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D22: Energy balance optimisation for an integrated arable/livestock farm unit

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Dissemination Level		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
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D22: Energy balance optimisation for an integrated arable/livestock farm unit

1 Introduction

Energy balance optimisation was made by evaluating and simulating energy balances of “Biogas from energy crops”-system. System started from cultivation of crops and ended up with biogas. Digestate was returned to the crop production and inorganic fertilisers were used only for compensating losses due to leaching and denitrification. With this model was also calculated a scenario where half of the produced crop was feeded to livestock.

2 System definition and source data

All calculations were made in primary energy. As the process has no by-products, all energy inputs can be allocated to biogas energy produced. In crop based scenarios, biogas production system consists of crop production, harvesting and pretreatments, storage, biogas reactor as well as post treatment and digestate storage. Energy inputs and output are out of system border (Fig. 1). Based on these allocations, energy balance is calculated as percentage how much of produced energy is required in production process. Results are also expressed as output:input ratio, which can be calculated as in formula 1.

Output:Input ratio=$E_{output} * E_{input}^{-1}$, where (1)
E_{output}=Energy produced from system
E_{input}=Energy required to run energy production system

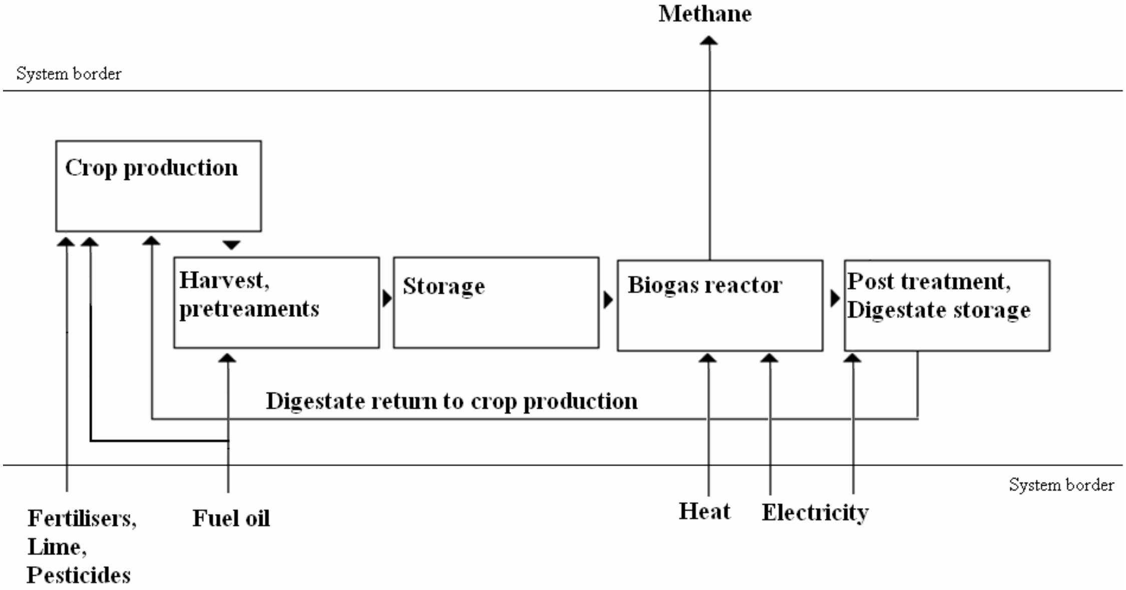

Figure 1. Biogas production system and system borders in crop based scenarios.

Calculations were made based on timothy grass, which can be easily cultivated with existing livestock infrastructure and prepared to silage. Timothy has also relatively high dry matter yield in boreal growing conditions compared to many other crops.

Cultivation and transporting was assumed to be made with Valtra tractor which fuel consumption is 18 l h^{-1} (FAT 2006). Energy content of fuel oil was assumed to be 11.6 kWh l^{-1}. Crops and solid digestion residue was transported in 10 ton trailer and liquid digestate in 15 m^3 container and returned empty. Average transport distance was assumed to be 4 km.

It was assumed that cultivation was made with machinery and practices that are generally used on Finnish farms (Table 1, Hyytiäinen ym. 1995, Evira 2006, Pahkala ym. 2005). Value below 1 indicates that procedure is carried less frequently than annually. Expected dry matter yield for timothy grass was 9 t ha^{-1} a^{-1}, but in first year half of normal, and assumed pasture renewal interval was four years. Pesticides (0,15 kg ha^{-1}) were assumed to be used every other year and silage was prepared using additive (formic acid 3 kg t^{-1}). Fertiliser requirements were 220 kg N, 10 kg P, 70 kg K and 1750 kg lime per hectare per annum. Energy requirements of chemical agents varied from 0.12 kWh kg^{-1} to 15.83 kWh kg^{-1} (Table 2). If digested residue is returned to crop production, the nutrients is cycled between digester and field. However, some of the nutrients are lost due to leaching and denitrification, which must be compensated with external fertilisation. In this study, annual loss of nutrients is estimated to be 10 % (Bouwman 1996, Esala 1998, Tolppa ym. 2002). Calculations were also done with assumption that digested residue was not used in crop production.

Energy usage of production of seed and packages were excluded from the study, since it has been shown to have only small effect and inclusion would have been complex (Katajajuuri ym. 1995). Production of farm machinery was also excluded due to the complexity, although it may be significant because the usage of some machinery may be minor during their life cycle (Börjesson 1996).

Table 1. Data used in order to calculate energy consumption in cultivation.

	Ploughing	Liquid fertilisation	Solid fertilisation	Harrowing	Seedbed cultivation	Rolling	Sowing and fertilisation	Moving	Harvest	Liming	Sprayning
Workwidth, m	2	15	6	4,5	4	4,5	3	3,2	6,4	12	20
Speed, km h^{-1}	7	8	8	7	7	7	6	7	7	7	8
Procedure carried pa	0,25	2	0,25	0,25	0,5	0,5	0,25	2	2	0,25	0,5

Table 2. Primary energy consumption of fertilisers, lime, pesticides and silage additive.

Chemical agent	Energy consumption kWh kg^{-1}	Source:
N fertiliser	13.89	Ramirez and Worrel 2005
P fertiliser	2.67	Ramirez and Worrel 2005
K fertiliser	1.86	Ramirez and Worrel 2005
Lime	0.12	Katajajuuri et al. 2000
Pesticides	15.83	Pimentel 1980
Silage additive	1.03	Grönroos and Voutilainen 2001

Biogas potential from timothy silage was 0.34 m^3CH_4 kg^{-1} VS_{added} (Lehtomäki 2006). During full scale digestion, 89 % of total potential was assumed to be achieved as this percentage is achieved during 50 day digestion in assay. Organic loading rate used in calculations was 3 kgVS m^{-3} d^{-1}, which is commonly used loading rate in agricultural biogas plants digesting energy crops (FAL 2005).

Electricity used in model was assumed to be average electricity produced in Finland. Energy efficiency in electricity production was calculated by dividing utilised electricity and heat energy produced by primary energy used in production (Tilastokeskus 2006). Average electricity production efficiency in Finland was 61 % when calculated this manner.

Heat transfer coefficients used in calculations were 0.06 W m^{-1} $^oK^{-1}$ for rock wool insulation and 1.2 W m^{-1} $^oK^{-1}$ for concrete (Ympäristöministeriö 2002). Parts of digester above ground were assumed to be insulated with 200 mm rock wool and foundation to be 400 mm thick concrete. Reactor was assumed to be cylindrical in shape, with diameter:height ratio of 1:1.5 and with working volume of 80 % of total reactor volume. Silage was assumed to have same specific heat as water, as silage has moisture content of 70-80 %. Average outside temperature was assumed to be 2 °C, which is average temperature in Central Finland. Efficiency in heat production was assumed to be 85 %, and 30 % of energy demand of heating feedstock was assumed to be met with heat exchangers. Formulas 2 and 3 were used to calculate heat energy demand of the biogas plant.

$hl = UA\Delta T$, where (2)

hl = heat loss, (kJ s^{-1})
U = overall coefficient of heat transfer, (W m^{-2}.°C)
A = cross-sectional area through which heat loss is occurring, (m^2)
ΔT = temperature drop across surface in question, (°K).

$q = CQ\Delta T$, where (3)

C = specific heat of the feedstock (MJ t^{-1} °C)
Q = amount of feedstock added (m^3)
ΔT = temperature difference between digester and feedstock, (°K).

Technical data of machinery in biogas plant were obtained from full scale plants and manufacturers. Constant energy requirements are mixing, 5 W $m^{-3}_{reactor}$ and keeping the pressure in gas holder, 0.2 kW. Pumps were assumed to be 4 kW with capacity of 20 m^3 h^{-1} and screw conveyors 15 kW and capacity 50 m^3 h^{-1}. Dewatering was made with belt press, power 1 kW and capacity of 200 kgDM h^{-1}. For vehicle use, biogas was purified which uses 0.3 kWh electricity per m^3 of scrubbed gas, and 2 % of methane is lost during process. In addition, compression to 250 bar uses 0.2 kWh electricity per m^3 (Nilsson 2003).

With this model, a scenario where half of the silage was used for livestock feeding was calculated as well. Calculations were made according to the assumption that one dairy cow produces 0.76 t of manure from 1 t of silage and methane production from manure was 0.22 $m^3CH_4\ kg^{-1}\ TS_{added}$. One dairy cow consumes heat energy and electricity of 1.25 MWh a^{-1} and 2.4 MWh a^{-1}, respectively (Hagström et al. 2005).

3 Results

Biogas production system using energy crops with reactor size of 1000 m^3 and with preceding assumptions uses 16.8 % of produced energy in production process. If expressed as output:input ratio, figure is 6.1. Required acreage of crop production for plant would be 140 ha. Net energy production per hectare would be 20 MWh per annum and plant's continuous power 374 kW.

Major energy consumer is heat energy required by heating the feedstock and maintaining the digester temperature, using 9.1 % of produced energy. Crop production uses 3.9 % of produced energy and electricity demand is 2.6 %. Transport and chemical additive to silage are lesser energy users, requiring 0.9 % and 0.5 % corresponding.

3.1 Sensitivity analysis

Specific methane yield affects energy balance; 20 % decrease or increase gives output:input ratios of 4.8 and 7.3. Specific methane yields can be affected to some extent by well-timed harvesting (Lehtomäki 2006). Selected level for crop yield also affects the energy balance. If dry matter yield of crop is 25 % lesser or greater, will output:input ratio be 5.5 or 6.3. Optimal harvest timing should be optimised regards both yield and methane potential.

If timothy grass is changed to an annual crop, oat, which is also utilised as silage, the share of crop production increases to 7.2 % of produced energy. Increase derives from more frequent tilling practices.

Of process parameters, organic loading rate has significant effect on energy balance, as higher load enables smaller reactor volumes and therefore decreases the reactor size and required heating and mixing energy. If organic loading rate could be raised from 3 kgVS $m^{-3}\ d^{-1}$ to 5 kgVS $m^{-3}\ d^{-1}$, output:input ratio would increase to 7.3. Organic loading rate of 5 kgVS $m^{-3}\ d^{-1}$ is realistic target, as it is currently used at several agricultural digesters (FAL 2005).

Heat demand of the digester is a major factor in energy balance. Removing heat exchangers from the system decreases output:input ratio to 5.4. Relative energy demand of the plant can be decreased by increasing volume, as reactor area increases slower than volume. Thermophilic process temperature uses 1.6 times more energy than mesophilic in 1000 m^3 reactor. If same energy output:input ratio is required in both process temperatures, thermophilic reactor must have 2.5 times higher organic loading rate and smaller reactor size in proportion.

In base scenario, metabolic heat produced by anaerobic bacteria was not taken into account when calculating heat energy demand. It has been reported that all heat energy demand can be satisfied with this metabolic heat, and even excess is produced, when co-digesting energy crops and manure in central Europe (Lindorfer et al. 2005, Weiland 2005). If in boreal conditions half of the heat energy demand would be met with metabolic heat, the output:input ratio rises to 8.2.

Transport has relatively small effect on energy balance. Transport distance has to be over 400 kilometres before energy balance turns negative despite of empty return. Although transportations energetical effect is small, it may be significant in economical approach.

3.2 Effect of biogas utilisation alternatives and system boundaries on energy balance

In base scenario, crop production was carried out with nutrient recycling. If system is assumed to be run with artificial fertilisers only, will output:input ratio decrease to 3.5. If annual nutrient loss is doubled from assumed, will output:input ratio be 5.5. In livestock scenario, energy requirements of livestock are 2.2 % of produced energy and total plant power decreases to 298 kW compared to 374 kW in base scenario.

If biogas upgrading to transport fuel is included in the system, decreases output:input ratio to 4.1, as it requires electricity and some of the methane are lost during upgrading process. Primary energy demand of upgrading (8.2 %) is almost as high as energy demand of heating.

If some of the energy used in the production chain will be covered by utilising biogas, will output:input ratio increase, but total plant power decrease as some of the gas is used in parasitic requirements. In these calculations, efficiency in heat production was assumed to be 85 %, CHP efficiency in electricity and heat 30 % and 55 %, respectively. If biogas is not upgraded to transport fuel and parasitic electricity of plant is met with own CHP, rest of the parasitic heat is covered with gas burner. If upgrading to transport fuel is included, parasitic electricity demand will be so high that excess heat will be produced. Energy balances taking into account scenarios with artificial fertilizers and parasitic energy requirements are presented in figures 2 and 3.

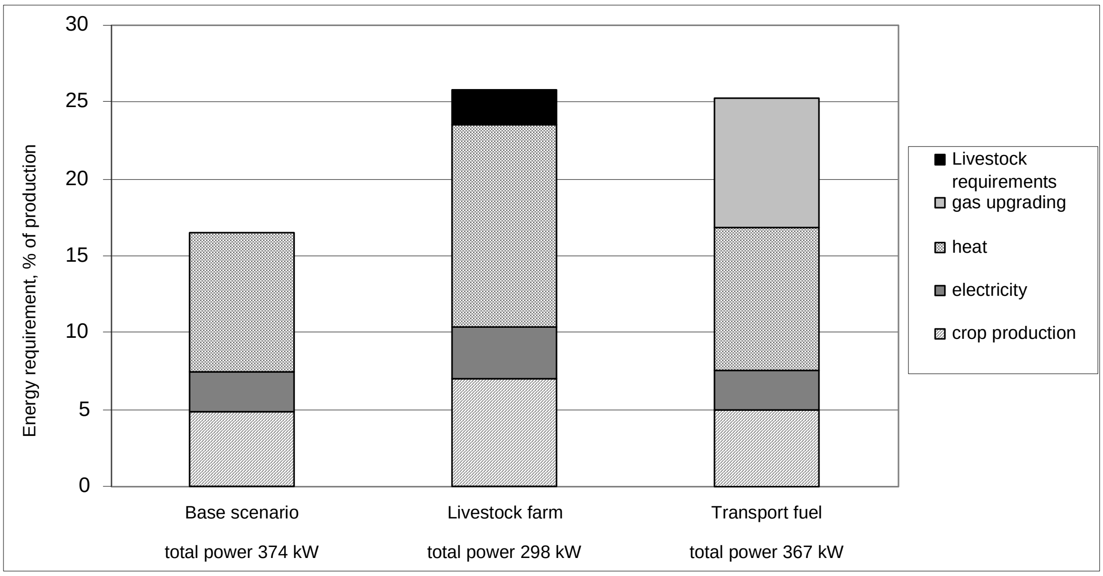

Figure 2. Effects of different biogas utilisation alternatives to energy balance and total plant power.

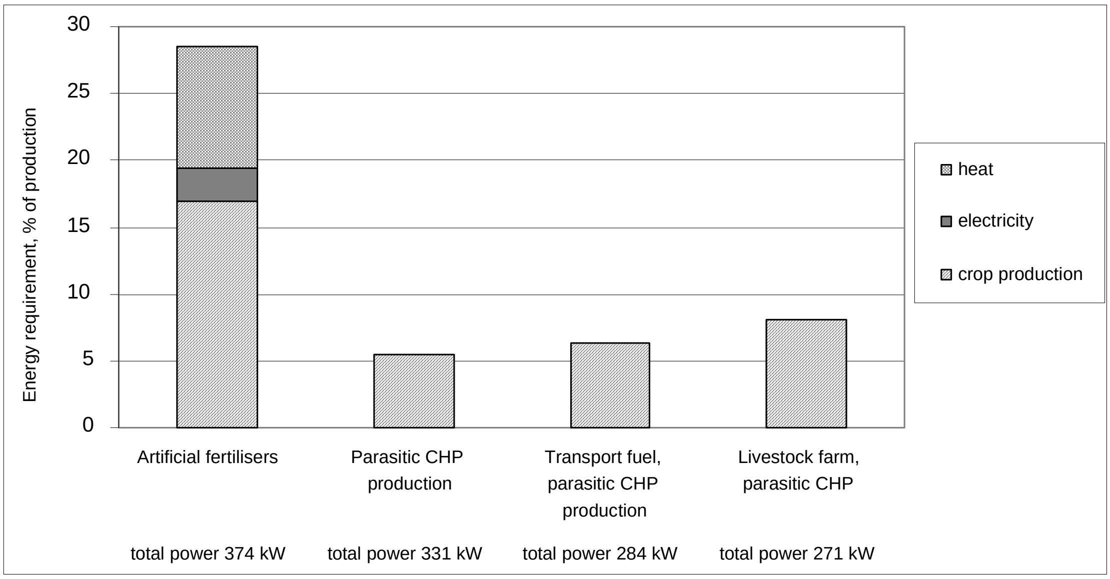

Figure 3. Effects of different system boundaries to energy balance and total plant power.

As a conclusion, energy output:input ratio varied significantly with different assumptions and system boundaries. Lowest ratio was with using artificial fertiliser instead of digestate recycling (3.5) and highest when metabolic heat produced by anaerobic bacteria was taken into account (8.2).

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