

Sustainability assessment of biorefinery and dry digestion systems

Case: Sweden

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1. Introduction

Aim of *Abowe* project is to enhance adoption of biological utilization of waste. Project is divided into work packages where dry digestion and biorefinery systems are piloted and assessed in regional impact point of view. Assessment of material, energy and greenhouse gas (GHG) emissions belongs to work package 2. The aim of the assessments is to support business modeling of the dry digestion and biorefinery systems. Anyway, aim of this study is to assess the most suitable scenarios for utilizing biodegradable waste by using biorefinery and biomethane production systems for decreasing greenhouse gas emissions.

It is known that integrated biogas and biomethane production systems have usually better material, energetic and greenhouse gas reduction performance than individual production systems. Still, it is a bit unclear that how the most important variables such as production yields and feedstock properties have effect on greenhouse gas reduction performance on these systems. Thus, this study evaluates how biochemical concentrations, biomethane potentials and feedstock total solid concentration have effect on greenhouse gas reductions. In addition, potential feedstocks for biological processes are introduced.

2. Feedstock potentials

Poultry farm related chicken and straw waste potential in Sweden is introduced since it those were selected as biorefinery feedstocks in *Abowe* project. In 2012 chicken, turkey and other poultry carcass mass for meat production were 109.67 kt, 3.01 kt and 374.25 kt, respectively (1). Still, total carcass consists of available meat for food production and slaughtering waste such as heads and feet. In case of chicken carcass it was reported that slaughtering waste can be 35 % of the total carcass mass (2). Thus, chicken slaughtering waste production in Sweden is about 38 000 t/year. For example, at *Hagby* chicken farm slaughtering waste production is annually about 6.912 ton (2).

In addition, there is need to find more suitable feedstock such as excess straw for fermentation processes to secure feedstock availability. Excess straw can be one interesting additional waste fraction since it is not considered as food or utilized as bed covering material for domestic animals. It was estimated that straw potential for energy purposes in Sweden is about 830 kt/year which could be used as feedstock for fermentation processes (3). Thus, distribution of agricultural land (Figure 1) reflects also the distribution of straw potential in Sweden.

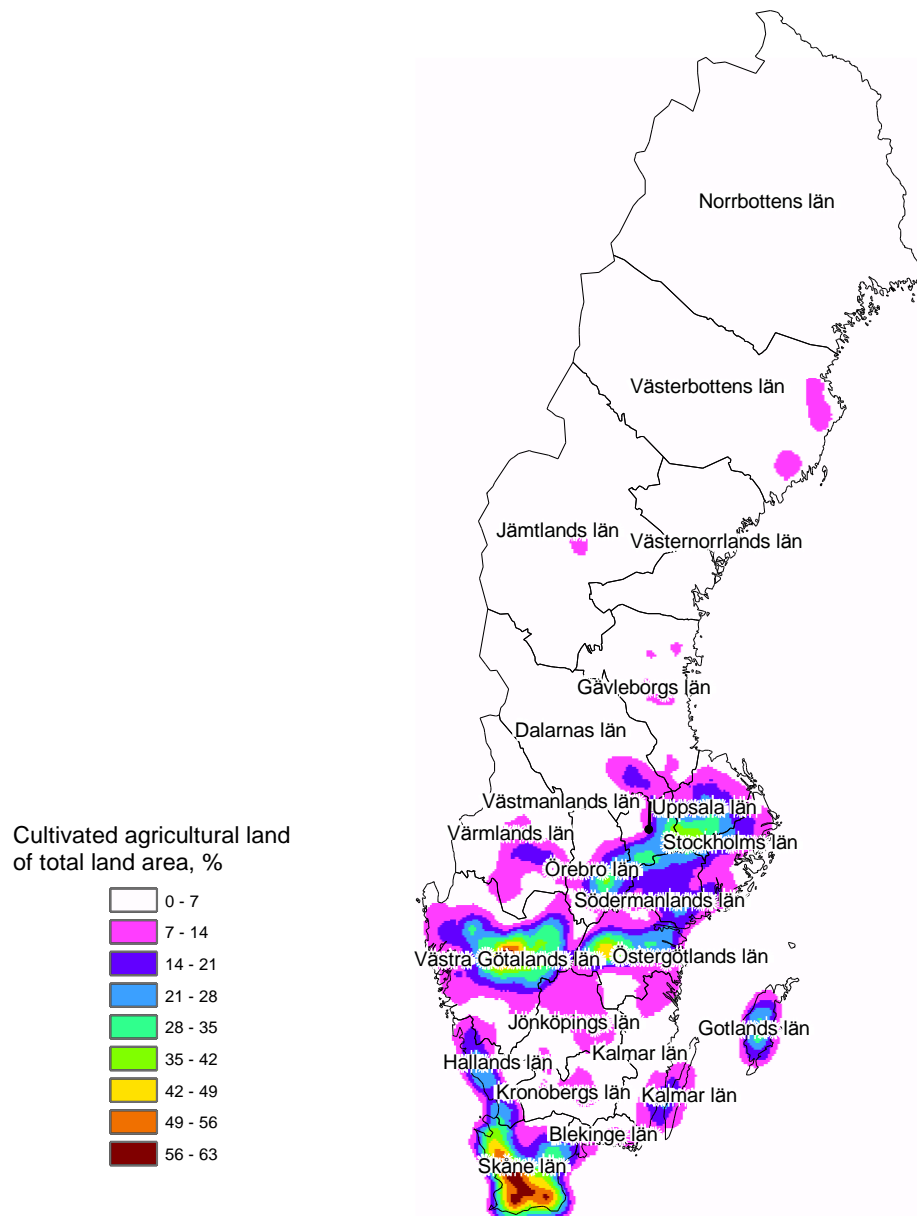


Figure 1. Distribution of agricultural land was calculated from field block data (4).

3. Biofuel production in sustainability point of view

Biological production of fuels and chemicals can help to achieve required GHG emission targets. Renewable energy directive (RED) (2009/28/EC) gives rules how to calculate GHG emissions for biofuel production and how GHG reductions are calculated from fossil fuel and biofuel productions. GHG reductions increases if it can be shown that by replacing fossil fuels, chemicals or current practices with biofuel production it is possible to emit less GHG emissions. For example, fossil fuel reference has GHG emissions of 302 kg CO₂ equivalent per MWh of the fuel (Table 1). If biofuel could be produced with lower GHG emissions per MWh it would cause GHG reductions. After first of January in 2018 biofuel production systems should have GHG reductions more than 60 % compared to this fossil fuel reference value. Table 1 shows that especially Butanediol is one of the most potential biofuels to be replaced and to achieve GHG reductions targets.

Biochemical GHG factors and lower heating values were derived from life cycle inventory data bases, but GHG factor for Butyric acid was missing and thus weighted average GHG factor of others was used to assess Butyric acid GHG factor (Table 1). Weight factors were adopted from mass distribution of produced biochemical from pilot A run nro. 2 in Sweden (Figure 2). Thus, the biochemical mixture (Table 1 and Figure 2) have weighted average GHG factor of 3.7 kg CO₂ eqv/(kg biochemical mixture) and lower heating value of 22.6 MJ/(kg biochemical mixture).

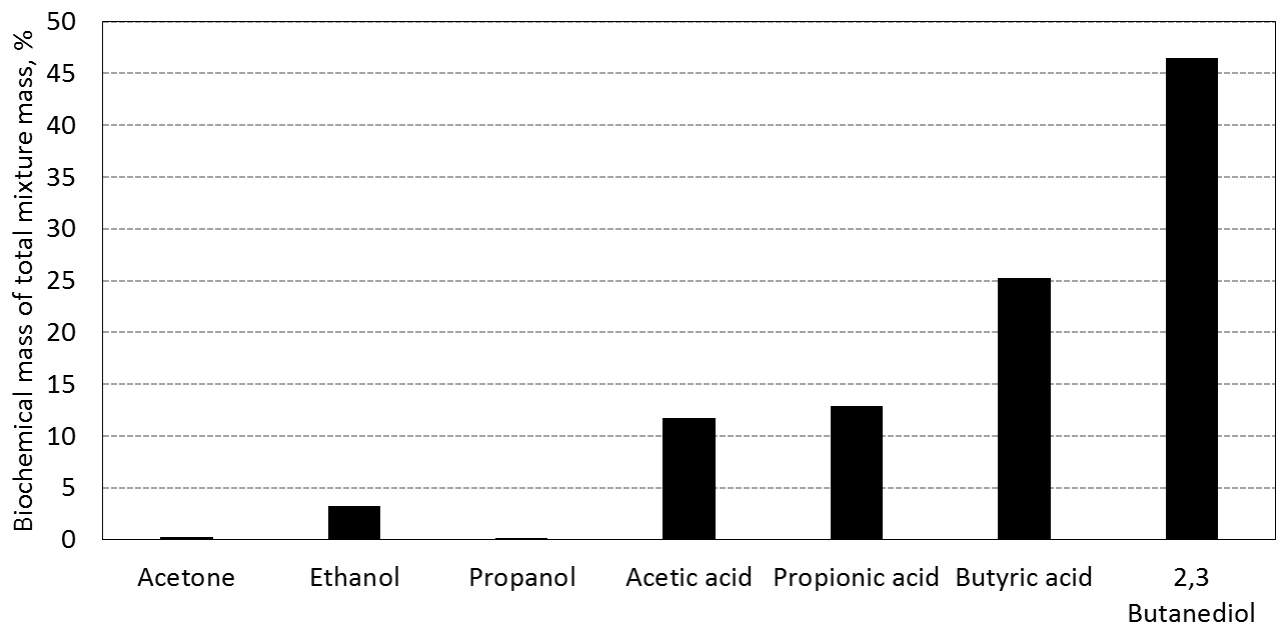


Figure 2. Biochemical mass distribution is same as in pilot A run nro.2 in Sweden.

In this study GHG emissions from electricity and heat production are considered. In Swedish average electricity production mix GHG emissions according to (2009/28/EC) guidelines are 253 kg CO₂/MWh (5). GHG emissions from heat production are assumed to correspond emissions from biomethane combustion which is 202 kg CO₂/MWh (6).

Table 1. GHG reductions from bio chemicals according to (2009/28/EC) directive and Gabi life cycle inventory data base (5).

Biofuel or chemical	kg CO ₂ eqv./ (kg fuel)	kg CO ₂ eqv/MWh
Acetone	1.61	204
Ethanol	2.24	301
Propanol	1.71	194
2,3 Butanediol	5.07	716
Butyric acid	2.55	402
Hydrogen	3.19	96
Acetic acid	1.16	318
Propionic acid	3.50	669
Fossil fuel reference (2009/28/EC)	3.60	302

4. Biorefinery and biomethane production system

General model for utilizing biodegradable waste in biochemical and biomethane production is introduced to estimate biochemical and biomethane yields in greenhouse gas reduction point of view. The model gives results to estimate that what are the required yields to implement downstream process for process broth that contains valuable biochemical. Process broth is the product from fermentation process.

Model considers heat and electricity demands and their contribution to total greenhouse gas emissions in biochemical and biomethane production systems. Model for heat and electricity demands in biomethane production system was already introduced (7) and it is also used in this study. Electricity demand model from biomethane model was adopted to fermentation model, but heat demand model is described here since it is different from biomethane production model.

4.1 Energy demands in biorefinery process (A)

Heat demands in fermentation process is introduced. In pretreatment process feedstock temperature is increased from 5 °C to 70 °C before it enters to heat exchanger that has heat exchange effectiveness of 50 %. This sanitation temperature was 10 °C lower than during pilot A testing run nro.2 in Sweden (8). This guarantees hygienic feedstock for fermentation and homogenous distribution for organic materials. After pretreatment process feedstock goes through heat recovery system (*HRC*) where it releases heat to incoming feedstock and at the same time it cools down to fermenter temperature of 35 °C. It is assumed that auxiliary heat is not needed in fermentation since microbiological processes have also capability for producing heat (9). After fermentation process there is need to remove ethanol from process broth which is usually done via distillation as in this case it is assumed. Then process broth temperature is increased from 35 °C to 78 °C which is ethanol boiling point. Ethanol evaporation heat is also considered.

Electricity in biochemical production is needed in belt filter press as well as mixing in fermentation and pretreatment processes. Electricity consumption models are adopted from the dry digestion model (7) assuming that organic loading rate in fermentation was 65 kg VS/(m³·d) as it was reported from Sweden pilot A run nro.2 (8). High organic loading rate means that biorefinery can have smaller fermenter reactor volume than traditional biogas plant reactors have. Usually traditional biogas plant reactors are operated with organic loading rate of 3 kg VS/(m³·d). Organic loading rate of 65 kg VS/(m³·d) and feedstock mass flow of 10 000 ton/year with 8 % volatile solid concentration of fresh mass would lead to reactor volume of 34 m³. With organic loading of 3 kg VS/(m³·d) and same volatile solid mass flow reactor volume would be 744 m³. Thus, it is considered that pilot A high organic loading rate results lower electricity demands in mixing due to smaller reactor volume compared to traditional biogas reactors.

4.2 Energy demands in biogas process (B)

Electricity and heat demands in biogas process correspond model and parameters already introduced (7) except that incoming feedstock have high temperature due to fermentation process prior to digestion. It is assumed that solid reject is cooled down to 20 °C before it enters to anaerobic digestion phase through heat exchanger with effectiveness of 50 % and finally via heater to the biogas reactor. Feedstock is heated up to 37 °C before it enter reactor. Heat for heating up feedstock is taken from produced biogas.

5. Greenhouse gas balance scenarios

Goal of GHG assessment is to proof that how biorefinery (A process) and biogas (B process) can fulfill demanded GHG reductions considering that there is a further need to separate biochemical from process broth. Assessment is done by calculating how much biochemical concentrations in process broth should be to have zero net GHG balance in scenario 1. In addition, the effect of minimum biochemical concentrations, biomethane potentials and feedstock total solid concentrations for GHG reductions of 60 % is evaluated in scenario 2. Electricity and heat demands in biorefinery and biogas process contribute emissions while produced biochemical and biomethane can be used to replace fossil based chemicals and fuels which contribute negative total GHG emissions from the production system (Section 3.). By considering GHG emission only from heat and electricity consumption it can be deduced that what are at least minimum needed process broth biochemical concentrations. If GHG emissions from other material inputs to these processes would be considered they would increase total GHG emissions and require higher amounts of end products that can be used to replace fossil fuels.

Thus, GHG assessment is done by comparing the required production yields in two scenario that are also represented in Figure 3:

1. **Biorefinery operates as individual process.** GHG balance is calculated over system boundary A. GHG emissions from electricity and heat demands are considered. Produced biochemical decrease GHG emissions, since they replace fossil based biochemical. Minimum biochemical yields are introduced to achieve zero net GHG emissions.
2. **Biorefinery and biomethane processes operate in series.** Feedstock goes via biorefinery process to biogas process. Biomethane is the main product and thus MWh of biomethane is functional unit in GHG assessment. GHG balance is calculated for processes restricted by system boundaries A and B. Minimum biochemical and biomethane yields are introduced to have 60 % GHG reductions according to renewable energy directive (2009/28/EC).

The key question of this scenario set-up is to found required yields to start implement downstream process for process broth.

6. Results

To assess GHG balances in biorefinery and biomethane production systems their production yields are evaluated in two scenarios that are introduced in Section 5. . At first, there is evaluated scenario 1 where biochemical are produced in individual unit (Figure 3). In second scenario, there is evaluated biochemical and biomethane yields from an integrated system (System boundary A and B) of biorefinery (System boundary A) and biomethane production systems (System boundary A).

It is assumed that 10 000 ton/year of feedstock with total solid concentration of 10 % of fresh mass and volatile solid concentration of 81.5 % of total solids enters to heat recovery system (HRC). After pretreatment, fermentation, distillation and mechanical separation, solid residue is considered for biomethane production and liquid fraction for downstream process which is restricted out of system boundary. It is assumed that belt filter press is capable on drying input material up to total solid concentration of 22 % (7). In Figure 3 it is also assumed that solid residue from process broth can have biomethane potential of 300 Nm³/(t VS).

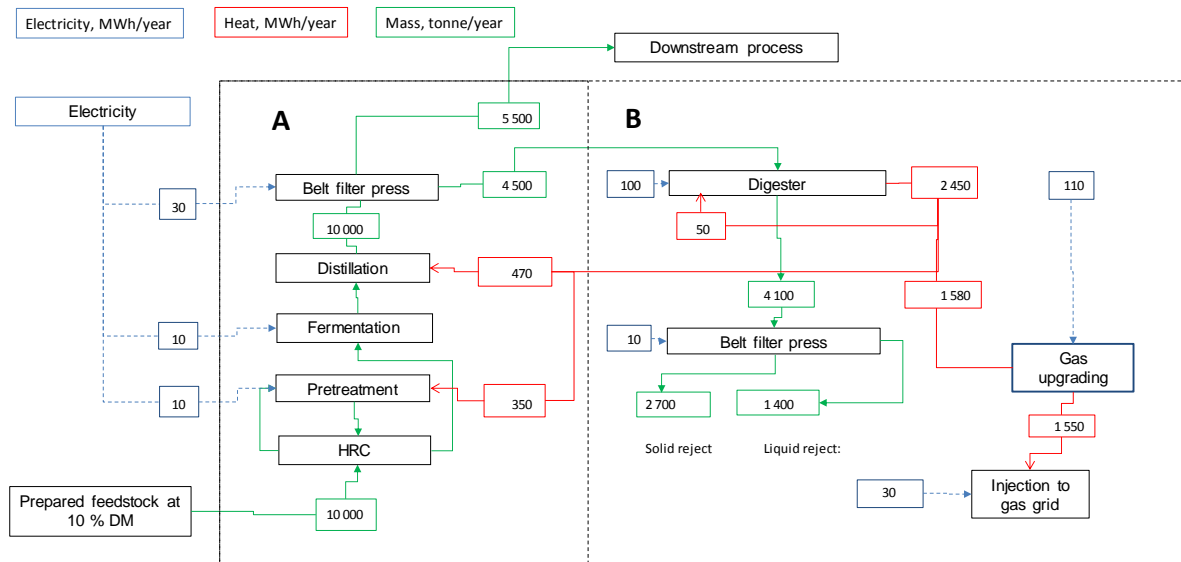


Figure 3. System boundary A includes biochemical production and system boundary B includes anaerobic digestion of solid residue.

6.1 Scenario 1.

Required biochemical yields (Table 2) are calculated to get net GHG balance as zero. Heat and electricity demands increase net GHG emissions while produced biochemical decrease it by replacing fossil based chemicals. GHG emissions are generated from electricity consumption of 50 MWh/year and from heat consumption of 820 MWh/year for feedstock pretreatment and ethanol distillation (Figure 3). Electricity consumption in mixing is considered in pretreatment and fermentation processes. In, addition 3 kWh/t of electricity is needed in belt filter press. Mixing electricity consumption of 2 kWh/t in this study is quite low compared to electricity consumption in a biogas plant which is 11 kWh/year (10). One of the reasons to relatively low electricity consumption is small reactor volume of 34 m³ which results from high organic loading of 65 kg VS/(m³·d) and volatile solid mass flow of 815 t/year.

To get zero net GHG emissions, needed biochemical concentrations for a typical biochemical mixture (Table 1 and Figure 2) are shown in Table 2. If this biochemical mixture have biochemical concentrations more than shown in Table 2 it means that it is reasonable to consider downstream process for that process broth. If biochemical concentrations are less than shown in Table 2 in this mixture, it means that net GHG emissions are positive. In other words, it means that further treatment to separate biochemical produce more GHG emissions than it can be replaced by end products and the net GHG balance remains positive.

Table 2. Minimum biochemical concentrations are shown in scenario 1.

	mg/L
Acetone	11
Ethanol	161
Propanol	6
Acetic acid	575
Propionic acid	634
Butyric acid	1 236
2,3 Butanediol	2 279
Total	4 903

6.2 Scenario 2.

Process broth biochemical concentration and biomethane potential as well as feedstock total solid concentration was determined over system boundary A and B when there is demand for GHG reduction of 60 % compared to fossil fuel reference (Figure 4). It can be deduced that the more is biomethane potential and biochemical concentration the more are GHG reductions. Biochemical and biomethane yields at 60 % GHG reduction demand depend strongly on feedstock total solid concentration as it can be seeing from Figure 4. When biorefinery and biogas processes are combined, required biochemical concentrations (Figure 4) are also lower than required concentrations from individual operation of biorefinery (Table 2). This means that integrated system of biorefinery and biomethane process result into higher GHG reduction than individual biorefinery.

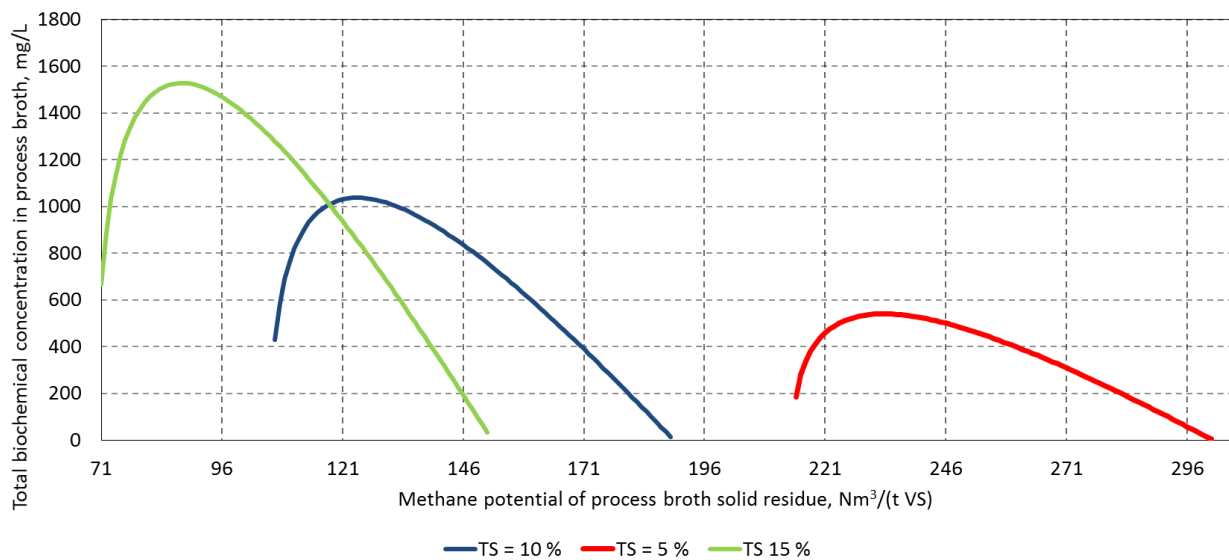


Figure 4. Minimum biochemical concentrations are represented over system boundaries A and B from scenario 2.

7. Conclusions

Results of this assessment can be applied together with experimental results about biochemical concentrations in process broth and biomethane productivity of process broth solid fraction. If biochemical yields are more than shown in Table 2 or in Figure 4 downstream process could be considered for process broth. In reality, mentioned minimum production yields tend to be higher since feedstock specific material and energetic inputs would increase total generated GHG emissions. Still, in general level it can be concluded that if solid fraction of process broth is capable in producing biogas or enhancing it, integrated biogas and biorefinery process could have much higher GHG reductions than individual biorefinery process. In addition to this, it is valuable to conclude that by integrating biorefinery and biogas process to power plant heat network, energy efficiency and GHG reductions of overall system can be increased. By utilizing condensate fluids from power plant the theoretical power production efficiency can be increased. Thus, in sustainable biochemical production system there is need to **combine biomethane, biorefinery and power production** systems.

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