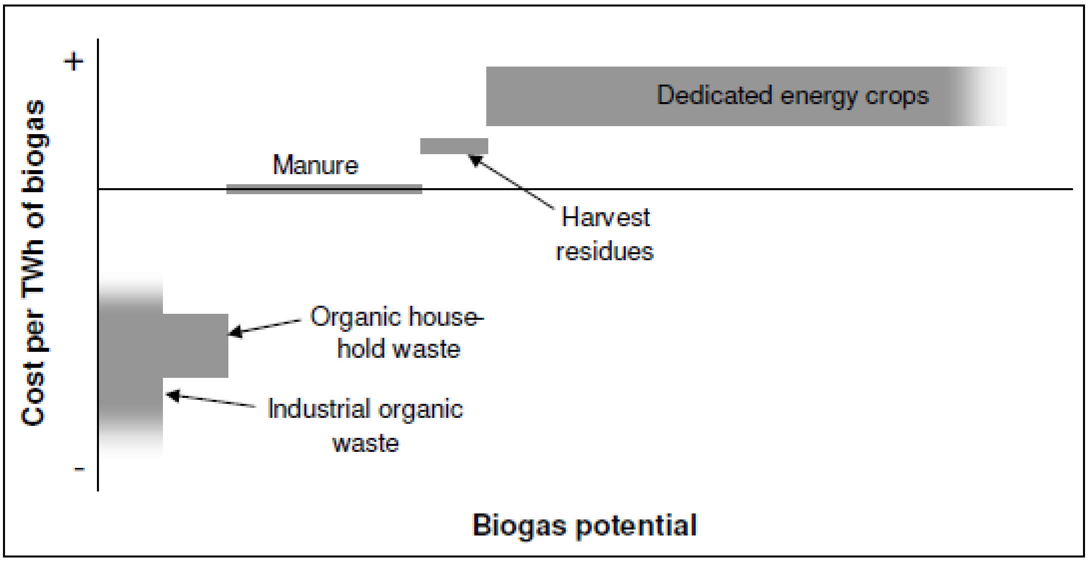

Figure 4 Current income (-) and potential cost (+) of various raw materials available. (Berglund, 2006)

The graph still assembles a similar shape and division of feedstocks as the figures in the previous section.

To keep in mind when looking at any estimation about feedstock costs for biogas is that the situation will most probably change in the future.

- With growing competition, the existence of gate fees as an income for biogas plants is likely to shift into the opposite; a price for the feedstocks that the biogas plants will need to pay (Grontmij AB, 2009).
- Farmers might not be as willing to lend their manure for free for someone else to make profit on in the future, especially if the received digestate is of insufficient "quality" (e.g. pig manure could have higher concentration of nitrogen than the received digestate if the biogas plant uses a lot of cattle manure, implying gains for

cattle farmers and losses for pig farmers)[3]. There is a suggestion of introducing subsidies for digestion of manure (Energimyndigheten, 2010a), which most certainly will have an impact on this issue if adopted.

- The prices on energy crops are strongly linked to the prices of regular food crops (Grontmij AB, 2009), meaning another source of influence that can change feedstock costs.

A recent report by Lantz & Börjesson (2010) features a figure similar to those in the previous section, see figure 5. It has been composed by merging data from various sources, each with different assumptions that might not be in line with each other. Its purpose is thus not to provide an in depth detailed picture, but more of an overview. Another important thing to note is that it displays the production costs for raw gas, not upgraded biogas. Since upgrading implies a considerable part of the cost of biogas production, costs presented in figure 2 and figure 3 are somewhat higher than they are in figure 5.

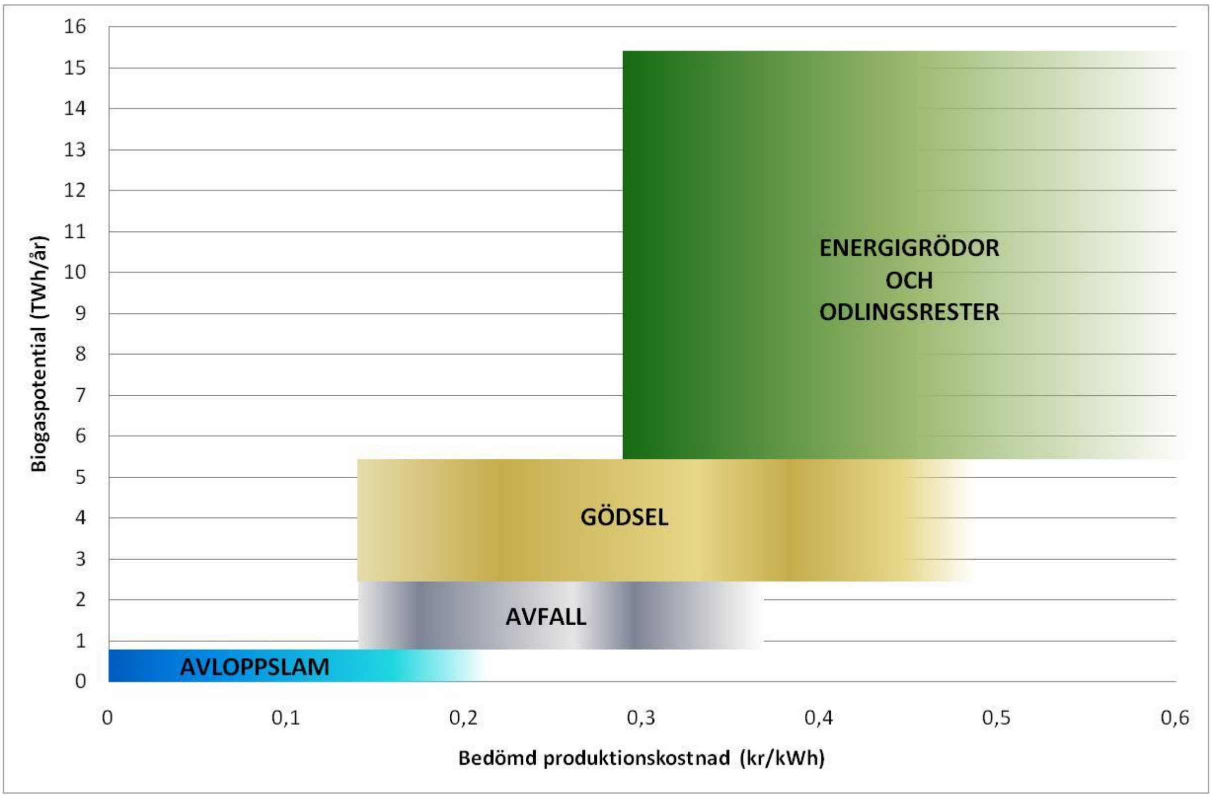

Figure 5 Estimated production cost (raw gas) and biogas potential for each feedstock category. år = year, avloppslam = sewage treatment sludge, avfall = wastes, gödsel = manure, energigrödor och odlingsrester = energy crops and harvest residues. (Lantz & Börjesson, 2010)

[3] Sara B Nilsson. Personal communication March 2010. Växa.

A notable difference when comparing figure 5 to the figure 2 and figure 3 is that the production costs in figure 5 never fall bellow 0 SEK/kWh. The most likely reason for this is that different assumptions of gate fees have been made. As stated earlier, gate fees vary both with time and location, thus it is hard to make estimations and it is not surprising that they might differ between studies. Apart from that, figure 5 still displays similar price ranges for the other feedstocks, if compensation for upgrading of the biogas is taken into consideration.

Some overall cost calculations of the biogas value chain have been made by Energimyndigheten (2010a) which results are presented in table 10. These calculations are based on theoretical figures and do not imply real limits. The average total cost for the whole value chain is estimated to be around 1.50 SEK/kWh (Energimyndigheten, 2010a).

Since there has been no consideration of costs connected to distribution or sales in this study, a comparison with the figures in the previous section should be made by adding production and upgrading, resulting in a price range of 0.45-0.9 SEK/kWh.

Table 10 Estimated current costs in the biogas value chain (Energimyndigheten, 2010a). [a]According to Urban Kärrmarck who has performed the calculations, this figure is incorrect and should probably be in the range of 0.20-0.30 SEK/kWh, though it has not been cross checked.

	Production SEK/kWh	**Upgrading** SEK/kWh	**Distribution** SEK/kWh	**Sales** SEK/kWh	**Sum** **SEK/kWh**
Best case	0.30	0.15	0.50[a]	0.25	**1.20**
Worst case	0.70	0.20	1.10	0.40	**2.40**

Compared to results of this study, the cost estimation seems somewhat high. The underlying assumptions for these calculations also include biogas plants of smaller size, which increases the average cost per energy unit (economies of scale are highly relevant for investment costs of a biogas plant).

Another estimation of costs has been made by Nordberg (2006), displayed in table 11. Whether investment costs have been taken into consideration is not stated, though since production cost can reach zero, it is probably not included. Exactly what “compression” involves is not totally clear either, though it seems to be expensive to carry out on biogas from energy crops.

Table 11 Costs for production of biogas (Nordberg, 2006). The figures have been converted to SEK/kWh from SEK/m^3_n, otherwise left untouched (the summation is incorrect in the source document as well).

	Production	Upgrading	Compression	Sum
Biogas from...	SEK/kWh	SEK/kWh	SEK/kWh	**SEK/kWh**
Sewage treatment works	0–0.15	0.10–0.20	0.10	**0.20–0.46**
Central biogas plants	0.15–0.26	0.10–0.20	0.10	**0.31–0.56**
Crops	0.46	0.10	0.20–0.46	**0.64–0.74**

For biogas originating from sewage treatment works and central biogas plants, the cost estimations by Nordberg (2006) are somewhat higher than the results shown in figure 2 and figure 3. For energy crops, they are considerably higher. The reason for this is hard to tell, since little is explained about what assumptions that have been made to achieve the figures in table 11. Additionally, the figures do not add up correctly, making you wonder which figures are correct and which are incorrect.

4.2 Feedstock properties and mixing of feedstocks

Feedstock properties are estimations based on different observations, not definitive facts. Most often, different feedstocks are digested together, which impact the overall properties of the digestion mix. Since two mixed feedstocks complement each other with different properties, the properties of the resulting digestion mix can be more optimal for digestion than if the feedstocks had been digested separately, resulting in a higher methane yield (Carlsson & Uldal, 2009).

The chemical compositions of different feedstocks make them more or less suitable to be mixed with other feedstocks. Some feedstocks, like manure, are often available in bigger proportions than others, thus forming a kind of base feedstock. DM content, C:N ratio, feedstock dimensions etc. all need to be appropriate in the final digestion mix. Thus what feedstocks that are locally available and their suitability of being mixed together is essential to assess when planning a biogas plant.

Mixing different feedstocks have other impacts on the process as well. Feedstock with animal origin require hygienisation, see previous section In order to draw the cost/supply curves, another assumption about the transportation must be made. Since transport distances vary, so does the cost of the feedstock. How the transport distances vary is hard to tell, and might differ considerably between different feedstocks. It is assumed that the transportation distances vary linearly.

Price/compensation

Some feedstock are bought (e.g. energy crops), some are “borrowed” for free (e.g. manure) and some even generate income to the plant (e.g. waste). The unit used most often is SEK per tonne.

Facilities that take care of waste get economic compensation for the service, also known as gate fees. Some feedstocks have a variance in gate fees that implies bigger changes in the total cost than the variance of transportation distance. For these feedstocks, the gate fees are assumed to vary linearly, while each bearing the cost of its estimated average transportation distance.

Costs associated with gathering of feedstock

Depending on what agreements that have been made between the biogas plant and its feedstock providers, gathering the feedstock might be undertaken by the plant itself. Such actions naturally imply costs.

Hygienisation. The cost of hygienisation has only been included for those feedstocks that legally require it, though in reality, if other feedstocks (not requiring hygienisation) are mixed with such feedstock, they are also hygienised and thus also contribute to the cost of hygienisation. This is because the hygienisation occurs just prior to the digestion, thus the feedstocks are mixed prior to the hygienisation.

Using a range of different feedstocks also provides better robustness to the biogas plant since the security of supply is shared between different suppliers.

In conclusion, feedstock properties differ depending on specific biogas plant conditions, implying that feedstock costs linked to the properties differ as well.

4.3 Digestate

Anaerobic digestion does not only produce biogas, a lot of solids and liquid still remain. This so called digestate has high concentrations of plant nutrients (nitrogen and phosphor), making it interesting for farmers and forest owners to use it as fertiliser.

The feedstocks the digestate originates from decides where it legally can be spread. Digestate from sewage sludge is not allowed on land growing food crops (because of heavy metal content), though it can be spread in a forest or on land growing energy crops. If sewage sludge is not used in the plant, then generally the digestate is allowed to be spread on any arable land.

Depending on what agreements a plant has with its feedstock providers, the digestate could be a source of income, in addition to the biogas. Plants collecting manure from farms often borrow the manure and return the digestate to the farmers as payment for the favour. In other cases, the digestate could be sold as a substitution for commercial fertilisers. The tax on commercial fertilisers was recently (January 2010) removed by the Swedish government, so the willingness to pay will probably decrease for the conventional farmers. Some plants have certified their digestate, allowing it to be used by organic farmers in addition to conventional farmers.

In the calculations done within this study, no consideration about possible income from selling of digestate has been made.

4.4 Transportation distances

What assumptions one make about the transportation distances deeply influence the look of the cost/supply curve (together with the properties of the lorry). Many factors influence the transportation distance, such as geographical and infrastructural conditions and what kind of feedstocks that are used.

For household wastes, transportation consists of the gathering of waste and the transportation of the waste to the biogas plant. Since it is assumed that the municipality takes care of the gathering, that cost is not included in the calculations in this study. Berglund & Börjesson (2003) estimates the mean distances for different living areas; 10 km in population centres, 20 km in suburbs and 40 km in rural areas. The assumption made for the calculation in this study was to use the average distance of 20 km (letting the gate fee be variable).

For other feedstocks (manure, harvest residues, energy crops, slaughterhouse residues) the transportation distance is often assumed to be no more than 15 km (Berglund & Börjesson, 2003; Börjesson & Berglund, 2003; Börjesson & Berglund, 2006), and an average distance of 10 km is sometimes used (Börjesson & Berglund, 2003; Börjesson & Berglund, 2006). Though for bigger plants (300 GWh/year) utilising energy crops, the average transportation distance could be as high as 24 km (Benjaminsson & Linné, 2007). In Germany, a biogas plant producing 450 GWh/year has a catchment area covered by a 40 km radius (Benjaminsson & Linné, 2007).

In this study, the maximum transportation distance exceeds those estimations made by others. The main reason for this is that the purpose is not to only cover feedstocks within an economically feasible transportation range, but all that is considered to be practically available (considering the gathering of the feedstocks).

4.5 Feedstock availability

In some parts of Sweden feedstocks might be located sparsely (low amount of feedstocks within a specific area), making it more suitable with farm based biogas plants instead of a central biogas plant. Farm based biogas plants rarely upgrade the biogas because of the investment costs it implies and/or lack of nearby market. In other words, such cases are beyond the scope of this study (since the focus is on central biogas plants that upgrade the biogas). The assumed realistic availability of feedstocks though, most probably includes feedstocks of such kind. To assess the concentration of feedstocks within different areas is outside the scope of this study. The real feedstock availability for central biogas plants might thus be smaller than what is assumed in the calculations.

4.6 Biogas versus petrol

As earlier stated, if the biogas is upgraded and sold as vehicle fuel, it needs to be sold at a price below 0.87 SEK/kWh (without VAT) to be competitive with petrol. Considering the estimated costs for distribution and sales from Energimyndigheten (2010a), it will not be profitable to sell upgraded biogas from some feedstocks.

In the best case according to Energimyndigheten (2010a), distribution and sales costs would add up to approximately 0.50 SEK/kWh (see table 10), resulting in an upper production cost limit of 0.37 SEK/kWh (if the biogas is to be sold at 0.87 SEK/kWh excluding VAT, as previously suggested). By assuming that, an economic potential of biogas can be derived to about 5 200 GWh/year, see figure 6.

Within this potential though, grain is included; an energy crop. The extent of energy crops grown can be altered relatively easy (in contrary to the amount of waste created). Thus by increasing the grain production in excess of the amount suggested previously in the report (and decreasing the production of other energy crops), the potential could be increased.

The worst case costs for distribution and sales according to Energimyndigheten (2010a) adds up to 1.50 SEK/kWh, of which distribution costs contribute 1.10 SEK/kWh. Such high costs would mean economic losses for the biogas plant instead of profit, no matter what feedstocks used for production. An intermediate case in which costs for distribution and sales adds up to 1 SEK/kWh would still render most production without profit and the economic potential of upgraded biogas at around 140 GWh/year (with biosludge and slaughterhouse sludge as feedstocks).

A conclusion that can be drawn from this is that at present, financial support and/or other regulations are needed to make it economically feasible to produce upgraded biogas in larger quantities, if competing with petrol.

Between 1998 and 2008, Lokala investeringsprogram (LIP) and Klimatinvesteringsprogram (KLIMP) provided significant financial support for investments of biogas plants (Energimyndigheten, 2010a; Naturvårdsverket, 2005a). At present, it is possible to seek support for investment through the ordinance about renewable gasses, SFS 2009:938 (Energimyndigheten, 2010a).

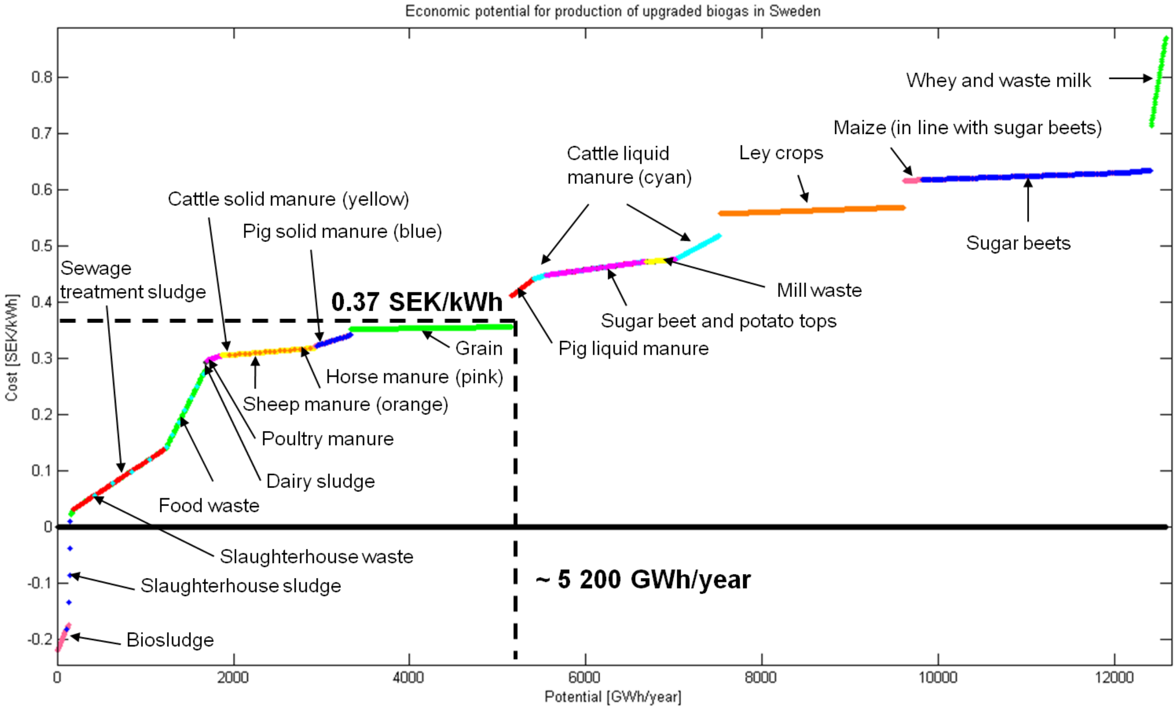

Figure 6 The economic potential of biogas if production and upgrading costs needs to be lower than 0.37 SEK/kWh.

Another way to make biogas more competitive against petrol is by increasing the energy tax or CO_2 tax on petrol, allowing for a higher price on biogas. Such changes are politically sensitive and have indirect impacts on other business sectors in addition to the vehicle fuel sector. Additionally, the purpose of the energy tax on vehicle fuel is to internalise external costs connected to the use of transportation infrastructure (such as wear, pollution and noise) (Vägverket, 2010). Since vehicles utilising biogas also contribute to these costs, logically energy tax should be put on biogas as well. If the same energy tax on petrol (0.34 SEK/kWh) was put on biogas as well, then the economic potential would be almost non-existent, even if the distribution and sales costs were low, see figure 6.

To increase the biogas price (i.e. decrease the 20 percent price difference between petrol and biogas) would imply direct increase of income in the short-term and a higher economic potential. Considering the long-term effects though, customers might refrain from buying biogas vehicles since it will not be as economically attractive, inhibiting the potential growth of the market. An average gas fuelled car costs about 30 000 SEK more than the corresponding petrol model and consumes 7.5 m_n^3/100 km. With a gas price 20 percent lower than a petrol price of 1.36 SEK/kWh (12.38 SEK/litre) and an annual driving distance of 15 000 km, it takes about 10 years to reach break-even. At present, owners of gas fuelled cars are economically compensated by not having to pay any vehicle tax the first five years of operation and sometimes local privileges (free parking, no congestion charge etc.), resulting in break-even being reached a few years earlier.

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Appendix A – Complete table of feedstock properties

Except for energy crops, Linné et al. (2008) has been the exclusive source for data concerning availability. In it, the practically availability of each separate feedstock is not always stated clearly in plain text. Sometimes, the data is given in ktonnes DM, especially when DM content is tricky to determine. Data about energy crop availability in Linné et al., 2005 was also given in mass of DM.

In table A-1, properties of each feedstock including DM properties are given. When both ktonne DM and ktonne wet are listed, the wet property has been derived from the DM property.

Average yield is presented for DM content if the availability source was in DM. It is then converted and presented in wet yield as well. The only exception is mill wastes, which availability is originally given in DM, though the average yield is given in wet.

DM content is presented for every feedstock since it gives a hint about whether the feedstock is solid or liquid (<12% is generally considered liquid).

Table A-1 Complete table of feedstock properties. *LM = liquid manure, SM = solid manure

Feedstock	Availability[a]		Average yield[c]		DM content[c]
	ktonne DM/yr	ktonne wet/yr	m^3_n CH_4/tonne DM	m^3_n CH_4/tonne wet	%
Cattle LM*		6 656		14	8.5
Cattle SM*		1 532		60	30
Pig LM*		3 142		17	8
Pig SM*		297		40	16
Poultry manure	99	239	190	79	41.5
Horse manure	213	708	136	41	30
Sheep manure	44	145	200	60	30
Sugar beet and potato tops	179	1 054	280	48	17
Food waste		663		118	27
Biosludge	71	1 014	175[d]	12	7
Mill waste		57	306[a]	272	89[e]
Dairy sludge	10	140	648	45	7[f]
Whey & waste milk	39	970	459[a]	18[a]	4
Slaughter-house sludge		54		61	16
Slaughter-house waste		40		128	23
Sewage sludge	361[b]	1 805[b]	195[a]	39	20[g]
Ley crops	810[b]	2 455[b]	263	87	33
Maize	540[b]	1 800[b]	317	95	30
Grain	486[b]	565[b]	382	329	86
Sugar beets	297[b]	1 188[b]	386	95	25
Sugar beet tops	97[b]	572[b]	280	48	17

[a]Derived from Linné et al., 2008, unless otherwise stated.

[b]Derived from Linné et al., 2005

[c]Carlsson & Uldal, 2009, unless otherwise stated.

[d]Truong et al., 2010

[e]Nilsson & Bernesson, 2008

[f]Hagelberg et al., 1988

[g]Halldorf et al., 2010.