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Energy efficient model for biogas production in farm scale

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Abstract: Energy efficient solutions for six farm biogas production was found by calculating mass and energy balance in different scenarios. Raw materials in biogas production were cow manure and grass silage that were produced in these farms. There were calculated mass and energy balances on average for one year biogas prouduction that consisted of grass silage production, raw material transportation and biogas production in the biogas plant. In addition, direct greenhouse gases from biogas production were estimated. The direct mass and energy flows were calculated. It turned out that one input energy unit can produce 5.0 to 5.5 energy units as heat and electricity. Biogas reactor consumed heat from 42 to 66 % of the produced electricity. The electricity consumption in the biogas plant was from 12 to 18 % of the produced electricity. Energy consumption in the raw material transportation was from 7 to 14 % of the produced electricity. Energy consumption in the grass silage production was from 11 to 16 % of the produced electricity. In the electricity production the heat is also produced that should be utilized to keep the total energy balance positive. If the heat utilizer would not considered, the direct CO_2 emissions and the energy consumption in transportation could be decreased by one third. The energy consumption in the grass silage production consisted of an energy consumption in the field and a transportation energy consumption between farms and their field blocks. It turned out that the transportation energy consumption can be even more than half of the energy consumption in the field. By replacing mineral fertilizers with digestate, it could be possible to half the need of mineral fertilizers from present situation.

Suomenkielinen tiivistelmä: Kuuden suomalaisen maatilan biokaasun tuotannolle etsittiin energiatehokkaita ratkaisuja laskemalla massa- ja energiatase eri tarkasteluskenaarioissa. Raaka-aineina biokaasun tuotannon mallintamisessa käytettiin lehmän lantaa sekä maatiloilla tuotettua nurmisäilörehua. Massa- ja energiatase koostuivat keskimäärin yhden vuoden aikana syntyneistä energia- ja massavirtauksista nurmisäilörehun tuotannossa, raaka-aineiden kuljetuksissa sekä biokaasun tuotannossa biokaasulaitoksella. Lisäksi arvioitiin myös biokaasun tuotannon elinkaaren aikana syntyviä suoria kasvihuonekaasupäästöjä. Taseessa huomioitiin suorat energia- ja massavirrat. Kävi ilmi, että yksi energiapanos biokaasun tuotantoon voisi tuottaa 5.0 - 5.5 energiayksikköä sähkönä ja lämpönä. Biokaasureaktori kulutti lämpöä 42 - 66 % tuotetusta sähköenergiasta. Sähkönkulutus biokaasulaitoksella oli 12 - 18 % tuotetusta sähköenergiasta. Raaka-aineiden kuljetusten osuus tuotetusta sähköenergiasta oli 7 - 14 %. Säilörehun tuotannon energian kulutus oli 11 - 16 % tuotetun sähköenergian määrästä. Sähkön tuotannossa syntyy myös lämpöä, joka on kokonaisenergiataseen kannalta ehdottomasti hyödynnettävä. Jos lämmön kuluttajaa ei tarvitsisi huomioida, niin raaka-aineiden kuljetusten suoria CO_2 päästöjä ja kuljetusenergian kulutusta voitaisiin pienentää kolmanneksella. Nurmitehun tuotannon energiatase laskettiin peltotyönä sekä tiekuljetustyönä maatilojen sekä niiden peltolohkojen välillä. Osoittautui, että tiekuljetustyön osuus voi olla jopa yli puolet peltotyön osuudesta. Korvaamalla keinolannoitteita käsittelyjäännöksellä, voitaisiin keinolannoitteden määrä tiputtaa alle puoleen nykyisestä.

Keywords: Biogas production, LCA, grass silage production, transportation, energy consumption, greenhouse gas emissions, the cluster of farms, biogas reactor, mass and energy balance
Avainsanat: Biokaasun tuotanto, LCA, nurmirehun tuotanto, kuljetukset, energian kulutus, kasvihuonekaasupäästöt, maatilakeskittymä, biokaasureaktori, massa- ja energiatase

Preface

This work would not have been possible without the funding of Agrifood Research Finland, MTT. Ph.D Sari Luostarinen from MTT, gave me the problem set-up and the work was carried out in Kuopio where the University of Eastern Finland offered me possibility to do this work in the group of environmental informatics. I greatly thank for the people in MTT for giving me the possibility to do the master's thesis from very hot topic, mass and energy balance from biogas production. Especially Sari Luostarinen gave me highly professional academic experience about working in MTT which was important for making the right decisions in the modeling work. M.Sc Ville Pyykkönen, did great job during the measument period in MTT's biogas plant and supported this work by giving a relevant input data. M.Sc and Upcoming Ph.D, Auvo Sairanen gave professional comments for grass silage production processes that was one of the third important sections in this work.

I thank also the people in the University of Eastern Finland that were supporting my decision making in this cross scientifical working process. Professor Juhani Ruuskanen, had a far-reaching sight of this field of study that was very important when crucial decisions were made. M.Sc and upcoming Ph.D, Harri Niska give his experience for testing numerical tools for the work that is highly important in the future when the calculation tools should be also in a high level. With Ph.D Helvi Heinonen-Tanski, we were also planning a future scenario considering slurry pumping in a farm cluster, but that subject was restricted out of this work.

The base knowlegle and experience came from The University of Jyväskylä. The structure of this work was made with Ph.D Jussi Maunuksela which was highly important in this cross scientifical work. Jussi was also the first inspector of this work. The second inspector professor Jukka Rintala, have years of experience in this field of study which increased the scientific value of this work.

The last, but not the least I want to thank my friends who did not wanted to be mentioned, but who were involved in this work in a very positive way. As an example, my farmer and student colleagues gave vital comments for this work. The most of all, I want to thank my family for all support for my studies.

Glossary

A_i	ha	Surface area of field block i.
A_{BT}	m^2	Bottom area of biomass in MTT's biogas reactor.
A_S	ha	Sowed area.
A_{ST}	m^2	Side area of biomass in the test version.
A_{TT}	m^2	Top area of biomass in the test version.
C_D	kJ/(kgK)	Specific heat capacity of total solids in manure and grass.
C_F	kg/h	Tractor's maximum fuel consumption in fertilizer spread.
C_{HC}	kg/h	Tractor's maximum fuel consumption in harvest cut process.
C_{HH}	kg/h	Tractor's maximum fuel consumption in harvesting with pick up trailer.
C_{HS}	kg/h	Tractor's maximum fuel consumption in harvested grass storing.
C_L	kg/h	Tractor's maximum fuel consumption in lime spread and transport.
C_P	[1]	Dimensionless power constant.
C_R	kg/h	Tractor's maximum fuel consumption in grass renewing process.
C_S	kg/h	Tractor's maximum fuel consumption in slurry spread and transport.
C_W	kJ/(kgK)	The specific heat capacity of water.
C_{SP}	kg/h	Tractor's maximum fuel consumption in spraying process.
C_{TG}	kg/h	Tractor's maximum fuel consumption in grass silage transportation.
d_M	mm	Effective diameter of mixer's blade.
d_i	km	Shortest distance from generalized farm into the field block i.
d_{Ti}	km	Distance from farm i into the biogas plant.
d_0	km	Optimal position for biogas plant.
Δt	s	A time interval.
$\Delta_f H^o$	kJ/mol	Standard enthalpy of formation.
$\Delta_r H^o$	kJ/mol	Heat released or needed in chemical reaction.
θ_f	[1]	$\theta_f = f_f/f_M$, Input voltage relative frequency of mixer.
ϕ_F	[1]	The share of feedstock massflow in test version BGP of the feedstock massflow in LCA - model.
ϕ_G	[1]	The grass silage fresh mass flow of the slurry manure fresh mass flow.
ϕ_P	[1]	A time needed to pump slurry of the minimum possible time.
ϕ_{VSG}	[1]	Grass silage volatile solids of the total volatile solids.
FC	[1]	Fixing factor in grass silage and slurry manure co - digestion.
f_f	rpm	Revolution speed of mixer.
f_M	rpm	Maximum revolution speed of mixer.
g	$\mathrm{m/s}^2$	Gravitation constant.
η_E	%	Efficiency of electricity production in CHP.
η_H	%	Efficiency of heat production in CHP.
η_{max}	%	Efficiency of pump at best efficiency point (BEP).
ρ_{CH_4}	$\mathrm{kg/m}^3$	Density of methane.
ρ_G	$\mathrm{kg/m}^3$	Density of grass silage.

ρ_M	kg/m^3	Density of slurry manure.
ρ_{BM}	kg/l	Density of biomass in the reactor.
ρ_W	kg/l	Density of water.
H	m	Pump head.
H_F	MJ/kg	Lower heating value of diesel.
H_{CH_4}	MJ/m^3	Lower heating value of methane.
$\dot{H}_{CH_4}$	kW	Heat power content of methane.
HRT	d	Hydraulic retention time.
k	[1]	Number of field blocks and routes from farms into their field blocks.
L_{FS}	%	Tractor's fuel consumption of the max. in fertilizer spread.
L_{FT}	%	Tractor's fuel consumption of the max. in fertilizer transport.
L_G	%	Tractor's fuel consumption of the max. in grass silage transportation with full load.
L_{GE}	%	Tractor's fuel consumption of the max. in grass silage transportation with empty load.
L_{GL}	%	Tractor's fuel consumption of the max. in grass silage loading.
L_{HC}	%	Tractor's fuel consumption of the max. in harvest cut on field.
L_{HCT}	%	Tractor's fuel consumption of the max. in moving machine transportation.
L_{HH}	%	Tractor's fuel consumption of the max. in harvesting with pick up trailer.
L_{HS}	%	Tractor's fuel consumption of the max. in harvested grass storing.
L_{HT}	%	Tractor's fuel consumption of the max. in harvested grass transportation.
L_{LL}	%	Tractor's fuel consumption of the max. in lime load into the lime trailer.
L_{LSP}	%	Tractor's fuel consumption of the max. in lime spread.
L_{LT}	%	Tractor's fuel consumption of the max. in lime transport.
L_{RH}	%	Tractor's fuel consumption of the max. harrowing.
L_{RP}	%	Tractor's fuel consumption of the max. in ploughing process.
L_{RR}	%	Tractor's fuel consumption of the max. in rolling process.
L_{RS}	%	Tractor's fuel consumption of the max. in sowinging process.
L_{RT}	%	Tractor's fuel consumption of the max. in transportation in renewing process.
L_{SL}	%	Tractor's fuel consumption of the max. in slurry load.
L_{SP}	%	Tractor's fuel consumption of the max. in spraying.
L_{SPT}	%	Tractor's fuel consumption of the max. in sprays transport into field block.
L_{SS}	%	Tractor's fuel consumption of the max. in slurry spread.
L_{ST}	%	Tractor's fuel consumption of the max. in slurry transportations.
L_{TSE}	%	Tractor's fuel consumption of the max. in slurry transportations when slurry tank is empty.
l_T	m	Height of biomass in the test version.
l_M	m	Height of biomass in the LCA model.
MPR	m^3/(tVS)	Methane productivity from volatile solids.
MPR$_G$	Nm^3/(tVS)	Methane productivity from grass silage.
MPR$_M$	Nm^3/(tVS)	Methane productivity from slurry manure.
m_{CH_4}	t	Produced mass of methane from biogas plant.
m_{DM}	t	Total amount of digestate from biogas plant.
m_{Di}	t	The amount of digestate that is transported into the farm i.
m_{EB}	t	Total amount of all greenhouse gases from biogas production.

m_{EGF}	t	Total amount of all greenhouse gases from grass production in field.
m_{EGT}	t	Total amount of all greenhouse gases from transportation in grass silage production.
m_{ETS}	t	Total amount of greenhouse gases from slurry transportation.
m_{ETG}	t	Total amount of greenhouse gases from grass silage transportation.
m_{FL}	kg	Fertilizer load in broadcaster machine.
m_{GM}	t	Total amount of grass silage produced in the farm cluster that goes into the biogas plant.
m_{Gi}	t	The mass of grass silage from farm i into the biogas plant.
m_{GL}	t	The mass of grass silage that is loaded in the transportation trailer.
m_{HL}	kg	Mass of one harvested load in the pick up trailer.
m_{IN}	t	Total mass of substances imported into the grass production.
m_{LL}	kg	Mass of one lime load.
m_{MM}	t	Total amount of manure from farms into the biogas plant.
m_{Mi}	t	Mass of manure from farm i produced into the biogas plant.
m_{RFL}	kg	Fertilizer load in a sowing machine.
m_{SL}	t	Mass of slurry that tanker can carry [11].
m_{SPL}	kg	Spray solution load in spray tanker.
$\dot{m}_{DM}$	kg/s	Mass flow of digestate in LCA model.
$\dot{m}_{DT}$	kg/s	Mass flow of digestate in test version's biogas plant.
$\dot{m}_{GM}$	kg/s	Mass flow of grass silage in LCA model.
$\dot{m}_{GT}$	kg/s	Mass flow of grass silage in test version's biogas plant.
$\dot{m}_{MM}$	kg/s	Mass flow of slurry manure in LCA model.
$\dot{m}_{MT}$	kg/s	Mass flow of slurry manure in test version's biogas plant.
$\dot{m}_{STP}$	t/min	Mass flow rate of slurry tanker pump [11].
$\tilde{m}_{FR}$	kg/ha	Fertilizer requirement.
$\tilde{m}_{LR}$	kg/ha	Lime requirement.
$\tilde{m}_{RFR}$	kg/ha	Fertilizer requirement in renewing process.
$\tilde{m}_{SPR}$	kg/ha	Spraying requirement.
$(\dot{m}h)_{MT}$	kW	Heat power content of slurry manure in test version.
$(\dot{m}h)_{GT}$	kW	Heat power content of grass silage in test version.
$(\dot{m}h)_{DT}$	kW	Heat power content of digestate in test version.
$(\dot{m}h)_{BG}$	kW	Heat power content of biogas in test version.
$(\dot{m}h)_{MM}$	kW	Heat power content of slurry manure in LCA model.
$(\dot{m}h)_{GM}$	kW	Heat power content of grass silage in LCA model.
$(\dot{m}h)_{DM}$	kW	Heat power content of digestate in LCA model.
$\tilde{m}_{SR}$	t/ha	Slurry (manure or digestate) requirement per hectare.
n_{Fi}	[1]	Number of fertilizer loads needed at field block i in fertilizer spread.
n_{Hi}	[1]	Number of harvested grass loads from field block i.
n_{HCi}	[1]	Number of times needed to drive into field block i with moving machine.
n_{Li}	[1]	Number of times needed to drive into field block i with lime trailer.
n_m	[1]	The number of field blocks that farm m has.
n_{Ri}	[1]	Number of times needed to drive into field block i with sowing machine.
n_{RHi}	[1]	Number of times needed to drive into field block i with harrow device.
n_{RPi}	[1]	Number of times needed to drive into field block i with plough device.
n_{RRi}	[1]	Number of times needed to drive into field block i with roll device.

n_{Si}	[1]	Number of slurry loads needed for field block i in slurry management.
n_{SPi}	[1]	Number of spray tank loads needed for field block i.
n_{TGi}	[1]	Number of grass silage loads from farm i into the biogas plant.
n_{TSi}	[1]	Number of slurry loads from farm i into the biogas plant.
n_{TSEi}	[1]	Number of slurry loads from farm i into the biogas plant when one of two loads is empty.
OLR	kgVS/(m^{3}d)	Organic loading rate.
OLR$_M$	kgVS/(m^{3}d)	Maximum organic loading rate.
P_F	kW	Tractor's maximum power in fertilizing.
P_H	kW	Tractor's maximum power in grass harvesting.
P_L	kW	Tractor's maximum power in lime spread.
P_R	kW	Tractor's maximum power in grass renewing process.
P_S	kW	Tractor's maximum power in slurry management.
P_{SP}	kW	Tractor's maximum power in spraying.
Q_W	l/s	Volume flow of water.
Q_M	GJ	Energy needed in 1^{st} reactor heating.
q_{LM}	kW	Heat power leakage from LCA model's biomass.
q_{LT}	kW	Heat power leakage from test version's biomass.
q_T	kW	Heat power needed in test version's 1^{st} reactor heating.
q_M	kW	Heat power needed in LCA model's 1^{st} reactor heating.
q''_B	W/m^2	Surface heat power loss from biomass bottom inside the 1^{st} reactor.
q''_S	W/m^2	Surface heat power loss from biomass side's inside the 1^{st} reactor.
q''_T	W/m^2	Surface heat power loss from biomass top inside the 1^{st} reactor.
r_M	m	Radius of biomass in LCA model.
r_T	m	Radius of biomass in test version.
T_{DM}	K	Temperature of digestate from the 1^{st} reactor in LCA model.
T_{DT}	K	Temperature of digestate from the 1^{st} reactor in test version.
T_{GM}	K	Temperature of grass silage in the LCA model.
T_{GT}	K	Temperature of grass silage in the test version.
T_{MM}	K	Temperature of slurry manure in the LCA model.
T_{MT}	K	The temperature of slurry manure in the test version.
TS$_{DM}$	%	The total solid content of digestate after the 1^{st} reactor in the LCA model.
TS$_{DT}$	%	The total solid content of digestate after the 1^{st} reactor in the test version.
TS$_{GM}$	%	The total solid content of grass silage in the LCA model.
TS$_{GT}$	%	The total solid content of grass silage in the test version.
TS$_{MM}$	%	The total solid content of slurry manure in the LCA model.
TS$_{MT}$	%	The total solid content of slurry manure in the test version.
t_i	min	Time interval i that mixer runs at a certain power.
t_{GC}	h	Time of one grass silage load cut from storage and upload into trailer.
t_{GU}	h	Time of one grass silage load unload from trailer.
t_{HH}	h	Time of harvesting one grass load with pick up trailer.
t_{HL}	h	Time of unloading one load from pick up trailer.
t_{HS}	h	Time of storing one load of grass.
t_{LL}	h	Time to load one lime load of m_{LL} into the lime trailer.
t_{SP}	h	Time to pump one load of slurry into the slurry tanker.
t_{WP}	h	Time of working period in field.

Y_G	(kg ww)/ha	Grass yield in terms of wet weight per hecrate.
V_F	kg	Total fuel consumption in fertilizing.
V_{FS}	kg	Fuel consumption in fertilizer spread.
V_{FT}	kg	Fuel consumption in fertilizer tranportation.
V_H	kg	Total fuel consumption in harvesting process.
V_{HHF}	kg	Total fuel consumption in grass harvesting in field.
V_{HHT}	kg	Total fuel consumption in harvested grass transportation.
V_{HCF}	kg	Fuel consumption in harvest cut in field.
V_{HCT}	kg	Fuel consumption in mowing machine transportation.
V_L	kg	Fuel consumption in lime spread and transportation.
V_{LF}	kg	Fuel consumption in field in lime spread.
V_{LT}	kg	Fuel consumption in lime transportation.
V_M	m^3	Volume of biomass inside the 1^{st} reactor in the LCA model.
V_R	kg	Total fuel consumption in grass renewing process.
V_{RF}	kg	Total fuel consumption in field in grass renewing process.
V_{RT}	kg	Total fuel consumption in road in grass renewing process.
V_S	kg	Total fuel consumption in slurry management.
V_{SL}	kg	Fuel consumption in slurry load.
V_{SP}	kg	Fuel consumption in spraying process.
V_{SPF}	kg	Fuel consumption in field in spraying process.
V_{SPT}	kg	Fuel consumption in sprays transportation.
V_{SS}	kg	Fuel consumption in slurry spread and load.
V_{ST}	kg	Fuel consumption in slurry transportation.
V_T	m^3	Volume of biomass inside the 1^{st} reactor in test version.
V_{TG}	kg	Total fuel consumption in grass silage transportation.
V_{TGi}	kg	Total fuel consumption in grass silage transportation between farm i and the biogas plant.
V_{TGT}	kg	Fuel consumption in road in grass silage transportation into the biogas plant.
V_{TS}	kg	Fuel consumption in slurry transportations between farms and the biogas plant.
V_{TSi}	kg	Fuel consumption in slurry transportations between farm i and the biogas plant.
V_{TSE}	kg	Fuel consumption in slurry transportations between farms and biogas plant when one load from two is empty.
V_{TSEi}	kg	Fuel consumption in slurry transportations between farm i and the biogas plant when one load from two is empty.
V_{TST}	kg	Fuel consumption in slurry transportations between farm and biogas plant.
VS_G	%	Volatile solids from grass silage wet weight.
VS_M	%	Volatile solids from slurry manure wet weight.
v_{FS}	km/h	Tractor's speed in fertilizer spread.
v_{FT}	km/h	Tractor's speed in fertilizer transport.
v_G	km/h	Tractor's speed in grass silage transportation.
v_{HC}	km/h	Mowing machine working speed in field.
v_{HH}	km/h	The speed of pick up trailer.
v_{HT}	km/h	Tractor's speed in moving machine/pick up trailer transportation.
v_{LSP}	km/h	Tractor's speed in lime spread.
v_{LT}	km/h	Tractor's speed in lime transportation.
v_{RH}	km/h	Tractor's speed in harrowing process.

v_{RP}	km/h	Tractor's speed in ploughing process.
v_{RR}	km/h	Tractor's speed in rolling process.
v_{RS}	km/h	Tractor's speed in sowing process.
v_{RT}	km/h	Tractor's speed in transportation in renewing process.
v_{SP}	km/h	Tractor's speed in spraying in field.
v_{SPT}	km/h	Tractor's speed in sprays transportation.
v_{SS}	km/h	Tractor's speed in slurry spread.
v_{ST}	kg/h	Tractor's speed in slurry transport.
W_B	GJ	Total amount of energy that is needed to run biogas plant.
W_{CM}	GJ	Mixer's input energy derived from power measurements.
W_{EL}	GJ	Total amount of electricity produced from biogas.
W_G	GJ	Total amount of work that is needed in grass production.
W_{GF}	GJ	Work needed for grass silage production in field.
W_{GT}	GJ	Work needed for grass silage production in road transportations.
W_M	GJ	Mixer's energy derived from dimensional analysis.
W_{MINOR}	GJ	Energy needed to run minor energy devices in biogas plant.
W_P	GJ	Total energy needed in pumping in biogas plant.
W_{TS}	GJ	Work needed for slurry transportation.
W_{TSi}	GJ	Work needed for slurry transportation between farm i and the biogas plant.
W_{TG}	GJ	Work needed for grass silage transportation.
W_{TGi}	GJ	Work needed for grass silage transportation between farm i and the biogas plant.
$\dot{W}_M$	kW	Actual power of 15 kW mixer.
$\dot{W}_{CM}$	kW	Actual power of 7,5 kW mixer.
$\dot{W}_P$	kW	Input power of one slurry pump.
$\dot{W}_X$	kW	Actual power of mixer X.
$\bar{\dot{W}}_X$	kW	Average power of pump X.
w_i	kg^2/h	Weight factor needed in biogas plant optimal positioning.
w_{FS}	m	Working width of fertilizer broadcasting unit [12].
w_{HC}	m	Working width of moving machine.
w_{HH}	m	Working width of pick up trailer, usually $w_{HH} = w_{HC}$.
w_{LSP}	m	Working width of broadcaster in lime trailer.
w_{RH}	m	Working width of harrow.
w_{RP}	m	Working width of plough device.
w_{RR}	m	Working width of roll device.
w_{RS}	m	Working width of combined seed and fertilizer sowing machine.
w_{SS}	m	Working width of slurry tanker [11].
w_{SP}	m	Working width of spraying unit.
w_i	kg^2/h	Weight factor for fuel consumption and transported load.
Q_{HEAT}	GJ	Net heat produced from biogas.

Contents

1 Introduction

The European parliament has set a goal for Finland to increase its renewable energy production up to 38 % of the total production by 2020 [1]. Electricity production from renewable sources was 31 % of the total electricity consumption of 87.2 TWh in Finland in 2008 [2]. The share of biogas energy consumption was just 0.4 % from total renewable energy mix in 2006 [3]. Biogas production can be used to increase the share of renewable energy production in Finland. German research proved that electricity produced from biogas reduces greenhouse gas emissions in terms of carbon dioxide equivalents compared to typical electricity mix [4]. It is also known from previous studies that biogas production processes have more energy outputs than energy inputs.

Previous studies from biogas production have shown that there is a need for local data about biogas production in Finnish conditions. Most studies have considered energy flows in crop production, transportation and biogas production in the plant. Those studies showed the need of local data, because weather conditions in Finland effect crop production, transportations and biogas production. That is why in this study mass and energy balance were calculated for biogas production in Finnish conditions based on exact transportation distances in crop production and measured data from a Finnish biogas plant. Mass and energy balances were calculated for three different scenarios when only direct energy inputs were considered. As a conclusion an energy efficient model for biogas production in a farm scale was reported.

1.1 Previous studies

Earlier Juha Luostarinen calculated an energy balance for biogas production in a farm scale [5]. He suggested that one energy unit into the biogas production produced 5.9 energy units. Both indirect and direct energy inputs in timothy grass production, biogas production and combined heat and power production were included in his energy balance calculations. Time interval in calculations was one year and energy inputs in infrastructure were excluded. In the crop production process he assumed that the average distance between farm and field was four kilometers. In addition he assumed that after 50 days crop would have produced 89 % of its maximum biogas potential.

Mass and energy balance for biogas production in farm scale was also calculated in the CropGen project [6]. The one unit of energy into the biogas production produced

2.8 units of energy, while timothy grass was used as a raw material in the digester. Both direct and indirect energy inputs were included in crop production, biogas production and combined heat and power production. The time interval was 20 years, when energy inputs in infrastructure were included in calculations.

It was shown in the CropGen project that one of the biggest energy consumption factors in the anaerobic digestion process is reactor heating, which is needed to keep the conditions suitable for biogas formation by microbes. For example, in a 2000 m^3 digester with a 34.8 t/d feed, the parasitic heat requirement was 2133 GJ/a. Other energy requirements were 5311 GJ/a for crop production, 93 GJ/a for crop transportations, 420 GJ/a for parasitic electricity, 1350 GJ/a for digester embodied energy and 260 GJ/a for digestate disposal energy. [7]

In addition to the mass and energy balance studies, LCA modelling was done for biogas production in a farm scale in Germany in 2010. Biogas was produced from several raw materials such as liquid and solid manure (4.41 and 1.03 t/a), corn silage (9.18 t/a), grass silage (3.65 t/a) and grain (4.38 t/a). Heat and electricity consumption were based on measured data and electric power production capacity was 186 kW. It was calculated that electricity consumption in the biogas plant was 9.8 % of the produced electricity. The heat requirement was calculated to be 18 % of the produced heat. The main result was that electricity produced from biogas will decrease the global warming potential in terms of CO_2 equivalents compared to the present electricity energy mix in Germany. At the same time eutrophication and acidification potentials will be increased in crop production compared to eutrophication and acidification potentials in fallow land. [4]

1.2 Goal of the study

The main goal of this study was to calculate mass and energy balance in farm scale biogas production. Energy balance consists of energy inputs in grass silage production, transportations and energy inputs and outputs in the biogas plant. Mass balance consists of nutrient, greenhouse gas and product mass flows. Experimental data from Finnish biogas production and exact transportation distances brought new results in this field of study. The factors that have an effect on a physically and environmentally reasonable way to produce biogas in farm scale were also estimated.

1.3 Review of the study

The goal of this study was achieved by calculating mass and energy balances in three different scenarios. In the first scenario mass and energy balances were calculated when six farms were producing grass silage. These six farms were chosen because they form a cluster of farms in a Finnish village. In the second scenario all six farms were supplying slurry manure and grass silage into the biogas plant where the heat is used directly. In the third scenario only two farms were supplying grass silage and the three closest farms supply slurry manure into the biogas plant, where heat cannot be used directly. The second and third scenarios consisted of grass silage production, transportation and biogas production processes. The biogas production was considered a continuously stirred two stage biogas plant operating at mesophilic temperature. The effect of seasonal variations of energy consumption in biogas production processes was eliminated by averaging the mass and energy balances for one year of biogas production. In the end the results of energy and mass balances in the scenarios were compared in Chapter 8. (Chapter 2)

What has not previously been taken into account is that transportation can have significant effect on total energy consumption in grass silage production. In this thesis a functional energy consumption model was derived for each work process in grass silage production. The functional model took into account the energy consumption in road transportation between farm and field. Energy consumption in each farm and field was also taken into account. The total energy consumption in grass silage production was an annual average energy consumption during a four year cultivation period. Energy consumption in the grass silage production process took into account the area that would be needed in grass silage production for the biogas plant. (Chapter 4)

In feedstock transportation energy consumption model was derived when the heat produced in biogas plant could be and could not be utilized directly from biogas plant. A method was presented to minimize the energy consumption in feedstock and digestate transportation by locating the biogas plant and choosing feedstock suppliers in the most energy efficient way. The result of the most energy efficient model in feedstock and digestate transportation was that heat could not be directly utilized from the biogas plant, but significant energy savings were obtained. (Chapter 5)

Physical and chemical analysis with new experimental data from the biogas plant would give more realistic knowledge about the energy balance in the biogas plant. Biogas plants were dimensioned in two different ways. One option was to dimension the biogas plant when the annual quantities of available grass silage and slurry manures were known. On the other hand the amount of grass silage could be increased when the maximum organic loading rate gave the limit for the size of the biogas reactor in the farm cluster. Heat and electricity production were modeled when efficiencies of electricity and heat production were known from product details. In methane heat content calculations the water needed to be evaporated in combustion was also taken into account. Minimum energy consumption in pumping was estimated according to product details. Mixers energy consumptions were estimated in the biogas plant by using measured mixer's power data from MTT's biogas plant and dimensional analysis. Heat consumption of the 1^{st} reactor was modeled by using measured heat consumption from the 1^{st} reactor from MTT's biogas plant when feedstock mass flows and properties were known. (Chapter 6)

Mass flows were related to energy balance. Nutrient leaches were estimated in grass silage production when the land type was assumed to be silt soil. Greenhouse gas emissions were determined for fuel combustion in machinery work, biogas combustion in the biogas plant and harmful dissipated greenhouse gases from grass silage production. The nutrient balance in the biogas plant was modeled according to measured nutrient data from a farm scale biogas plant and statistics from grass silage and slurry manure nutrients in Finland. In grass silage production the nutrient balance was modeled according to an average annual fertilizing requirement and fertilizing legislation in Finland. (Chapter 7)

2 Modelling biogas production

Biogas production was modelled in the farm cluster in three different scenarios. The objective of scenario set up was to find an LCA model that gives an energy efficient result for biogas production in a farm scale. In the LCA model mass and energy balances were calculated for direct mass and energy flows, because the biogas plant must be located and dimensioned optimally. In scenario 1 the LCA model was calculated for current grass silage production in the farm cluster. In scenario 2 the LCA model was calculated when the biogas plant is included in the farm cluster considering the current needs for heat and grass silage production. In scenario 3 an LCA model was calculated for a biogas plant that was located and dimensioned in an optimal way considering the current technology and raw material inputs into the biogas plant. The LCA models in the three scenarios were calculated for one year of operation. The goal was to compare mass and energy balances from each of the scenarios. The scenarios used in this research had the following conditions.

- Scenario 1: Grass silage is produced separately in each of the six farms. Manure is used as a fertilizer in grass silage production. Biogas production in the farm cluster is not yet considered.

- Scenario 2: The biogas plant uses grass silage and manure as a raw materials produced by the six farm cluster. The grass silage wet weight of the slurry manure wet weight is 8 %. All manure from the farm cluster is imported into the biogas plant. Digestate is used as a fertilizer in grass silage production in each farm.

- Scenario 3: Two farms that are producing grass silage in most energy efficient way would produce all grass silage that is needed in the biogas plant. These two farms would change their source of livelihood into grass silage production. When the biogas plant is located optimally, only the two nearest farms would supply manure into the biogas plant. The biogas plant is dimensioned when the maximum organic loading rate into the biogas plant is 3 kgVS/(m^{3}d).

Also, a condition in all scenarios was to produce the same amount of grass silage m_{GM}. The boundary condition for the amount of produced grass silage comes from scenario 2. The amount of grass silage wet weight m_{GM} imported into the biogas plant should be 8 % of the slurry manure wet weight m_{MM}. The amount of grass silage m_{GM} needed in scenario 1 and 2 was taken aside from the total amount of produced grass silage in each farm. The amount of grass silage taken aside in each of the six farms was directly proportional to its own grass silage production of the total grass silage production in the farm cluster. In scenario 3 the total amount of grass silage needed in the biogas plant was produced in two farms. In the LCA model it is assumed that grass silage was stored in silos that were perfectly covered and any dissipation of greenhouse gases could not occur. Because each of the scenarios were compared, the produced amount of grass silage had to be the same in all scenarios.

2.1 Scenario 1

In scenario 1 the LCA model was calculated when grass silage was produced separately in the six farms. In grass silage production work was done for grass silage production in field W_{GF} and work for transportation W_{GT} between farms and their field blocks. Cultivation substances m_{IN} such as mineral fertilizers, lime, grass, seeds and pesticides were transported from each farm into their field blocks. The amount of m_{MM} slurry manure was transported and spread into the fields. Annually an average m_{GM} tons of grass silage was produced. More detailed descriptions of cultivation processes in grass silage production are presented in chapter 4. In grass silage production in the field there were emissions from fuel combustion in machinery work and dissipation of harmful greenhouse gases that were denoted to m_{EGF}. In road transportation between farms and their field block there were greenhouse gas emissions of m_{EGT}. Leaching of nutrients was based on the amount of fertilizers. (fig. 2.1)

2.2 Scenarios 2 and 3

In the second and third scenarios the LCA model was calculated when grass silage and manure were used as raw materials for biogas production. The total amount of grass silage was produced separately in the farms and a relative part of the produced grass from each farm was transported into the biogas plant. The parameter m_{GM} describes the total amount of collected grass silage from the farms. The system boundary in grass silage production was the same as is in scenario 1, because scenario 1 was compared to scenarios 2 and 3. The only difference in grass silage production in scenarios 2 and 3 from grass silage production in scenario 1 was that digestate was used as a fertilizer instead of manure. Manure from every farm with a total amount of m_{MM} had to be

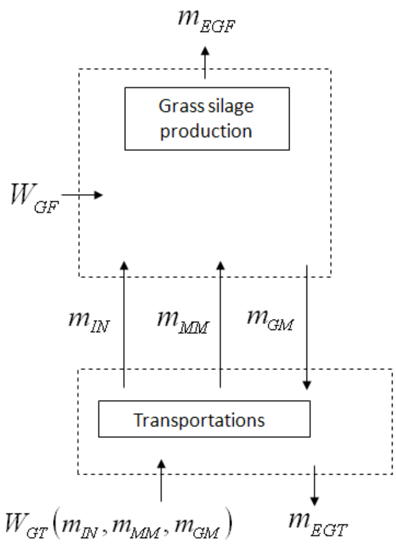


Figure 2.1: Grass and manure in a dairy cattle farm.

transported into the biogas plant. At the same time digestate with the amount of m_{DM} was transported into the same farms that were supplying manure. In the transportation processes work was done for slurry transportation W_{TS} and grass silage transportation W_{TG}. Slurry and grass silage transportation caused greenhouse gas emissions of m_{ETS} and m_{ETG} respectively. To run the biogas plant work was needed for W_B for example in pumping, mixing and heating the reactor. In combined heat and power (CHP) - unit the chemical energy of biogas was converted into heat Q_{HEAT} and electricity W_{EL} at certain efficiencies. The only major source of greenhouse gas emissions m_{EB} from the system boundary in biogas production was CHP - unit when biogas was burnt. (fig. 2.2)

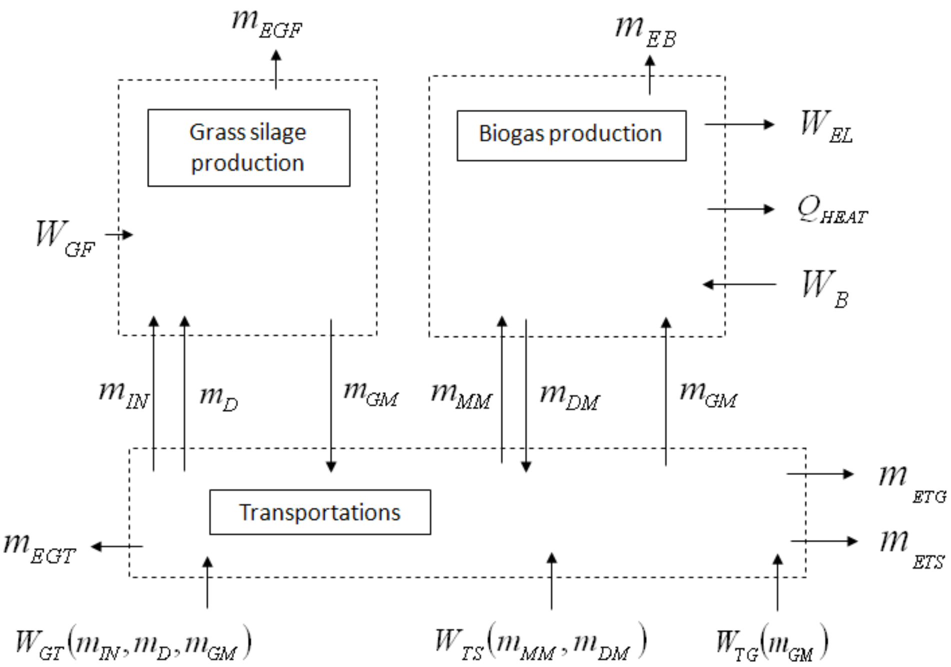


Figure 2.2: Grass and manure in biogas production.

3 Methods and Materials

Energy consumption factors in biogas production were calculated in each scenario according to energy consumption functions. The functions for energy consumption in grass silage production were similar in each scenario (Chapter 4). The input values like the amount of fertilizers and nutrient contents of slurries were given for these energy consumption functions in grass silage production. The properties of mass flows in each scenario are presented in more detail in chapter 7.

Energy consumption in grass silage, slurry manure and digestate transportation was calculated in scenarios 2 and 3 when the fuel consumption models were similar, but the transported amount of substances was different for each farm (Chapter 5).

Because of the boundary conditions in the scenarios 2 and 3, the feedstock mass flows and the volumes of reactors in scenarios were different. This required determining functions for energy consumption devices that were needed in biogas production (Chapter 6). Some results like heat consumption of the 1^{st} reactor and electric energy consumption data were measured from a real farm scale biogas plant in Maaninka. The plant is owned by Agrifood Research Finland, MTT. The biogas plant has two continous stirred reactors that have volumes of 300 m^3. During heat consumption measurements about 10 t/d of slurry manure and 800 kg/d of onion waste were pumped in.

3.1 Grass silage production and transportations

The energy that was needed in grass silage production was calculated based on fuel the consumption model that is presented in more detail in chapter 4. The fuel consumption model consisted of machinery work that is done in field and road, so field block areas and transportation distances were needed. Coordinates and cultivated grass silage production areas A_i were retrieved from the Finnish agriculture database from 2009 [8].

The number of domestic animals was also retrieved from the Finnish agriculture database from 1996 [8]. Annual slurry manure productions were assumed to be 24, 24, 15 and 4 m^3 for milk cow, heifer over six months, bull and calf under six months, respectively. When the density of slurry manure was 992.7 kg/m^3, the slurry manure produced in each farm is shown in table 3.1 [9].

Table 3.1: Slurry manure produced in each farm.

Farm:	m_{Mi} t
1	3795
2	1836
3	1927
4	2476
5	1449
6	462

Distances in feedstock and digestate transportation between the biogas plant and the farms were calculated from the digiroad 2009 road database when walkways were neglected [10]. In the grass silage production process the shortest distances d_i were calculated between each farm and its field blocks. Transportation between farms and their field blocks are described more in chapter 4. The shortest distance between the biogas plant and the farms d_{Ti} was also calculated in slurry manure, grass silage and digestate transportation. Transportation between farms and the biogas plant are described in more detail in chapter 5.

3.2 Biogas production

Methane productivities were calculated in scenarios 2 and 3 based on measured methane productivities from a two staged mesophilic biogas plant from Maaninka and batch reactor experiments for grass silage and slurry manure.

Methane productivity was measured for grass silage MPR_G and slurry manure MPR_M by using batch reactor experiments. In batch reactor experiments, the sample is held a certain time in mesophilic temperature and the methane yield is measured. Methane productivity from biodegradable substances used in co-digestion depends on, among other factors, mass proportions. The total batch experiment methane productivities of grass silage and slurry manure are different from methane productivity in grass silage and slurry manure co - digestion. That is why so-called fixing factor FC was used to scale the batch experiment methane productivities to correspond to the actual co-digestion methane productivities. In scenario 2 the fixing factor was assumed to be 1.21 at a hydraulic retention time of 30 days. When in scenario 3 the volatile solid mass proportion was increased up to 64 % of the total volatile solids and the hydraulic retention time was kept to 30 days, the fixing factor was assumed to be one. Methane productivities in scenarios 2 and 3 were then 282 and 309 $\mathrm{Nm}^3/(\mathrm{t\ VS})$, respectively

Table 3.2: Methane production rates in the LCA model.

OLR_M	ϕ_{VSG}	MPR_M	MPR_G	$\frac{\mathrm{MPR}}{\mathrm{FC}}$	FC	MPR
$\frac{\mathrm{kgVS}}{\mathrm{m^3d}}$	%	$\mathrm{Nm^3/(t\ VS)}$	$\mathrm{Nm^3/(t\ VS)}$	$\mathrm{m^3/(t\ VS)}$		$\mathrm{m^3/(t\ VS)}$
2.0	33	140	364	233	1.21	282
3.0	64	140	364	309	1.00	309

(table 3.2). The methane productivity of grass silage and slurry manure co-digestion is

$$\mathrm{MPR} = [\mathrm{MPR}_G\phi_{VSG} + \mathrm{MPR}_M(1-\phi_{VSG})]\,\frac{298\ \mathrm{K}}{273.15\ \mathrm{K}}\ \cdot\ \mathrm{FC}, \tag{3.1}$$

where grass volatile solids of the total solids in feedstock is

$$\phi_{VSG} = \frac{\phi_G \mathrm{VS}_G}{\mathrm{VS}_M + \phi_G \mathrm{VS}_G}. \tag{3.2}$$

The methane productivity was defined in the co-digestion plant in Maaninka at 273.15 K, but this LCA model assumes that biogas enters into the CHP plant at 298 K. The density of methane changes then by the factor 298/273.15.

In this LCA model the heat consumptions of the 1^{st} reactors in scenarios 2 and 3 were calculated according to measured heat consumption, feedstock mass flows and total solids contents of feedstock. Measured heat consumption of the 1^{st} reactor q_T, feedstock mass flows ($\dot{m}_{MT}$ and $\dot{m}_{GT}$), total solid contents of feedstock (TS_{MT} and TS_{GT}) and total solid content of digestate TS_{DT} after processing in the 1^{st} reactor are presented in more detail in chapter 6 and table 6.4.

Heat consumption of the 1^{st} reactor was measured in spring when the outside temperature ranged from - 16 °C to 6 °C (figure 3.1). During the 44 day measuring period the average heat power consumption of the 1^{st} reactor was 14 kW when the average outside temperature was 0 °C.

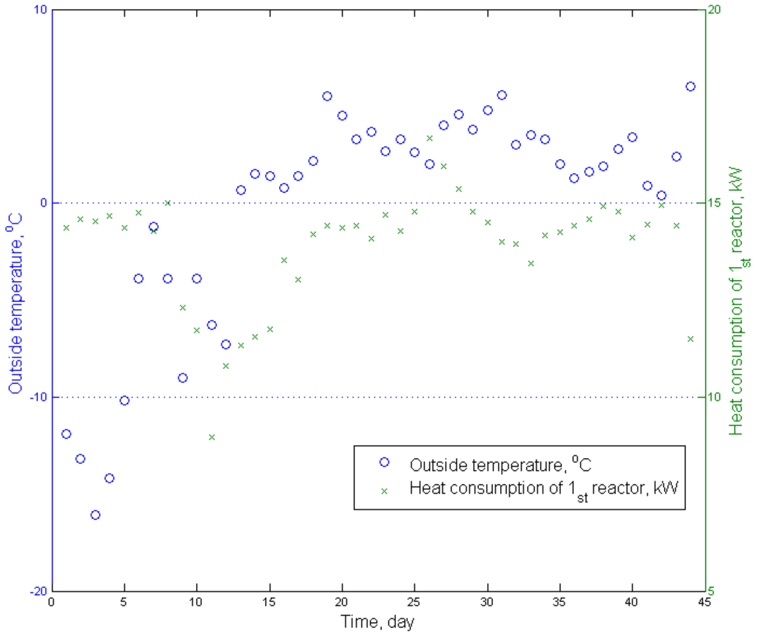


Figure 3.1: Heat consumption was measured from 14.3.2010 to 26.4.2010 in MTT's biogas plant in Maaninka.

4 Grass silage production

Energy consumption in grass silage production is calculated by using a fuel consumption model for each process in grass silage production. One year's average energy consumption during a four year cultivation period is calculated for each field process. Work done for field W_{GF} and road W_{GT} are separated from total work done for total grass silage production W_G. In autumn before grass is sowed, the land is sprayed with *Roundup* to prevent weeds. In winter before sowing, lime is spread on the field. In spring the slurry is spread on the field by using an injection spread system. The field is then ploughed and harrowed two times before seeds and fertilizers are spread on the field. Finally, the field is rolled. At late summer the first year, the grass yield is harvested by using a pick up trailer. Three years after the first harvest two yields per year are harvested before the second grass renewing period. During this three year period, mineral fertilizers are spread in spring, because the land base is usually very soft after winter. After the first harvest, the land base is dry enough for slurry spread on the fields. The numbers of cultivation processes in all scenarios during the four year period are listed in table 4.1.

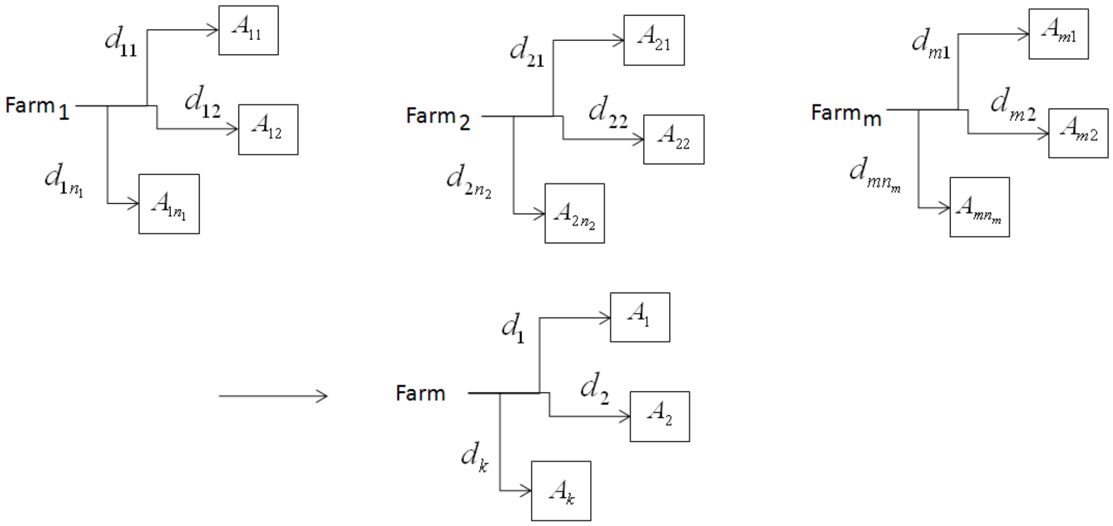


Figure 4.1: Field work done separately in each farm can be simplied into the model, where work is done for one farm.

The same field processes are carried out in every farm, where the farmer starts the field process from his farm. All field processes consists of cycles of work done with a tractor in the field and road. At first the farmer does preparation work in the farm with the tractor before he his able to drive the tractor into the field block with thr cultivation device. After field work is done, the farmer drives back to his farm. In scenarios 1 and 2 the work done for grass silage production in field and roads is calculated when all six farms are producing grass silage. The number of field blocks considered in scenarios 1 and 2 is

$$k = \sum_{m=1}^{6} n_m, \tag{4.1}$$

where n_m is the number of field blocks at farm m (fig. 4.1). Later on in chapter 8 it will be shown that energy consumption in grass silage production fluctuates between farms. That's why in scenario 3 only farms 4 and 5 are chosen to produce grass silage into the biogas plant. In scenario 3 the total number of field blocks in farms 4 and 5 is $(k = n_4 + n_5)$. Work done in grass silage production is the sum of work done for each cultivation process,

$$\begin{aligned} W_G &= H_F \sum_{i=1}^{k} \left(V_{Si} + V_{Fi} + V_{Hi} + V_{Ri} + V_{SPi} + V_{Li}\right) \\ W_G &= H_F \left(V_S + V_F + V_H + V_R + V_{SP} + V_L\right), \end{aligned} \tag{4.2}$$

where k is the number of field blocks and H_F is the combustion heat of diesel. Grass silage production processes are described more detail in table 4.1. Work done in the field in grass silage production is a sum of work done in each cultivation process,

$$W_{GF} = H_F(V_{SS} + V_{FS} + V_{HCF} + V_{HHF} + V_{RF} + V_{SPF} + V_{LF}). \tag{4.3}$$

Work done in transportation in grass silage production processes is

$$W_{GT} = H_F(V_{ST} + V_{FT} + V_{HCT} + V_{HHT} + V_{RT} + V_{SPT} + V_{LT}). \tag{4.4}$$

4.1 Slurry management

The slurry management process consists of transporting slurry manure or digestate return from the farm into the field, loading the tanker, and spreading the slurry manure. To avoid dissipation of nutrients, slurry is injected into the ground with a tanker that carries 17 tons of slurry m_{SL} [11] (table 4.2). The slurry tank is pulled by a 204 kW –

Table 4.1: Fuel consumption in grass silage production.

Cultivation method	Fuel consumption in field	Fuel consumption in transportations	Fuel consumption in total	Number of times per 4 - year,
Slurry spread	V_{SS}	V_{ST}	V_S	4
Fertilizing	V_{FS}	V_{FT}	V_F	4
Harvesting	$V_{HCF} + V_{HHF}$	$V_{HCT} + V_{HHT}$	V_H	7
Renewing	V_{RF}	V_{RT}	V_R	1
Spaying	V_{SPF}	V_{SPT}	V_{SP}	1
Lime spread	V_{LF}	V_{LT}	V_L	1

tractor. Fuel consumption in slurry spread is

$$V_{SS} = \sum_{i=1}^{k} \left(\frac{L_{SS} C_S m_{SL}}{w_{SS} v_{SS} \tilde{m}_{SR}} n_{Si} + V_{SL} n_{Si} \right), \tag{4.5}$$

where n_{Si} is the number of slurry loads m_{SL} needed for each field block and V_{SL} is the fuel consumption in the slurry load. When the field area is A_i, the number of slurry loads into each field block is

$$n_{Si} = \frac{A_i}{m_{SL}} \tilde{m}_{SR}. \tag{4.6}$$

In scenario 1 the slurry spread requirement $\tilde{m}_{SR}$ is 40.5 t/ha when in scenarios 2 and 3 the slurry spread requirement is 42 t/ha. When the maximum pumping capacity of the pump is 6 tons per minute $\dot{m}_{STP}$, the fuel consumption in the slurry load done by the 204 kW tractor is

$$V_{SL} = \frac{L_{SL}}{\dot{m}_{STP}} C_S m_{SL}. \tag{4.7}$$

Fuel consumption in slurry transportation on the road at a tractor's load factor of L_{ST} is

$$V_{ST} = \frac{2 C_S L_{ST}}{v_{ST}} \sum_{i=1}^{k} n_{Si} d_i. \tag{4.8}$$

Fuel consumption in slurry management is the sum of fuel consumption in slurry spread, load and transportation. This is expressed as

$$V_S = V_{SS} + V_{ST}. \tag{4.9}$$

Table 4.2: Parameters in the slurry management process.

Sc. 1 & 2 & 3											Sc. 1	Sc. 2 & 3
w_{SS}	P_S	L_{SS}	L_{SL}	L_{ST}	C_S	v_{SS}	v_{ST}	m_{SL}	$\dot{m}_{STP}$	V_{SL}	$\tilde{m}_{SR}$	$\tilde{m}_{SR}$
m	kW	%	%	%	kg/h	km/h	km/h	t	t/min	kg Diesel	t/ha	t/ha
12	204	80	75	75	28	5	25	17	6	0.98	40.5	42.0

4.2 Fertilizing

The fertilizing process consists of mineral fertilizer spread in the field and transportation from the farm to the field and back. Fertilizers are spread with broadcasting devices that have a working width w_{FS} of 10 meters [12]. Other process parameters such as driving speeds and load factors are represented in table 4.3. Fuel consumption in fertilizer spread is

$$V_{FS} = \frac{L_{FS} C_F m_{FL}}{\tilde{m}_{FR} w_{FS} v_{FS}} \sum_{i=1}^{k} n_{Fi}. \tag{4.10}$$

When fertilizing requirement $\tilde{m}_{FR}$, fertilizer load m_{FL} and field area A_i are known, the number of loads that the farmer needs to transport into the field is

$$n_{Fi} = \frac{\tilde{m}_{FR}}{m_{FL}} A_i. \tag{4.11}$$

In scenarios 1, 2 and 3 the mineral fertilizing requirements $\tilde{m}_{FR}$ are shown in table 4.3. Fuel consumption on the road is

$$V_{FT} = \frac{2 C_F L_{FT}}{v_{FT}} \sum_{i=1}^{k} n_{Fi} d_i, \tag{4.12}$$

when the tractor's fuel consumption is L_{FT} per cent of its maximum fuel consumption. Total fuel consumption is

$$V_F = V_{FS} + V_{FT}, \tag{4.13}$$

which consists of fuel consumption in spread V_{FS} and transportation V_{FT}.

Table 4.3: Parameters in the fertilizing process.

Sc. 1 & 2 & 3								Sc. 1	Sc. 2	Sc. 3
w_{FS}	P_F	L_{FS}	L_{FT}	C_F	v_{FS}	v_{FT}	m_{FL}	$\tilde{m}_{FR}$	$\tilde{m}_{FR}$	$\tilde{m}_{FR}$
m	kW	%	%	kg/h	km/h	km/h	kg	kg/ha	kg/ha	kg/ha
10	163	60	50	22	7	25	910	312	223	247

4.3 Harvesting

Grass is cut by a 163 kW tractor with a mowing machine (*GMS 320 JF-STOLL*) that has a working width w_{HC} of 3.6 m [13] (table 4.4). It is assumed that the tractor's maximum fuel consumptions in the grass cutting in the field and moving machine transportation are 70 % and 60 % of the tractors maximum fuel consumption, respectively. Driving speeds in the field and road are assumed to be seven and 25 km/h respectively. It is typical that the farmer works five hour periods t_{WP} in the field. When the field size is A_i, the number of times that the farmer needs to drive into the field block is

$$n_{HCi} = \frac{A_i}{w_{HC} v_{HC} t_{WP}}. \tag{4.14}$$

Harvest cut and transportation are done seven times during the four year cultivation period, which averages 7/4 times per year. Fuel consumption in will be

$$V_{HCF} = \frac{7}{4} \cdot \frac{L_{HC} C_{HC}}{w_{HC} v_{HC}} \sum_{i=1}^{k} A_i, \text{ and} \tag{4.15}$$

$$V_{HCT} = \frac{7}{4} \cdot \frac{2 C_{HC} L_{HCT}}{v_{HT}} \sum_{i=1}^{k} n_{HCi} d_i \text{ respectively.} \tag{4.16}$$

A pick up trailer (*Krone Titan6/40L*) sized 40 m^3 is used in harvesting [14]. If the harvested grass in the pick up trailer is assumed to have an average packing density of 250 $\mathrm{kg/m}^3$, the harvested grass mass m_{HL} in the trailer is 10 tons. According to grass silage yield statistics in Finland from 1999 to 2008 the annual average grass silage yield was 17.64 t [15]. If two yields per year are harvested the yield per one harvest Y_G would be 8.82 t/ha. When grass yield Y_G, working width w_{HH} and driving speed in the field are known, the time to collect grass from swath into the trailer is

$$t_{HH} = \frac{m_{HL}}{w_{HH} v_{HH} Y_G}. \tag{4.17}$$

When the field area is A_i, the pick up trailer is needed to drive between farm and field n_{Hi} times,

$$n_{Hi} = \frac{Y_G}{m_{HL}} A_i. \tag{4.18}$$

While 204 kW tractor harvests one load of grass at time t_{HH}, unloaded grass is stored by 136 kW tractor at the equal time $t_{HS} = t_{HH}$ (table 4.4). It is assumed that it takes just 5 minutes (t_{HL}) to unload the grass load into the silo. When grass harvesting is done seven times during the four year cultivation period, it is done on average 7/4 times per year. Fuel consumptions in grass harvesting in the field and harvest transportation are

$$V_{HHF} = \frac{7}{4} \cdot \sum_{i=1}^{k} n_{Hi} \left(L_{HH} C_{HH} t_{HH} + L_{HS} C_{HS} t_{HS} + L_{HH} C_{HH} t_{HL} \right) \text{ and} \tag{4.19}$$

$$V_{HHT} = \frac{7}{4} \cdot \frac{2 C_{HH} L_{HT}}{v_{HT}} \sum_{i=1}^{k} n_{Hi} d_i \text{ respectively.} \tag{4.20}$$

Total fuel consumption in grass harvesting consists of fuel consumption in the field, harvest storing, unloading, cutting and transporting both harvested loads and mowing machine between farm and field. This is expressed as

$$V_H = V_{HCF} + V_{HCT} + V_{HHF} + V_{HHT}. \tag{4.21}$$

Table 4.4: Parameters in the harvesting process in all scenarios.

Cutting:

w_{HC} m	P_H kW	L_{HC} %	L_{HCT} %	C_{HC} kg/h	v_{HC} km/h	t_{WP} h
3.6	163	70	60	22	7	5

Harvesting:

w_{HH} m	P kW	L_{HH} %	L_{HT} %	C_{HH} kg/h	v_{HH} km/h	v_{HT} km/h	t_{HH} min	t_{HL} min	Y_G kgFM/ha	m_{HL} kg
3.6	204	85	60	28	5	25	38	5	8.82	10 000

Storing:

P kW	L_{HS} %	C_{HS} kg/h	$t_{HS} = t_{HH}$ min
136	40	18	38

4.4 Renewal

The renewal process consists of ploughing, harrowing two times, rolling and sowing seeds and fertilizers (table 4.5). All these processes are done by a 163 kW tractor that has a maximum fuel consumption C_R of 22 kg/h. When grass renewing is done in every fourth year, fuel consumption in the field is

$$V_{RF} = \frac{1}{4} \cdot C_R \sum_{i=1}^{k} A_i \left(\left(\frac{L}{wv} \right)_{RP} + \left(\frac{2L}{wv} \right)_{RH} + \left(\frac{L}{wv} \right)_{RR} + \left(\frac{L}{wv} \right)_{RS} \right). \tag{4.22}$$

Subscripts are RP, RH, RR, RS that refer respectively to plough, harrow, roll and sowing processes. The area harrowed, rolled and ploughed depends on the working period t_{WP} that the farmer works continually. The wider the working width w and the higher the driving speed v in the field, the bigger the area is done in the field. The number of times needed to drive into the block in each these work phases is

$$n_{(RP,RH,RR)i} = \left(\frac{A_i}{wvt_{WP}}\right)_{(RP,RH,RR)}. \tag{4.23}$$

Seeds and fertilizers are sowed by combined seed and fertilizer unit (*Juko HT300S*) [16]. Grass seeds are usually very small and seed mixture of 14 kg/ha is needed to fulfill the seeding requirement. The fertilizer requirement is much higher, usually some hundreds of kilograms per hectare. Fertilizers run out first when an area of A_S of the A_i is sowed. Then seeds and fertilizers need to be refilled and transported into the field n_{Ri} times,

$$n_{Ri} = \frac{A_i}{A_S}. \tag{4.24}$$

Sowed area A_S depends on the fertilizing requirement per hectare $\tilde{m}_{RFR}$, when the fertilizer load m_{RFL} in sowing unit is 1.3 tons. In scenarios 1, 2 and 3 mineral fertilizing requirements are 312, 223 and 247 kg/ha respectively. Sowed area is

$$A_S = \frac{m_{RFL}}{\tilde{m}_{RFR}}. \tag{4.25}$$

Driving speed v_{RT} on the road is 25 km/h when a 163 kW tractor is assumed to consume (L_{RT}) 60 % of its maximum fuel consumption. As mentioned before, grass renewing is done every fourth year, so the average number of renewing during one year is 1/4. When the number of times needed to drive (n_{RP}, n_{RH}, n_{RR}) and transport (n_{Ri}) in each block are known, the fuel consumption on the road is

$$V_{RT} = \frac{1}{4} \cdot C_R L_{RT} \sum_{i=1}^{k} \left(n_{RPi} + 2n_{RHi} + n_{RRi} + n_{Ri}\right) \frac{2d_i}{v_{RT}}. \tag{4.26}$$

The total fuel consumption V_R in the renewing process is the sum of fuel consumption on the road and in the field,

$$V_R = V_{RF} + V_{RT}. \tag{4.27}$$

Table 4.5: Parameters in the grass renewing process in all scenarios.

	w m	P_R kW	L %	C_R kg/h	v km/h
Plough, RP:	1.6	163	85	22	5
Harrow, RH:	6	163	75	22	6
Rolling, RR:	4	163	70	22	7
Sowing, RS:	3	163	75	22	6

4.5 Spraying

The control substance is spread by using a 136 kW tractor with a spraying tank (*Amazone UF901*) [17]. The number of times n_{SPi} needed to load the spraying tank for each field block depends on spraying tank load m_{SPL}, spraying requirement $\tilde{m}_{SPR}$ and field block area A_i (table 4.6). Number of spraying loads into field block i is

$$n_{SPi} = \frac{m_{SPL}}{\tilde{m}_{SPR}} A_i. \tag{4.28}$$

Total fuel consumption in spraying is the sum of fuel consumption in field spraying V_{SPF} and distances from the farm to the field block and back V_{SPT} (eq. 4.31). When the average number of spraying times per year is 1/4, and fuel consumption per hour $L_{SP}C_{SP}$, working width w_{SP}, driving speed v_{SP} and total field area are known, the fuel consumption in the field is

$$V_{SPF} = \frac{1}{4} \cdot \frac{L_{SP}C_{SP}}{w_{SP}v_{SP}} \sum_{i=1}^{k} A_i. \tag{4.29}$$

When road transportation average fuel consumption per hour $L_{SPT}C_{SP}$, driving speed v_{SPT}, number of loads n_{SPi} and transportation distances d_i are known, the fuel consumption on the road is

$$V_{SPT} = \frac{1}{4} \cdot \frac{2L_{SPT}C_{SP}}{v_{SPT}} \sum_{i=1}^{k} n_{SPi}d_i. \tag{4.30}$$

In total the fuel consumption in the spraying process is

$$V_{SP} = V_{SPF} + V_{SPT}. \tag{4.31}$$

Table 4.6: Parameters in the spraying process in all scenarios.

w_{SP} m	P_{SP} kW	L_{SP} %	L_{SPT} %	C_{SP} kg/h	v_{SP} km/h	v_{SPT} km/h	$\tilde{m}_{SPR}$ kg/ha	m_{SPL} kg
12	136	70	60	18	8	25	203	1050

4.6 Lime spread

Lime is spread by using a 204 kW tractor with a *Magna spread* lime trailer [18]. The volume of the trailer is 8.3 m^3 and it carries 12 t loads m_{LL}, if the density of limestone powder is 1394 kg/m^3 (table 4.7). When the lime requirement is $\tilde{m}_{LR}$ the number of loads into each field block is

$$n_{Li} = \frac{\tilde{m}_{LR}}{m_{LL}} A_i. \tag{4.32}$$

A trailer is needed to load the lime at the farm which takes the time t_{LL}. Total fuel consumption in lime spread V_L consists of fuel consumption in field V_{LF} and transportation between farm and field V_{LT} (eq. 4.35). When lime spread is done on average 1/4 times per year, the fuel consumption in lime spread in the field and lime loadings at the farm is

$$V_{LF} = \frac{C_L}{4} \cdot \sum_{i=1}^{k} \left(\frac{L_{LSP} A_i}{w_{LSP} v_{LSP}} + L_{LL} t_{LL} n_{Li} \right). \tag{4.33}$$

When fuel consumption in lime transportation $L_{LT}C_L$, driving speed v_{LT}, number of loads n_{Li} and transportation distances are known, the fuel consumption on the road is on average per year

$$V_{LT} = \frac{1}{4} \cdot \frac{2L_{LT}C_L}{v_{LT}} \sum_{i=1}^{k} n_{Li} d_i. \tag{4.34}$$

In total the fuel consumption in the lime spread process is

$$V_L = V_{LF} + V_{LT}. \tag{4.35}$$

Table 4.7: Parameters in the lime spread process in all scenarios.

w_{LSP} m	P_L kW	L_{LSP} %	L_{LT} %	L_{LL} %	C_L kg/h	v_{LSP} km/h	v_{LT} km/h	$\tilde{m}_{LR}$ kg/ha	m_{LL} t	t_{LL} min
18.3	204	80	60	60	28	5	25	6000	12	5

5 Transportation

The energy needed for grass silage and slurry transportation between farms and the biogas plant is calculated from the fuel consumption model in each process. In scenario 2, the biogas plant is located in a place (**HB**, in figure 5.1.) where heat can be used directly. The fuel consumption model in scenario 2 takes into account six farms that have the distance d_{Ti} from the biogas plant. In scenario 3, the biogas plant is located d_0 km from **HB** by using the positioning algorithm in chapter 5.1 when it's known that only two farms would supply grass silage into the plant. The fuel consumption model in scenario 3 takes into account the distances $|d_0 - d_{Ti}|$ between the farms and the biogas plant. Energy consumption values in grass silage and slurry transportation are W_{TG} and W_{TS} respectively. When the combustion heat of diesel is H_F, the energy in grass silage transportation between the farms and the biogas plant is

$$W_{TG} = H_F V_{TG}. \tag{5.1}$$

Energy consumption in slurry transportation is

$$W_{TS} = H_F \left(V_{TS} + V_{TSE}\right), \tag{5.2}$$

where fuel consumption values in empty load and full load transportation are V_{TSE} and V_{TS} respectively.

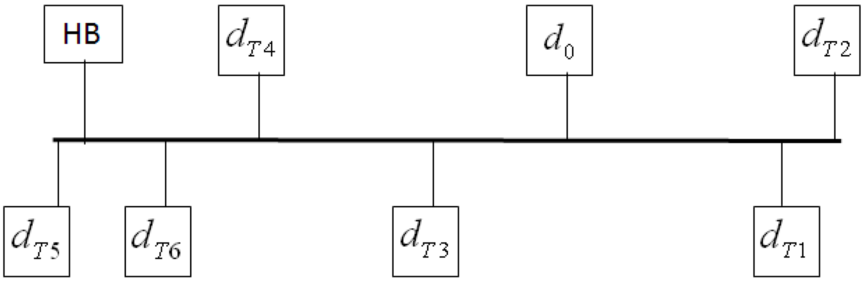


Figure 5.1: Distances between farms and heat buyer **HB** are d_{Ti}.

5.1 Minimum energy consumption in transportation

The optimal place for the biogas plant is found by using an algoritm (steps 1 to 2) that includes the positioning equation 5.3. The positioning equation gives the minimum energy consumption for grass silage and manure transportation into the biogas plant and also the energy needed in digestate transportation back to the farms. When m farms are taken into account the optimal place for the biogas plant is

$$d_0 = \frac{\sum_{i=1}^{m} d_{Ti} w_i}{\sum_{i=1}^{m} w_i}, \tag{5.3}$$

where weight factors w_i can be calculated from

$$w_i = 2C_S L_{ST} m_{Mi} + C_{TG}(L_G + L_{GE}) m_{Gi} + C_S(L_{ST} + L_{TSE}) \left| m_{Di} - m_{Mi} \right| . \tag{5.4}$$

In scenario 3 the optimal place for the biogas plant is calculated by using the following algorithm.

1. First, farms 4 and 5 are chosen to supply grass silage into the biogas plant. Later on in chapter 8 it will be shown that these farms are producing grass silage in the most efficient way.
2. The following steps are repeated while the farms supplying manure cannot be chosen differently.
    - (a) The optimal place for the biogas plant is calculated according to equation 5.3.
    - (b) All farms are ranked in decreasing order where the closest farm from the biogas plant has ranking number 1.
    - (c) The following steps are repeated while there is enough manure for the biogas plant.
        - i. If farm i has not already been chosen, then farm i that has closest distance $|d_0 - d_{Ti}|$ from the biogas plant is chosen.
        - ii. If the farm i has enough manure m_{Mi}, then just the amount of manure that is needed is taken into the biogas plant from farm i.
        - iii. If there is not enough manure m_{Mi} from farm i step 2(c)i is repeated for the next farm in the ranking order.

5.2 Grass silage transportation

Fuel consumption consists of a tractor's fuel consumption in the following phases. First, in the farm i, the grass silage is cut from the silo and loaded into the trailer at a time t_{GC}. Then the grass silage load is transported d_{Ti} km from farm i to the biogas plant when the tractor's fuel consumption is L_G per cent of its maximum fuel consumption. The grass load is unloaded from the trailer at a time t_{GU} when the tractor's fuel consumption is L_{GL} per cent of its maximum fuel consumption. The same distance d_{Ti} is driven back to the farm i with an empty load when the tractor's fuel consumption is L_{GE} of its maximum fuel consumption (table 5.1). When grass is transported from m farms into the biogas plant the fuel consumption for road transportation is

$$V_{TGT} = C_{TG} \frac{L_G + L_{GE}}{v_G} \sum_{i=1}^{m} n_{TGi} d_{Ti}. \tag{5.5}$$

When loadings are also considered the fuel consumption for grass silage transportation from m farms is

$$V_{TG} = C_{TG} L_{GL} \left(t_{GC} + t_{GU} \right) \sum_{i=1}^{m} n_{TGi} + V_{TGT}. \tag{5.6}$$

When in a farm i the amount of grass silage transported into the biogas plant is annually m_{Gi} and the grass silage load of the trailer is m_{GL}, the number of loads from farm i needed to be transported into the biogas plant is

$$n_{TGi} = \text{integer} \left(\frac{m_{Gi}}{m_{GL}} \right)_+ . \tag{5.7}$$

The plus sign in the subscript means that the value of loads is rounded up.

Table 5.1: Parameters in the grass silage transportation process.

C_{TG}	L_G	L_{GE}	L_{GL}	v_G	m_{GL}	t_{GC}	t_{GO}
kg/h	%	%	%	km/h	t	min	min
22	75	60	70	25	10.5	10	5

5.3 Slurry transportation

In the farm cluster slurry is transported in two ways. In two way transportation manure is transported into the biogas plant and the same amount of digestate is transported back to each farm. The fuel consumption in two way transportation is V_{TS}. There is also so called one way transportation when only digestate or slurry manure is transported to the destination point in one round. The fuel consumption in one way transportation is V_{TSE}.

In two way transportation fuel consumption consists of fuel consumption on the road V_{TST} and fuel consumption in the slurry load. In a farm i slurry manure is pumped up into a tanker at time t_{SP} when the tractor's fuel consumption is L_{SL} per cent of its maximum fuel consumption C_S (tab. 5.2). Slurry manure is unloaded in the biogas plant also at time t_{SP} and the same amount of digestate is pumped up into the tanker. After digestate is transported back to the farm it is unloaded into farmer i's slurry storage. In total there are needed four times of pumping up or down and during the year this should be done n_{TSi} times on the farm i. The fuel consumption in slurry transportation can then be represented as the sum of fuel consumption in pumping and road transportation from each m farms during the year,

$$V_{TS} = 4C_S L_{SL} t_{SP} \sum_{i=1}^{m} n_{TSi} + V_{TST}. \tag{5.8}$$

Fuel consumption in road transportation from m farms is

$$V_{TST} = 2C_S \frac{L_{ST}}{v_{ST}} \sum_{i=1}^{m} n_{TSi} d_{Ti}. \tag{5.9}$$

Two way slurry transportation can be done when there is always slurry to transport both ways. Because there are unequal amounts of slurry manure and digestate related to each farm, two way transportation is limited to the amount of slurry manure or digestate that runs out first. When one slurry load is m_{SL} 16.5 tons the number of two way transports is

$$n_{TSi} = \text{integer}\left(\frac{m_{Mi}}{m_{SL}}\right)_+ \ \textbf{or} \ \text{integer}\left(\frac{m_{Di}}{m_{SL}}\right)_+ . \tag{5.10}$$

The plus sign in the subscript means that the value of loads is rounded up.

In one way transportation the tractor has a fuel consumption of L_{TSE} per cent of its maximum and the number of loads needing transportation is now n_{TSEi}. In total the fuel consumption from m farms is

$$V_{TSE} = C_S \sum_{i=1}^{m} n_{TSEi} \left(2L_{ST} t_{SP} + \frac{L_{ST} + L_{TSE}}{v_{ST}} d_{Ti}\right), \tag{5.11}$$

where the number of loads from farm i is

$$n_{TSEi} = \left| \text{integer}\left(\frac{m_{Mi}}{m_{SL}}\right)_+ - \text{integer}\left(\frac{m_{Di}}{m_{SL}}\right)_+ \right|. \tag{5.12}$$

Table 5.2: Parameters in slurry transportation between farms and the biogas plant.

C_S kg/h	L_{SL} %	L_{ST} %	L_{TSE} %	v_{ST} km/h	t_{SP} min
28	75	75	60	25	2.75

6 Biogas production

Energy balance terms were calculated in the LCA model according to measured data and product details for a one year period Δt (figure 6.1). Heat Q_{HEAT} and electricity W_{EL} production from the biogas plant were defined in scenarios 2 and 3 when methane production rates were defined according to measured data from MTT's biogas plant and efficiencies of electricity and heat production were known from product details. The methane production rate was measured from a two stage biogas plant when the hydraulic retention time was 30 days for one reactor. In scenario 2 the biogas plant was dimensioned to operate at the current manure production rate. The biogas plant was dimensioned in scenario 3 when the maximum organic loading rate could be 3 kgVS/(m^{3}d). Energy needed in pumping (W_P) was calculated according to the product details. Dimensional analysis, product data and measured mixer's power data were used in mixing energy calculations (W_{CM1}, W_{CM2}, W_{CM3}, W_{M1} and W_{M2}). The measured heat consumption of the 1^{st} reactor from the two stage biogas reactor from Maaninka was used in the LCA model's 1^{st} reactor heat consumption calculations. Energy consumption in mixing, pumping and heating are described more detail in chapters 6.3, 6.4 and 6.5 respectively.

In both scenarios work is required for grass silage loading, heat transfer liquid pumping from CHP into the 1^{st} reactor and air pumping into the weather covers of the reactors. All this kind of work was denoted to be minor energy consumption W_{MINOR}. Other energy consumption such as electric energy consumption of control devices was assumed to be neglible. A total amount of 2.6 tons grass silage is pumped with a screw pump into the pre storage in scenarios 2 and 3. When the pumping capacity is 15 m^3/h and density of grass silage is assumed to be 750 kg/m^3 the average power of the screw pump is

$$5.5\ \text{kW} \cdot \frac{2.62\ \text{t}}{15\ \text{m}^3/\text{h} \cdot 0.75\ \text{t/m}^3 \cdot 24\ \text{h}} \ = \ 53\ \text{W}.$$

Each circulation pump is assumed to be needed all the time, so continous power of the circulation pump is 750 W. It is assumed similarly that each air pump is running continously and has an average power of 180 W. Work required for one year is the sum of electric input power needed in minor energy consumer devices times the one year time period. The minor energy consumptions in scenarios 2 and 3 are 71.7 and 36.7 GJ respectively (table 6.1).

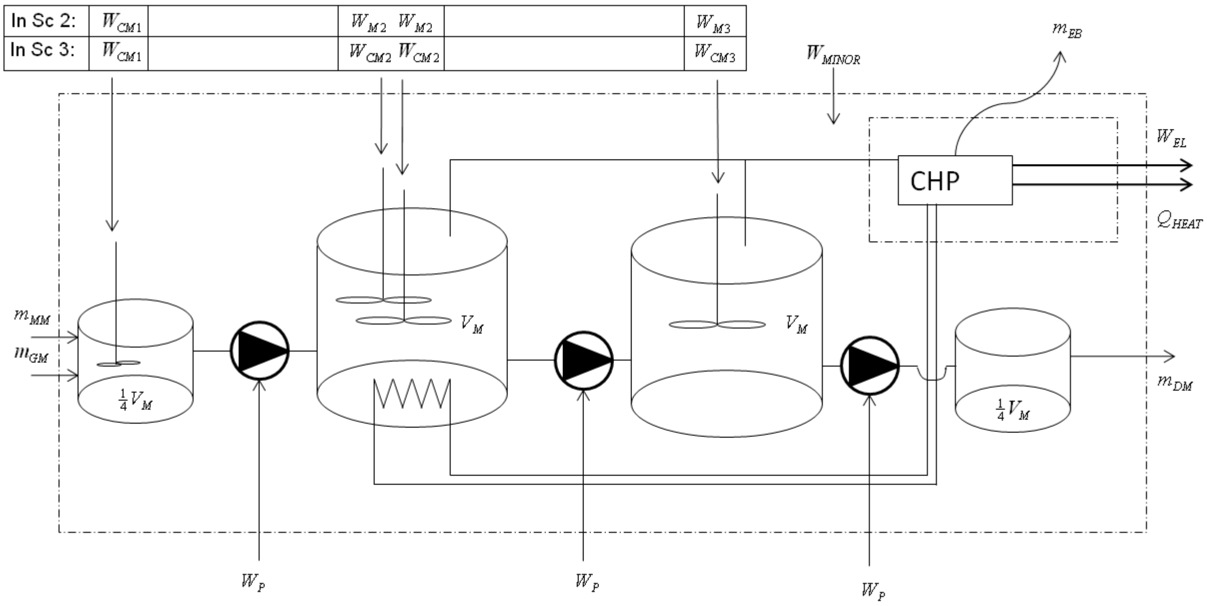


Figure 6.1: Energy balance terms in biogas production with mass flows included in the energy balance.

Table 6.1: Minor energy consumption in the LCA model.

Scenario 2:		
Screw pump for grass silage import	53	W
Two circulation pumps	1500	W
Four pieces of air pumps	720	W
Minor energy consumption, W_{MINOR}	71.69	GJ
Scenario 3:		
Screw pump for grass silage import	53	W
Circulation pump	750	W
Two pieces of air pumps	360	W
Minor energy consumption, W_{MINOR}	36.69	GJ

6.1 Heat and electricity production

Methane productivity was defined in this LCA model according to batch experiment data and measured fixing factors as described in chapter 3.2. When, in addition, the combustion heat of methane H_{CH_4}, mass flows (table 6.4) and volatile solid contents (table 7.4) of feedstock were known the heat power content of methane is

$$\dot{H}_{CH_4} = H_{CH_4} \left(\mathrm{VS}_G \dot{m}_{GM} + \mathrm{VS}_M \dot{m}_{MM}\right) \mathrm{MPR}. \tag{6.1}$$

In a combined heat and power plant (CHP), produced biogas is burnt in a gas engine. The efficiencies of electric and heat power output are 36.6 and 54.1 % of the total heat power content of methane in scenario 2 (table 6.2). At electric production efficiency of η_E the electric energy production from the biogas plant during time Δt is

$$W_{EL} = \eta_E \dot{H}_{CH_4} \Delta t. \tag{6.2}$$

The total amount of heat power $\eta_H \dot{H}_{CH_4}$ is produced in CHP, but there is a need to heat the 1^{st} reactor at heat power of q_M. The net produced heat energy from the biogas plant during time Δt is

$$Q_{HEAT} = \left(\eta_H \dot{H}_{CH_4} - q_M\right) \Delta t. \tag{6.3}$$

Table 6.2: The properties of CHP unit in each scenario.

	Scenario 2 [19]	Scenario 3 [20]	
Maximum electric power output	140.0	70.0	kW
Maximum heat power output	207.0	115.0	kW
Total efficiency	90.7	90.7	%
η_E	36.6	34.3	%
η_H	54.1	56.4	%

The lower heating value (LHV) of methane H_{CH_4} was defined at 298 K. First the higher heating value ($\Delta_r H^o$(298 K)) of methane was calculated(equation 6.5). In combustion reaction gases such as carbon dioxide, nitrogen and water vapour receive the heat that is released in the methane combustion reaction. In this model it is assumed that the heat received by the water vapour is not recovered, but the heat received by other gases is recovered. In other words, there is considered a case when the heat received by the water is not recovered in the energy conversion unit. When it is assumed that water does not release its heat back to the energy conversion unit, a lower heating value (LHV) of methane in terms of MJ/m^3 is used to calculate the heat received by the energy conversion unit. In perfect methane combustion the chemical reaction is

$$CH_4 \;+\; 2O_2 \;\rightarrow\; CO_2 \;+\; 2H_2O. \tag{6.4}$$

The heat released in equation 6.4 can be calculated from standard enthalpies of formation products and reactants [21],

$$\Delta_r H^o(298\text{ K}) \;=\; \sum \Delta_f H^o(\text{products}, 298\text{ K}) \;-\; \sum \Delta_f H^o(\text{reactants}, 298\text{ K}). \tag{6.5}$$

When standard enthalpies of carbon dioxide, water, oxygen and methane are -393.5 kJ/mol, -286 kJ/mol, 0 kJ/mol and -74 kJ/mol respectively the heat released in the reaction is (equation 6.5)

$$\Delta_r H^o(298\,\text{K}) \;=\; (-393.5 - 2\cdot 286 - (-74))\,\text{kJ/mol} \;=\; -\,891.5\,\text{kJ/mol} = \;-\,55.573\,\text{kJ/g}.$$

From the reaction equation 6.4 it can be seen that one kilogram of methane produces 2.246 kg of water (H_2O). This amount of water is vaporized in total combustion. When the heat needed in water vaporizarion is reduced from the total combustion heat per mass unit the lower heating value of methane in terms of MJ/kg is

$$55.573\text{MJ/kg} - \frac{2.246\text{ kg H}_2\text{O}}{1.0\text{ kg CH}_4} 2.26\text{ MJ/kg} = 50.497\text{MJ/kg}.$$

When the density of methane at 298 K and 1 **atm** pressure is 656 g/m^3 the net combustion heat of methane H_{CH_4} is in terms of volume 33.13 MJ/m^3 [22]. In one literature source the lower heating value of methane was 910 Btu/ft^3 which is about 30 MJ/m^3 [23]. In this model the calculated lower heating value of methane H_{CH_4} was used.

6.2 Dimensioning the biogas plant

the biogas plant in the LCA model was dimensioned according to mass flows needed to run the plant. In scenario 2 slurry manure and grass silage mass flows were estimated from present mass flows in the farm cluster. The annual amounts of slurry manure were known in each farm. It was estimated that the grass silage mass flow of the slurry manure mass flow could be 8 % which is denoted as ϕ_G. In scenario 3 the mass flow of grass silage was set to be same as in scenario 2. Slurry manure mass flow in scenario 3 was calculated when the maximum organic loading rate was 3 kgVS/(m^{3}d) (table 3.2).

When the mass flow of slurry manure $\dot{m}_{MM}$ and the grass silage wet weight of the slurry manure wet weight ϕ_G are known the mass flow of grass silage into the biogas plant is

$$\dot{m}_{GM} = \phi_G \dot{m}_{MM}. \tag{6.6}$$

The volume of digester can be calculated when hydraulic retention time HRT, incoming mass flows ($\dot{m}_{GM}$, $\dot{m}_{MM}$) and densities of grass silage ρ_G and slurry manure ρ_M are known. Hydraulic retention time HRT is 30 days. Density of slurry manure is 998 kg/m^3, but density of grass is assumed to be 750 kg/m^3. In the two stage biogas plant the volume of both reactors is

$$V_M = \mathrm{HRT}\left(\frac{\dot{m}_{MM}}{\rho_M} + \frac{\dot{m}_{MG}}{\rho_G}\right). \tag{6.7}$$

In scenario 3 the mass flow of slurry manure was derived from grass silage mass flow and ϕ_G. The maximum organic loading rate OLR_M is 3 kgVS/(m^{3}d), hydraulic retention time is the same 30 days and volatile solid contents of slurry manure VS_M and grass silage VS_G were 4.48 and 27.9 per cent of the wet weight (table 7.4.). The share of grass silage wet weight of the slurry manure wet weight is

$$\phi_G = \frac{\frac{\mathrm{OLR}_M \mathrm{HRT}}{\rho_M} - \mathrm{VS}_M}{\mathrm{VS}_G - \frac{\mathrm{OLR}_M \mathrm{HRT}}{\rho_G}}. \tag{6.8}$$

When in scenario 3 the mass flow of grass silage was the same as in scenario 2 the slurry manure mass flow and the volume of digester were calculated according to equations 6.6 and 6.7.

6.3 Pumping

The energy needed in pumping is assumed to be the same as the energy needed in water pumping. The real energy consumption of pumping should be measured for each fluid. In the case of slurry pumping the fluid contains impurities that are harmful for pumping and may increase the energy consumption. One pump manufacturer claims that even slurry that has a total dry solids content of 8 % can be pumped [24]. It's commonly known that slurry manure that has a dry matter content of about 5 % can also be pumped. This gives a reason to evaluate at least the minimum energy that is needed in pumping according to the pump power measurements and product details done with water.

In this case the pump is designed to operate at its best efficiency point (BEP) where the volume flow rate and the pump's output power of the pump's input power reaches maximum values [25]. BEP is approximately found to be in a centrifugal pump *Flygt N3127* with a *487* - type impeller at a flow rate of 30 l/s, pump head of 14 m and pump's input power $\dot{W}_P$ of 5.4 kW [26]. If water is pumped, the pump maximum efficiency would be

$$\eta_{max} = \frac{HQ_W\rho_W g}{\dot{W}_P} = \frac{14\ \mathrm{m}\cdot 30\ \mathrm{l/s}\cdot 0.998\ \mathrm{kg/l}\cdot 9.81\ \mathrm{m/s^2}}{5.4\ \mathrm{kW}} = 76\ \%. \tag{6.9}$$

The volume flow rate at which slurry manure needs to be pumped from pre-storage to the 1^{st} reactor is 33 $\mathrm{m^3/d}$ in scenario 2. A constant volume flow of 0.38 l/s is needed, but most pumps cannot be used to pump such small volume flows. When the pump operates at its BEP, the time needed to pump slurry of the minimum pumping time at volume flow of Q_W is

$$\phi_P = \frac{\dot{m}_{MM}/\rho_M + \dot{m}_{GM}/\rho_G}{Q_W}. \tag{6.10}$$

When three pumps are needed in scenarios 2 and 3, the energy needed for pumping at time Δt is

$$W_P = 3\dot{W}_P\phi_P\Delta t. \tag{6.11}$$

6.4 Mixing

The energy consumption of mixers in the LCA model was calculated according to the mixer's operation time at a certain actual power. Dimensional analysis, product details and measured actual power were used to derive actual power for 7.5 and 15 kW mixers. In biogas plant these mixers operate in certain time intervals at certain actual power, so the average power of mixers was calculated when the time intervals and input signal relative frequencies were known. The power of a mixer that had nominal power of 7.5 kW was derived by fitting a polynom to measured power and input signal frequency. It was not possible to measure the same kind of power data for a mixer that had nominal power of 15 kW, so dimensional analysis and data curve fixing were used to estimate the actual power. Power measurements were done in MTT's biogas plant in Maaninka, so one must assume that the composition of biomass would be the same in the LCA model.

The actual power of the mixer was derived by using dimensional analysis and product details [25]. In dimensional analysis there is found a dimensionless variable or variables that describe the phenomena. The dimensionless variable in this case is the so called power constant C_P that is actually a group of variables. In terms of dimensionless power constant and other essential parameters, the power of mixer is

$$\dot{W}_M = C_P d_M^5 \rho_{BM} f_f^3. \tag{6.12}$$

The revolution speed of the mixer's axis was not possible to measure from the operating biogas plant, so the input voltage signal's relative frequency θ_f of the mixer was measured. It was necessary to assume that the revolution speed of the mixer's axis f_f is directly proportional to the input signal frequency. When the maximum relative frequency is 100 %, the revolution speed of the mixer's axis is assumed to have the maximum value of f_M. The higher the revolution speed of the mixer's axis f_f the more power is needed for mixing. Increasing the diameter of mixer's blade d_M would also increase the mixer's power. Mixing power depends even more on the type of substance that is mixed. In real life the input power of the mixer should be measured versus the diameter of the mixer's blade and speed of revolution of the mixer's axis for certain types of substances. In terms of the mixer's axis maximum revolution speed f_M and relative frequency $\theta_f = f_f/f_M$, the power of the mixer can be also expressed as

$$\dot{W}_M = C_P d_M^5 \rho_{BM} \left(f_M \theta_f\right)^3. \tag{6.13}$$

Product detail data was used to approximate the dimensionless mixing power constant C_P in equation 6.13. According to the product details, the 7.5 kW mixer axis's maximum speed of revolution f_M was assumed to be 470 **rpm** at maximum input power $\dot{W}_M$ of 9.16 kW and a blade diameter of 490 mm [27]. When the density of biomass is 998 kg/m^3 the dimensionless power constant C_P would be 0.676 when all parameters are converted into basic SI units.

The suitability of the 15 kW mixer's power derivation was estimated by doing dimensional analysis and data curve fixing for the 7.5 kW mixer. It was quite straightforward to derive the power of the 7.5 kW mixer, because the mixer's power in the LCA model would follow the measured data from MTT's biogas plant when the composition of biomasses are similar. A third degree polynom was fitted to measured power data (figure 6.2, solid curve). The result was that the fitted curve had power of 470 W when relative frequency θ_f had a value of zero. The actual input power of the 7.5 kW mixer is

$$\dot{W}_{CM} = \left[3.17 \cdot \theta_f^3 + 6.23 \cdot \theta_f^2 + 0.222 \cdot \theta_f + 0.47\right] \text{ kW}. \tag{6.14}$$

It was then assumed that the 7.5 kW mixer's power calculated from dimensional analysis had the same 470 W power at zero relative frequency. As shown in figure 6.2, theoretical and measured power of 7.5 kW mixers act in a similar way. This kind of dimensional analysis and data fitting was also used to derive the input power of the 15 kW mixer that is

$$\dot{W}_M = \left[C_P d_M^5 \left(f_M \theta_f\right)^3 + 0.47\right] \text{ kW}. \tag{6.15}$$

The power constant C_P of the 15 kW mixer would be 0.736 according to equation 6.13 when the mixer axis's maximum speed of revolution f_M was assumed to be 240 **rpm**, diameter of blade d_M is 820 mm and maximum input power $\dot{W}_M$ is 17.4 kW [27]. This approximated data point was used in dimensional analysis when the 15 kW mixer was assumed to have input power of 470 W at zero relative frequency. In real life several values of the mixer axis's revolution speed and the mixer's input power would have been measured. Because the actual mixer axis's revolution speed measurements were not possible to obtain, only one approximated data point and curve fixing were used to approximate the power of the mixer having nominal power of 15 kW (figure 6.2). The actual power of the 15 kW mixer was calculated according to equation 6.15.

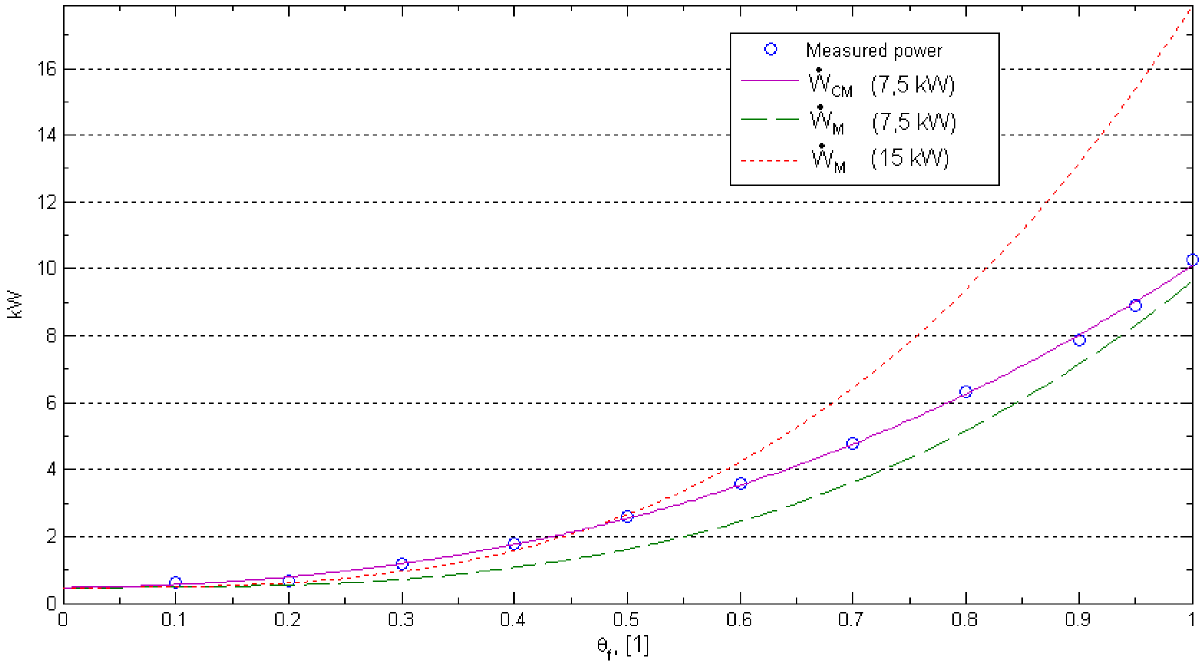


Figure 6.2: Dotted lines denote the theoretical mixer's power and the solid line denotes the measured mixer's power.

The energy consumption of each mixer was calculated according to their actual power, relative frequency and operating time. In operation, mixers are set to run at two power levels at a certain time. This is done by adjusting the input signal relative frequency θ_{fi} to a certain level at time t_i. Time steps are now denoted as t_1 and t_2 when corresponding input signal relative frequencies are θ_1 and θ_2 (table 6.3). The average power of the mixer is

$$\bar{\dot{W}}_X = \frac{\dot{W}_X(\theta_{f1})t_1 + \dot{W}_X(\theta_{f2})t_2}{t_1 + t_2}, \tag{6.16}$$

where X denotes to mixers $M2$, $M3$, $CM1$, $CM2$, $CM3$. The actual power was derived for mixers CM and M that had nominal power of 7.5 and 15 kW. At operating time Δt the energy consumption of mixer X is

$$W_X = \frac{\dot{W}_X(\theta_{f1})t_1 + \dot{W}_X(\theta_{f2})t_2}{t_1 + t_2}\Delta t. \tag{6.17}$$

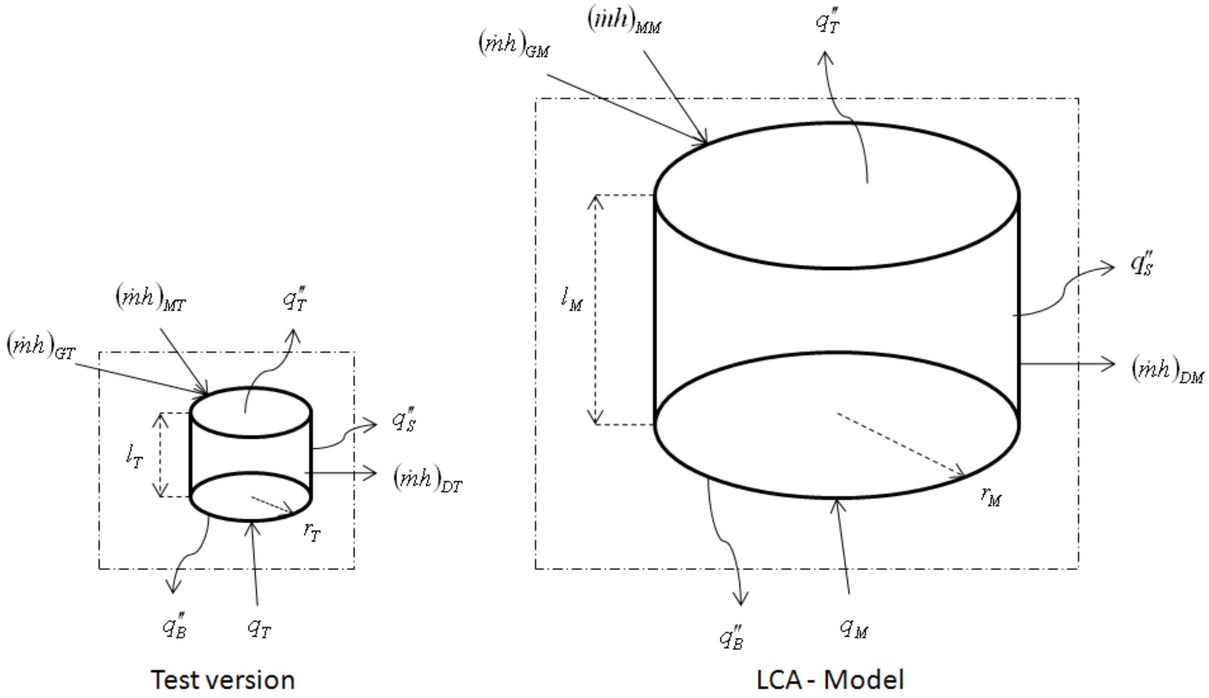
Table 6.3: The energy consumption of mixers when operating time Δt is one year.

mixer X	θ_{f1} %	t_1 min	θ_{f2} %	t_2 min	$\bar{\dot{W}}_X$ kW	W_X GJ
$M2$	25	240	90	2	0.84	26.6
$M3$	65	240	90	2	5.32	167.8
$CM1$	20	240	50	1	0.80	25.1
$CM2$	25	240	90	2	1.02	32.3
$CM3$	65	240	90	2	4.15	130.9

6.5 Reactor heating

Heat energy consumption of the 1^{st} reactor in the LCA model is calculated by using measured heat power consumption from the test reactor, volume of biomass in the LCA model's and test version's 1^{st} reactor and heat power contents of biomasses in the LCA model and test version. Feedstock means in this case imported grass silage and slurry manure. It is assumed that weather conditions, infrastructure, the temperatures of feedstock and digestates are similar both in the test version and the LCA model. The LCA model and the test version have the same surface heat losses, because the temperature difference between the biomass surface and surroundings in each part of the biomass are the same in the LCA model and test version (fig. 6.3). By using these base assumptions, the heat power consumption of the LCA model's 1^{st} reactor can be calculated.

Feedstock is loaded into the 1^{st} reactor when slurry manure is at 5 °C and grass silage is at 2 °C in the test version and LCA model. While feedstock is loaded into the 1^{st} reactor, the same amounts of digestate ($\dot{m}_{DT}$ and $\dot{m}_{DM}$) are pumped into the



Test version

LCA - Model

Figure 6.3: Heat balance of biomass inside the 1^{st} reactor in the case of the test version and LCA model.

2_{nd} reactor at a mesophilic temperature of 37 °C (table 6.4.). At the same time, heat losses occur from both the test version and LCA model, q_{LT} and q_{LM} respectively. The heat input needed for the test version q_T and feedstock mass flows in the test version ($\dot{m}_{MT}$ and $\dot{m}_{GT}$) and LCA model ($\dot{m}_{MM}$ and $\dot{m}_{GM}$) are known. The heat balance in the test version of the 1^{st} reactor in terms of power is

$$q_T + (\dot{m}h)_{MT} + (\dot{m}h)_{GT} = q_{LT} + (\dot{m}h)_{DT} + (\dot{m}h)_{BG}\,. \tag{6.18}$$

The heat power loss with biogas $(\dot{m}h)_{BG}$ can be now ignored, because the heat power loss of biogass is less than one per cent of the heat power loss of digestate. The specific heat capacities of methane and carbon dioxide are 2.2 and 0.8 kJ/(kg · K) respectively [22]. In scenario 2 the total CO_2 and CH_4 mass flows were 10.8 and 4.7 g/s respectively from both biogas reactors. If the mass flows of methane and carbon dioxide are assumed to be half of the total mass flows and biogas flows out of the reactor at +37 °C the heat power content of biogas is

$$(\dot{m}h)_{BG} = \left[\frac{10.8\ \mathrm{g/s}}{2} 0.8\ \mathrm{kJ/(kg \cdot K)} + \frac{4.7\ \mathrm{g/s}}{2} 2.2\ \mathrm{kJ/(kg \cdot K)}\right] \cdot (273.15 + 37)\,\mathrm{K} = 2.95\,\mathrm{kW},$$

which is one per cent less than the heat power content of digestate $(\dot{m}h)_{DM}$ from the 1^{st} reactor in scenario 2 that was 517 kW (eq. 6.31). The heat balance in the 1^{st} reactor becomes

$$q_T + (\dot{m}h)_{MT} + (\dot{m}h)_{GT} = q_{LT} + (\dot{m}h)_{DT} \,. \tag{6.19}$$

When the heat power content of biogas is ignored, the heat balance in the LCA model similarly becomes,

$$q_M + (\dot{m}h)_{MM} + (\dot{m}h)_{GM} = q_{LM} + (\dot{m}h)_{DM} \,. \tag{6.20}$$

The heat power loss from the test version's reactor surface q_{LT} consists of heat losses from the sides ($q_S^{"} A_{ST}$), bottom ($q_B^{"} A_{BT}$) and top ($q_T^{"} A_{TT}$) (fig 6.3),

$$q_{LT} = q_S^{"} A_{ST} + q_B^{"} A_{BT} + q_T^{"} A_{TT}, \tag{6.21}$$

where A_{ST}, A_{BT} and A_{TT} denote areas of the side, bottom and top of the test version. Heat fluxes $q_S^{"}$, $q_B^{"}$ and $q_T^{"}$ are from side, bottom and top in [W/m^2]. The ratio of the biomass's radius from height in the test version and LCA model is

$$\frac{r_T}{l_T} = \frac{r_M}{l_M} = 3/2.$$

The heat power loss from the LCA model's biomass surface q_{LM} is in same form as the heat power loss from the test version's biomass surface. As a result of short algebra, the heat loss from the test version's and LCA model's biomass surface becomes

$$q_{LT} = V_T^{2/3} \left(\frac{3\sqrt{\pi}}{2} \right)^{2/3} \left(\frac{4}{3} q_S^{"} + q_B^{"} + q_T^{"} \right) \tag{6.22}$$

$$q_{LM} = V_M^{2/3} \left(\frac{3\sqrt{\pi}}{2} \right)^{2/3} \left(\frac{4}{3} q_S^{"} + q_B^{"} + q_T^{"} \right), \tag{6.23}$$

where the volumes of the 1^{st} reactors are

$$V_T = \frac{2\pi r_T^3}{3} \quad \text{and} \quad V_M = \frac{2\pi r_M^3}{3}.$$

By substituting equations 6.22 and 6.23 into 6.19 and 6.20 and after some short algebra, the heat power q_M needed in the LCA model becomes

$$\begin{aligned} q_M &= \left[q_T + (\dot{m}h)_{MT} + (\dot{m}h)_{GT} - (\dot{m}h)_{DT} \right] \left(\frac{V_M}{V_T} \right)^{2/3} \\ &\quad - (\dot{m}h)_{MM} - (\dot{m}h)_{GM} + (\dot{m}h)_{DM} \,. \end{aligned} \tag{6.24}$$

When surface heat loss q_{LT} is substituted in equation 6.24, heat power consumption can also be denoted as

$$q_M = \underbrace{q_{LT}\left(\frac{V_M}{V_T}\right)^{2/3}}_{\text{Heat loss from surfaces}} + \underbrace{\left[(\dot{m}h)_{DM} - (\dot{m}h)_{MM} - (\dot{m}h)_{GM}\right]}_{\text{Heat loss from mass flows}}. \tag{6.25}$$

As seen from equation 6.25, the heat consumption of the 1^{st} reactor consists of heat loss from biomass surfaces and heat loss from mass flows.

Heat power contents of substances used in this model can be calculated from equations 6.26 to 6.31 where heat power contents consist of water and total solid heat contents. The heat capacity of water C_W is 4.19 kJ/(kgK). Total solids are assumed to have a heat capacity of 1.2 kJ/(kgK) which is the same as the heat capacity of wood. The heat capacity of total solids is denoted as C_D. The total solid contents of slurry manure TS_{MM} and grass silage TS_{GM} in the LCA model are known based on statistics and literature (table 7.4). Total solid contents of feedstock (TS_{MT} and TS_{GT}) and digestate (TS_{DT}) after the 1^{st} reactor in the test version were measured from MTT's biogas plant in Maaninka. Feedstock and digestate mass flows that are used in this model are represented in table 6.4. By inserting these values, the heat power consumption in the LCA model's 1^{st} reactor can be calculated according to equation 6.24, where

$$(\dot{m}h)_{MT} = (\dot{m}T)_{MT}\left[(1 - \mathrm{TS}_{MT})C_W + \mathrm{TS}_{MT}C_D\right], \tag{6.26}$$

$$(\dot{m}h)_{GT} = (\dot{m}T)_{GT}\left[(1 - \mathrm{TS}_{GT})C_W + \mathrm{TS}_{GT}C_D\right], \tag{6.27}$$

$$(\dot{m}h)_{DT} = (\dot{m}T)_{DT}\left[(1 - \mathrm{TS}_{DT})C_W + \mathrm{TS}_{DT}C_D\right], \tag{6.28}$$

$$(\dot{m}h)_{MM} = (\dot{m}T)_{MM}\left[(1 - \mathrm{TS}_{MM})C_W + \mathrm{TS}_{MM}C_D\right], \tag{6.29}$$

$$(\dot{m}h)_{GM} = (\dot{m}T)_{GM}\left[(1 - \mathrm{TS}_{GM})C_W + \mathrm{TS}_{GM}C_D\right], \tag{6.30}$$

$$(\dot{m}h)_{DM} = (\dot{m}T)_{DM}\left[(1 - \mathrm{TS}_{DM})C_W + \mathrm{TS}_{DM}C_D\right]. \tag{6.31}$$

When the operating time of the biogas plant is Δt, the heat consumption in the 1^{st} reactor is

$$Q_M = q_M \Delta t. \tag{6.32}$$

Table 6.4: The properties of mass flows in LCA model and test version.

$\dot{m}_{MT}$	9.7	t/d
$\dot{m}_{GT} = \phi_G \dot{m}_{MT}$	0.8	t/d
$\dot{m}_{DT} = (1 + \phi_G)\dot{m}_{MT}$	10.4	t/d
V_T	300	m^3
q_T	14.0	kW
$T_{MT} = T_{MM}$	5	°C
$T_{GT} = T_{DM}$	2	°C
$T_{DT} = T_{GM}$	37	°C
TS_{MT}	5.68	%
TS_{GT}	31.11	%
TS_{DT}	5.46	%
TS_{MM}	5.50	%
TS_{GM}	31.80	%
In Sc2:		
$\dot{m}_{MM}$	32.73	t/d
$\dot{m}_{GM}$	2.62	t/d
$\dot{m}_{DM} = \dot{m}_{MM} + \dot{m}_{GM}$	35.35	t/d
$\phi_F = \frac{V_M}{V_T}$	3.65	
TS_{DM}	3.84	%
In Sc3:		
$\dot{m}_{MM}$	9.09	t/d
$\dot{m}_{GM}$	2.62	t/d
$\dot{m}_{DM}$	11.71	t/d
$\phi_F = \frac{V_M}{V_T}$	1.26	
TS_{DM}	5.87	%

7 Mass flows

Mass flows included in each scenario were related to energy balance as described in chapters 4, 5 and 6. The properties and quantities of mass flows were estimated in this LCA model in the following way. Nitrogen and phosphorus leaches were estimated when land type in the LCA model was assumed to be silt soil. Greenhouse gas emissions came from grass silage production in the field, transportation in grass silage production, slurry manure transportation, grass silage transportation and biogas combustion. Nutrient contents of substances in the scenarios were based on nutrient statistics and known practices in nitrogen mineralization in anaerobic digestion. The amount of fertilizers were calculated according to the average fertilizing requirement in Finland. The quantities of slurry manure and grass silage in the farm cluster were based on boundary conditions that were described in chapter 2. Calculated mass flows are represented in more detail in chapter 8.

7.1 Nutrient leaches

Leaches of nutrients are affected mainly by land type, fertilizing, cultivation methods and weather conditions. Water flows through the plot affect the nutrient leaches. The more the land type can bind water, the less nutrients leach. For example, in 1982 in Jokioinen, nitrate leaches were recorded to be 1.6, 3.6, 4.2 and 4.2 kg/ha from peat, clay, silt and sand plots respectively [28]. Also the greater the slope in the field, the greater are the leaches. In the following it is also proven that leaches are directly proportional to the amount of fertilizing. Slurry spread by injection decreases surface leaches and ammonium losses from slurry. Leaches are usually classified as surface and underdrain leaches. The following research review on this topic highlights nitrogen and phosphorus leaches that are used in this LCA model.

Nitrogen leaches

Nitrogen leaches usually happen via run off and underdrains. Normal nitrogen leaches from 11 to 22 kg/ha were recorded in Finland [29]. Surface and drainage water leaches of nitrogen (NO_3-N) from clay soil were on average 4 and 13 kg/ha when measurements were done for cereal crops from 1976 to 1982. The field was fertilized with 100 kg/ha of nitrogen. One year after grass ley was sowed in a clay soil, underdrain nitrate nitrogen (NO_3-N) leaches were recorded to be 1.4 kg/ha and 3.0 kg/ha when 100 and 200 kg/ha of total nitrogen was used as fertilizer. [28]

Barley, timothy and meadow fescue were sowed in a fine sand soil and plots were fertilized by total nitrogen averages of 193, 202, 201 and 128 kg/ha during a four year period (tab. 7.1). Average nitrogen leaches from 1992 to 1996 take into account the current weather conditions and rains. In all experiments the average amount of fertilized nitrogen was annually 181 kg/ha and the average total nitrogen leach was annually 23.7 kg/ha.

Finnish nitrogen leach experiments done in Maaninka state that nitrogen leaches can be even greater in pastures. Nitrogen leaches from grass pasture were measured during four grazing years when 220 kg/ha of total nitrogen was annually used as fertilizer. Annually, the average N and NO_3-N leaches were 27.5 kg/ha and 25.5 kg/ha during four years when the renewal year was included. An average amount of total nitrogen of 4.0 kg/ha was recorded in the same experiment from runoff waters when the amount of NO_3-N was on average 0.72 kg/ha. [30]

It's been proven that nitrate nitrogen leaches are quite similar for silt and sand plots, so results from Toholampi can be taken as starting values in the LCA model [31]. The total nitrogen leach in the model is then about 23 kg/ha of total nitrogen.

Table 7.1: Annual average N leach from grass ley in Toholampi, Finland [31].

Fertilized N kg/ha	With drainage water kg/ha			With surface runoff kg/ha		
	NO_3N	NH_4-N	N-tot.	NO_3-N	NH_4-N	N-tot.
193	5.3	0.03	5.75	1.8	7.75	15
202	3.5	0.02	4	1.35	28.25	49.5
201	3.25	0.03	3.5	2.03	2.1	6.75
128	3	0.02	3.5	1.1	2.75	6.75

Phosphorus leaches

In Finland annual phosphorus leaches are recorded from 0.8 to 1.9 kg/ha [29] [32]. Phosphorus leaches via underdrains were less than leaches via run off waters [33]. In the LCA model phosphorus is fertilized about 24 kg/ha and the land base type is assumed to be silt soil. As in the case of nitrogen leach, the total leaches were quite similar in silt and sand land types [28]. The phosphorus leach result obtained from Toholampi could then also be used in this LCA model [31]. Total amount of leached nitrogen would then be about 1.2 kg/ha (table 7.2).

Table 7.2: Annual P leach from grass leys in Finland.

Fertilized P	Leach tot. P		Leached soluble P		Reference
	run off	underdrain	run off	underdrain	
kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	
42	1.27	0.32	0.87	0.15	[33]
82	1.27	0.34	0.87	0.19	[33]
27	1.21	0.007	0.66	0.002	[31]

7.2 Greenhouse gas emissions

The effect of greenhouse gases from each source is related to the amount of greenhouse gas and the heat content of produced biogas. In field cultivation there were greenhouse gases from dissipation of harmful gases and from fossil fuel combustion in machinery work m_{EGF}. Transportation between farms and their field caused carbon dioxide emissions m_{EGT} from fuel combustion. Slurry manure and grass silage transportation between farms and the biogas plant caused carbon dioxide emissions of m_{ETS} and m_{ETG} respectively. In the biogas plant, biogas was combusted and the total amount of carbon dioxide emissions was m_{EB}. Greenhouse gases from different sources are compared based on the definition of the carbon dioxide equivalent.

CO_2 equivalent

Greenhouse gases are one major reason for global warming. That's why the effects of greenhouse gases are compared according to their effect on radiative forcing which is the change in solar irradiance caused by the greenhouse gas. The comparison index is called global warming potential, GWP. It's the share of radiative forcing caused by a gas compound of the radiative forcing caused by CO_2 over the same time period.

The key greenhouse gases are methane, carbon dioxide and nitrous oxide. Global warming potentials over 100 years are, for example, 21 for methane and 310 for nitrous oxide. [34]

Greenhouse gases from the field

Nitrous oxide (N_2O-N) emissions have been found to be 1.25 % of the total amount of fertilized nitrogen [35]. For example, if soluble nitrogen of 89 kg/ha is spread on a field in the form of slurry manure, the N_2O-N emissions would be about 1100 g/ha. The intergovernmental panel on climate change, IPCC, recomments estimating N_2O-N emissions as 1 % of the total amount of fertilized nitrogen [36].

The method of slurry manure spread has been proven to have an effect on N_2O - emissions. A field experiment done in Vihti in Finland, proved that N_2O - emissions can be significantly high even if only an injection spread system is used. The experiment was carried out in five months during summer. In injection spread the nitrogen dissipation in the form of N_2O was 1100 g/ha when 157 kg/ha nitrogen was fertilized. When nitrogen of 79 kg/ha in the form of slurry with the injection spread system and additional nitrogen of 50 kg/ha in the form of mineral fertilizer were used, the total nitrogen dissipation in the form of N_2O was 660 g/ha. When in addition to previous experiment the land base was ploughed quickly after slurry spread, the total nitrogen dissipation in the form of N_2O was 400 g/ha. When nitrogen was fertilized with mineral fertilizers at 100 kg/ha, only 290 g/ha of nitrogen in the form of N_2O was observed. [37]

In the previous experiment in Vihti, the N_2O-N emissions were largest in slurry manure injection spread, 0.7 % of the total amount of fertilized nitrogen. In the LCA model, N_2O-N emissions are assumed to be about 0.7 % of the total fertilized nitrogen.

Almost half of NH_3-N was lost via dissipation when the broadcasting spread method was used. When the injection spread method was used, NH_3-N lost via dissipation almost disappeared [38]. A review claims that ammonia losses are 0.4 % of the soluble nitrogen in injection spread [39]. When the molar masses of nitrogen and hydrogen are 14.01 and 1.008 g/mol, the NH_3-N mass is 82 % of the NH_3 mass. The NH_3-N losses are 0.33 % of the fertilized soluble nitrogen. In the LCA model these NH_3-N and NH_3 losses were estimated to be 0.33 and 0.4 % of the fertilized soluble nitrogen.

Greenhouse gases from machinery work

Emission factors are commonly used in greenhouse gas emission calculations. Such emission factors are published by, for example, IPCC and VTT, Technical Research Centre of Finland. For example, the default factor for CO_2 emissions according to IPCC would be 74100 kg/TJ. When the combustion heat of diesel is 43 MJ/kg, the emission factor for CO_2 is 3.19 kg-CO_2/kg-diesel [40]. According to VTT the emission factor for CO_2 is 2.26 g/l [41]. When the density of diesel is 0.89 kg/l, the emission factor for CO_2 is 2.99 kg-CO_2/kg-diesel. Emission factors for a 71 kW tractor are represented in more detail in table 7.3. In perfect combustion, CO_2 emissions have the highest value and other minor emissions such as CO and small particles have minimum value. The concentration of minor gas emissions (except CO_2) is very small and the effect of minor gases in the amount of CO_2 equivalent is also very small (table 7.3). When one gram of diesel is burnt, the amount of CO_2eqv. is 3.02 grams, which is also taken as an initial value in the LCA model.

Table 7.3: Emission factors for most common greenhouse gases when [g em./g fuel] is denoted for one mass unit of emission per one mass unit of fuel.

	[g em./g fuel], [41]
CO	$9.55 \cdot 10^{-3}$
NMHC	$3.26 \cdot 10^{-3}$
NO_x	$28.09 \cdot 10^{-3}$
PM	$1.46 \cdot 10^{-3}$
CH_4	$16.85 \cdot 10^{-5}$
N_2O	$8.09 \cdot 10^{-5}$
SO_2	$1.91 \cdot 10^{-5}$
CO_2	2.99
CO_2eqv.	3.02

Greenhouse gases from biogas combustion

In the CHP unit carbon dioxide emissions come from biogas itself and from methane combustion. When methane and CO_2 concentrations in biogas are known, the total amount of CO_2 from complete combustion can be calculated. Methane and carbon dioxide concentration were 54.4 and 45.6 %. When feedstock mass flows, volatile solid content, methane productivity and density of methane ρ_{CH_4} were known, the produced methane during time Δt is

$$m_{CH_4} = (\mathrm{VS}_G \dot{m}_{GM} + \mathrm{VS}_M \dot{m}_{MM}) \cdot \mathrm{MPR} \cdot \rho_{CH_4} \cdot \Delta t. \tag{7.1}$$

In methane combustion, one mole methane produces one mole carbon dioxide (equation 6.4). When molar masses of methane and carbon dioxide are 16.02 and 44.01 g/mol, carbon dioxide from methane combustion is

$$\frac{44.01 \text{ g/mol}}{16.02 \text{ g/mol}} \cdot m_{CH_4}.$$

When the densities and concentrations of carbon dioxide and methane were known, the mass of carbon dioxide could be calculated. Densities of carbon dioxide and methane are 1.800 and 0.656 kg/m^3 at 1 **atm** and 298 K respectively. Carbon dioxide and methane concentrations in biogas were 45.6 and 54.4 %. Thus, the mass of carbon dioxide is

$$\frac{45.6\ \%}{54.4\ \%} \cdot \frac{1.800\ \mathrm{kg/m^3}}{0.656\ \mathrm{kg/m^3}} \cdot m_{CH_4}.$$

The total amount of carbon dioxide from the biogas plant is the sum of carbon dioxide in biogas and carbon dioxide from methane combustion,

$$m_{EB} = \left(\frac{45.6\ \%}{54.4\ \%} \cdot \frac{1.800\ \mathrm{kg/m^3}}{0.656\ \mathrm{kg/m^3}} + \frac{44.01\ \mathrm{g/mol}}{16.02\ \mathrm{g/mol}} \right) \cdot m_{CH_4}. \tag{7.2}$$

7.3 Nutrient balance in biogas production

The amount of slurry manure m_{MM} and grass silage m_{GM} were calculated according to boundary conditions in each scenario, but the amount of digestate m_{DM} from the biogas plant was calculated assuming that the amount of nitrogen does not change during anaerobic digestion. This leads to a problem when total mass balance is not exactly correct, but here it is wanted to point out that digestate contains the same amount of nitrogen as is coming into the biogas plant. It's also assumed that the mineralized nitrogen of the total solids and wet weight is similar in this LCA model to that in MTT's biogas plant. The nutrient concentrations of slurry manure and grass silage were known from statistics in Finland. When nutrient concentrations of feedstock and the relative change of ammonium nitrogen were known, the nutrient concentrations for digestate were calculated in each scenario. In addition, it was assumed that any dissipation of nutrients cannot happen, because manure and digestate storages were assumed to be covered.

Feedstock's properties

The concentrations of nutrients, total solids and volatile solids in feedstock are estimated in the LCA model according to statistics in Finland. The total solid concentration of slurry manure was averagely 5.5 % from 2000 to 2004 [9]. Volatile solids can be assumed to be 4.48 % of the wet weight, because in Lehtomäki's experiment the volatile solids were 81.5 % of the total solids [42]. Other properties of slurry manure in Finland from 2000 to 2004 are shown in table 7.4.

The latest statistical phosphorus and potassium concentrations of grass silage in Finland were published in 2006 [43]. When Lehtomäki did a batch reactor experiment for the biogas production of grass silage, she also measured nitrogen and ammonium nitrogen concentrations. Nitrogen and ammonium nitrogen concentrations in

Table 7.4: Properties of slurry manure and grass silage in the LCA model.

	TS %ww	VS %ww	N-tot mg/gTS	NH_4-N mg/gTS	N-tot %ww	NH_4-N %ww	P %ww	K %ww	Density kg/m^3
Slurry manure	5.50	4.48	54.55	32.73	0.30	0.18	0.05	0.33	992.7
Grass silage	31.80	27.90	37.00	3.30	1.18	0.10	0.09	0.91	
									ϕ_G, %
Feedstock in Sc2:	7.45	6.22	49.00	23.42	0.36	0.17	0.05	0.37	8.00
Feedstock in Sc3:	11.38	9.72	43.58	14.34	0.50	0.16	0.06	0.46	28.81

Lehtomäki's experiment were 37 and 3.3 mg/gTS when total solids and volatile solids were 31.8 and 27.9 % of the grass wet weight [42].

In scenario 2, eight fresh matter units grass silage of the slurry manure fresh matter ($\phi_G = 8$ %) are imported. When the grass silage fresh mass of the slurry manure fresh mass is 8 % and total solid concentrations of slurry manure and grass silage are 5.5 and 31.8 %, the grass silage total solids of the grass and manure total solids is 31.63 %. As an example, the total nitrogen content of feedstock would be

$$37 \text{ mg/gTS} \cdot 0.3163 + 54.55 \text{ mg/gTS} \cdot (1 - 0.3163) = 49.00 \text{ mg/gTS}.$$

When total solid concentrations of slurry manure and grass silage are known, the dry matter content of feedstock is

$$\frac{0.08 \cdot 31.8 \text{ \%ww } + \text{ } 5.5 \text{ \%ww}}{1 \text{ } + \text{ } 0.08} = 7.45 \text{ \%ww},$$

where the grass silage fresh mass of the slurry manure fresh mass is 0.08. The amount of total nitrogen is 0.36 % of the feedstock's wet weight when the feedstock's total solid concentration is 7.45 % and total nitrogen concentration in total solids is 49.00 mg/gTS. The ammonium nitrogen concentrations of feedstock in units %ww and mg/gTS are calculated similarly as nitrogen concentrations. Phosphorus, sodium and volatile solid concentrations were calculated similarly as dry matter content of feedstock when the phosphorus, sodium and volatile solid concentrations of slurry manure and grass silage were known at given mass proportion ϕ_G.

Digestate's properties

It's been proven by several research that ammonium nitrogen and total nitrogen concentrations of grass silage and slurry manure increase during anaerobic digestion. In this model it is assumed that during digestion, phosphorus and sodium concentrations are constant. The following research review done in this field of study reveals how ammonium nitrogen concentration changes during anaerobic digestion. In this LCA model the nutrient measurements done in Maaninka are used to predict the change of total nitrogen and ammonium nitrogen concentrations in digestion. In aerobic digestion, the change of total and volatile solids, total nitrogen concentration and loss of volatile solids were calculated in a similar way in scenarios 2 and 3, but the change of ammonium nitrogen was described separately in both scenarios.

The properties of digestate were estimated in scenario 2 according to the measurements in MTT's biogas plant in Maaninka. The nutrient measurements of digestate and feedstock state the increase of nitrogen concentrations in anaerobic digestion. Ammonium nitrogen concentration increased 154 % during 60 days when the feedstock's and digestate's ammonium nitrogen concentrations were 15.5 and 39.4 mg/gTS. At the same time volatile solid concentration decreased 60.3 % when the feedstock and digestate volatile solid concentrations were 6.5 and 2.6 %ww. The increase of total nitrogen concentration was at the same time about 66.5 % of the total solids when the concentrations of total nitrogen in feedstock and digestate were 37.14 and 61.82 mg/gTS. The increase of ammonium nitrogen concentration (154 %), the loss of volatile solids (60.3 %) and the increase in total nitrogen concentration (66.5 %) were adopted in scenario 2 (table 7.5), because the share of feedstock mass flows were similar to measurements done in Maaninka and in scenario 2. When the volatile solid concentration of feedstock in scenario 2 was 6.2 % (table 7.4) and the loss of volatile solid concentration was 60.3 %, the volatile solid concentration in digestate after anaerobic digestion would be about 2.5 % of the wet weight (table 7.5). Total solids after anaerobic digestion are

$$\frac{(7.45\ \%\mathrm{ww}\ -\ 6.22\ \%\mathrm{ww})\cdot 60.27\ \%}{1-0.6027\cdot 0.0622}\ =\ 3.84\ \%\mathrm{ww},$$

where total solids in feedstock are 7.45 % ww (table 7.4), volatile solids in feedstock 6.22 % ww (table 7.4) and the loss of volatile solid concentration was 60.27 %. Ammonium nitrogen concentration after AD is 59.48 mg/gTS (table 7.5) when the concentration before AD was 23.42 mg/gTS (table 7.4) and during AD the increase of ammonium nitrogen concentration in total solids was 154 % of the total solids. The total nitrogen concentration of digestate is 81.56 mg/gTS when the total nitrogen concentration of feedstock was 49.00 mg/gTS and the increase of total nitrogen concentration during AD was observed to be 66.5 % of the total solids. When the ammonium nitrogen, total nitrogen and total solid concentrations are known, the total nitrogen and ammonium nitrogen concentrations are 0.31 and 0.23 % of the wet weight respectively (table 7.5).

The properties of digestate in scenario 3 were based on the literature values, measurements done in MTT's biogas plant and some assumptions. The change of ammonium nitrogen concentration was observed during anaerobic co-digestion when the changes of ammonium nitrogen were reported for grass silage and assumed for slurry manure, respectively. It was assumed that during the digestion the increase of ammonium nitrogen was 62 % of the ammonium nitrogen before the digestion. The ammonium nitrogen concentration of grass silage in digestion increases. The batch reactor experiments done by Lehtomäki and Björnsson state that anaerobic digestion of grass silage increases the total amount of ammonium nitrogen up to 40 % of the total nitrogen. In the same experiment, the ammonium nitrogen concentration increased 3.5 times of its original concentration [44]. In scenario 3, the increase of ammonium nitrogen concentration in grass silage and slurry manure were estimated to be 62 and 350 % of the total nitrogen. The change in ammonium nitrogen concentration in scenario 3 is

$$\frac{3.30\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot 0.625 \cdot 3.5 + 32.73\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot (1-0.625) \cdot 0.62}{3.30\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot 0.625 + 32.73\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot (1-0.625)} = 103\ \%,$$

where 3.30 mg $\text{NH}_4\text{−N}$/(g TS) and 32.73 mg $\text{NH}_4\text{−N}$/(g TS) were ammonium nitrogen concentrations in grass silage and slurry manure respectively (table 7.4). The grass silage volatile solids of the total volatile solids in scenario 3 was 0.625 and the change of ammonium nitrogen concentrations in grass silage and slurry manure were 3.5 and 0.62, respectively. According to the previous studies of ammonium nitrogen change in AD, the change of ammonium nitrogen concentration in scenario 2 would have been

$$\frac{3.30\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot 0.316 \cdot 3.5 + 32.73\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot (1-0.316) \cdot 0.62}{3.30\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot 0.316 + 32.73\ \frac{\text{mg NH}_4\text{−N}}{\text{g TS}} \cdot (1-0.316)} = 75\ \%,$$

where in addition to previous calculations the grass volatile solids were 0.316 of the total feedstock volatile solids. The increase of ammonium nitrogen concentration from scenario 2 to scenario 3 was from 75 to 103 % which was the increase of 37 % from scenario 2 to scenario 3. As mentioned before the increase of ammonium nitrogen was assumed to be 154 % in scenario 2. If the increase of ammonium nitrogen concentration would have increased from scenario 2 by 37 %, the ammonium nitrogen increase in scenario 3 would have been 210 % which was also adopted in this LCA model (table 7.5). In scenario 3 it is also assumed that the increase of total nitrogen (66.5 %) and the loss of volatile solids (60.3 %) were same as in scenario 2.

Table 7.5: The properties of digestates after anaerobic digestion.

	Change in NH_4-N %TS	Loss in VS %	VS %ww	TS %ww	NH_4-N mg/gTS	N-tot mg/gTS	N-tot %ww	NH_4-N %ww
Digestate in Sc2:	154	60.3	2.47	3.84	59.48	81.56	0.31	0.23
Digestate in Sc3:	210	60.3	3.86	5.87	44.45	72.55	0.43	0.26

7.4 Nutrient balance in Grass silage production

Fertilizing was carried out in the LCA model so that the statistical fertilizing requirement was satisfied and the nitrogen directive gave the maximum limit for total nitrogen fertilizing. For grass lands, 250 kg/ha of total nitrogen fertilizers are allowed, if there is at least a two week brake between fertilizing. When slurry fertilizer is spread at one time, the nitrate directive allows 170 kg/ha of total nitrogen in fertilizing [45]. The fertilizing requirement in this LCA model is assumed to be the average annual fertilizing requirement of a Finnish field. The amount of slurry manure spread and total amounts of fertilized nitrogen and phosphorus were recorded from 1994 to 1999 in Finland [46]. Slurry manure spread on fields varied between 18.3 and 42 m^3/ha. On average, total fertilized nitrogen and phosphorus were, during this six year period, 156 and 20 kg/ha, respectively. In a research, fertilizing requirement from 32 farms was collected from 1995 to 2004 [47]. The total fertilizing requirement for nitrogen (N), phosphorus (P) and potassium (K) were 154 kg/ha, 20.5 kg/ha and 48 kg/ha respectively. At first the nitrogen fertilizing requirement was fulfilled according to the fertilizing requrements. Then the phosphorus and finally the potassium fertilizing requirements were fulfilled according to the fertilizing requirements. From mineral fertilizers, all nutrients were considered to satisfy the fertilizing requirement, but only ammonium nitrogen in slurry fertilizer was considered to satisfy the nitrogen fertilizing requirement.

8 Results and discussion

Mass and energy balances in grass silage production, transportation and biogas production were calculated. Mass and energy balances were calculated and presented at a more detailed level in scenario 1. Results in scenarios 2 and 3 concentrate more on comparing mass and energy balance results in grass silage production, transportation and biogas production. Between scenarios 2 and 3 comparisons were made between energy inputs per produced electricity unit. Finally, greenhouse gases between scenarios were compared.

8.1 Scenario 1

Energy consumption in grass silage production consisted of energy consumption in the field and on the road. Annual average direct energy consumptions were 171 GJ and 109 GJ in the field and on the road, respectively (figure 8.1). In the farm cluster, total produced slurry manure was about 11950 t (table 3.1) that was spread onto a 295 ha field area, but in this scenario 21 % of the total grass silage field area and the amount of slurry manure was considered. In total, slurry manure production from all farms was 2505 t when the total field area in the six farms was 62 ha field (figure 8.2).

In the first scenario, there was lack of nitrogen of five kg/ha, but there was an excess of phosphorus and sodium: seven and one kg/ha, respectively (figure 8.2). The positive value of the nutrient balance means that more nutrient is imported into the field than is exported. Nitrogen losses of 1527 kg consisted of losses from nitrogen leaches, nitrous oxide dissipation and ammonium dissipation from slurry manure spread. When nitrogen leaches were evaluated to be 23 kg/ha (Chapter 7.1) and total field area was 61.9 ha, total nitrogen leaches were 1424 kg. Nitrous dissipation in the form of nitrous oxide was 0.7 % of the total fertilized nitrogen (Chapter 7.2). When total fertilized nitrogen was 12.6 t, nitrous dissipation in the form of nitrous oxide was 88 kg. There was also nitrogen dissipation of 15 kg in the form of ammonia from slurry manure spread when total soluble nitrogen was 4.51 t and NH_3-N emissions were evaluated to be 0.33 % of the total soluble nitrogen (Chapter 7.2). When phosphorus leaches were evaluated to be 1.2 kg/ha, total phosphorus leaches from a 61.9 ha field were 74 kg. In nitrogen fertilizing, *Yara Mila pellon NP* and *YaraBela N26, S14* were used totally 420 and 18910 kg, respectively. When both mineral nitrogen fertilizers had a

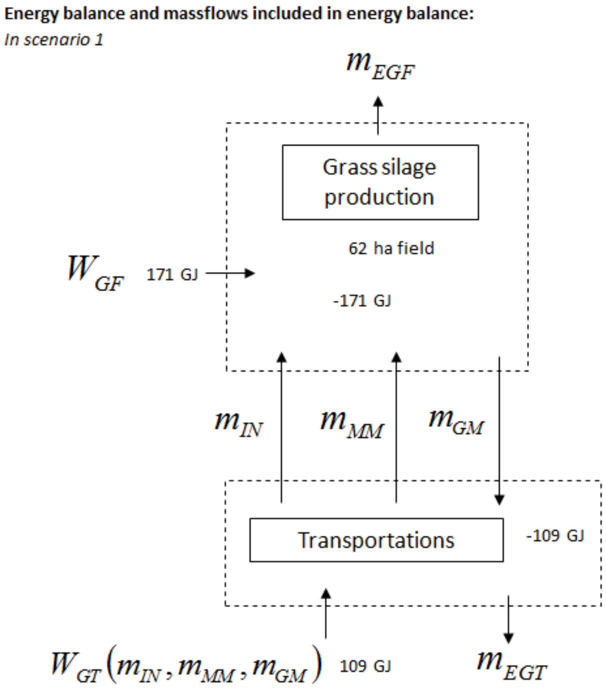


Figure 8.1: Energy balance in the LCA model.

nitrogen concentration of 26 % and *Yara Mila pellon NP* had phosphorus and sodium concentrations of four and one per cent, the total fertilized nitrogen, phosphorus and sodium were 5026, 17 and 4 kg, respectively (figure 8.2). Timothy, red clover and meadow fescue seeds were used at 10, 1 and 3 kg/ha, respectively in every fourth year for a 61.9 ha field [48]. Timothy seed nitrogen and phosphorus concentrations were 5.9 % and 0.31, % respectively [49]. Red clover and meadow fescue seeds had nitrogen and phosphorus concentrations of 3.4 % and 0.31, % respectively [49]. Nutrient balances were not zero, because nutrient contents of grass silage, fertilizers and seeds were based on literature values.

In Southern Finland nutrient balance data was collected from 130 farms from 1997 to 2000. In grass silage fields, nitrogen, phosphorus and sodium balances were 49, 3 and -65 kg/ha, respectively [50]. This meant that there was on average an excess of nitrogen and phosphorus and a lack of sodium in the field.

New information in grass silage production was that the energy consumption in road transportation in this farm cluster was 109 GJ when energy consumption in machinery work in the field was 171 GJ. Grass harvesting was the most energy intensive process (table 8.1). The biggest share of fuel consumption in road transportation was in the slurry manure spread process when machinery energy consumption in road transportation was 63 GJ from total machinery energy consumption of 80 GJ.

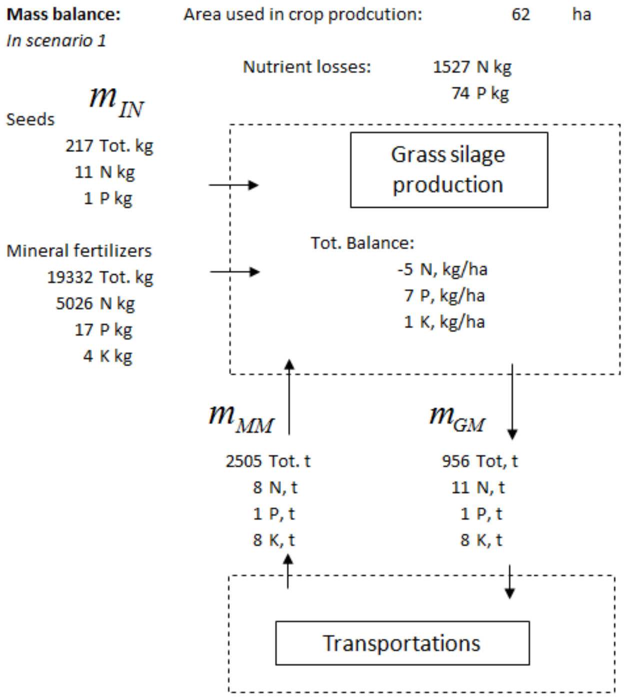


Figure 8.2: Nutrient and mass balance in the LCA model.

During the four year period, the fuel consumption in grass silage production in the field was reported to be 105 litres per hectare in the first year and 54 litres per hectare during the next three years [51]. Total fuel consumption during the four year period was 267 litres which included ploughing, solid fertilizing, harrowing, sowing and liming every fourth year; liquid fertilizing, moving and harvesting twice a year; seedbed cultivation, rolling and spraying every second year. When the fuel density is 0.89 kg/l, the cultivated field area is 61.9 ha and the combustion heat of diesel is 43 MJ/kg, machinery work done on average in one year is 158 GJ according to the CropGen project [22]. In this model, machinery energy consumption in the field was 171 GJ for a 61.9 ha field. When machinery work processes in the Cropgen project were quite similar to those presented in this thesis in chapter 4, the work done in the field were quite similar. In the CropGen project the work done in road transportation in grass silage production was not considered, but in this specific farm cluster the annual average work done on the road was 109 GJ.

Table 8.1: Annual average energy consumption in the grass silage production in scenario 1.

Grass silage production:	Tot. Production GJ	Prod. In field GJ	Transportation GJ
Spraying	-1.5	-0.8	-0.7
Lime spread	-5.3	-2.6	-2.7
Slurry manure spread	-79.5	-16.1	-63.4
Grass renewing	-34.5	-31.2	-3.3
Mineral fertilizer spread	-7.3	-3.7	-3.6
Harvesting	-151.1	-116.1	-35.0
Tot.	-279.2	-170.5	-108.7

8.2 Scenario 2

In scenario 2, one direct energy unit into the system produced 5 energy units as heat and electricity (table 8.4). The energy balance was calculated when all six farms were supplying relatively the same amount of grass silage and slurry manure into the biogas plant. The plant was located in a place where the potential heat consumer already was. In feedstock, the grass silage wet weight of the slurry manure wet weight ϕ_G was 8 %. In practise, it was found that six farms in the cluster could maximally donate 956 t of grass silage for biogas production (figure 8.4). In total, the required field area for grass silage production was 62 ha where digestate was used to replace mineral nitrogen fertilizer. The volume of the 1^{st} digester would be 3.6 times more than the volume of the 1^{st} digester ϕ_F in MTT's biogas plant in Maaninka. The organic loading rate at this biogas plant was 2 kgVS/(m^{3}d) (equation (6.8)).

Grass silage production

Digestate replaced mineral fertilizers in scenario 2, but more work was needed in slurry fertilizer spread in scenario 2. The energy consumption in grass silage production in scenario 2 was 295 GJ (figure 8.3) and in scenario 1 it was 280 GJ (figure 8.1), because in scenario 2 3149 t digestate fertilizer was used (figure 8.4) and in scenario 1 just 2505 t slurry manure was used (figure 8.2). Energy consumption in digestate spread was 100 GJ (table 8.4) in scenario 2 when in scenario 1 the energy consumption in slurry manure spread was 80 GJ (table 8.1). Only 145 kg/ha mineral fertilizer (*YaraBela N26, S14*) was used annually in scenario 2 when in scenario 1 the amount was in total 312 kg/ha (figure 8.4 and 8.2). In scenarios 1 and 2, energy consumption in mineral fertilizer spread was 7.3 GJ and 3.4 GJ respectively (table 8.1 and table 8.4). Also, in scenario

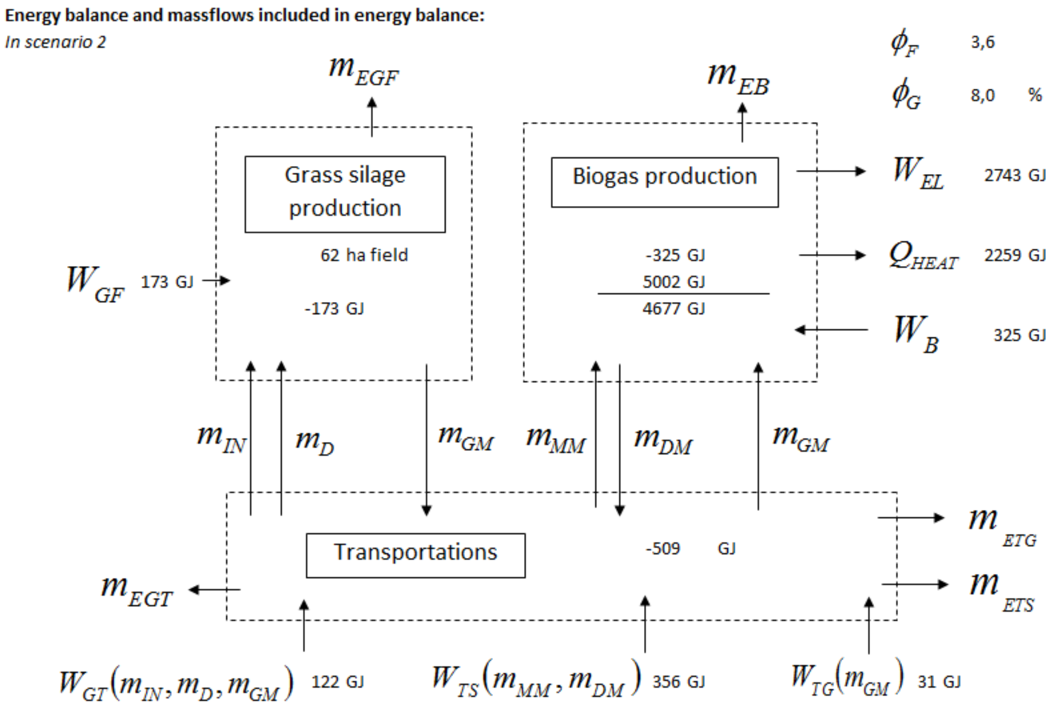


Figure 8.3: Energy balance in the LCA model.

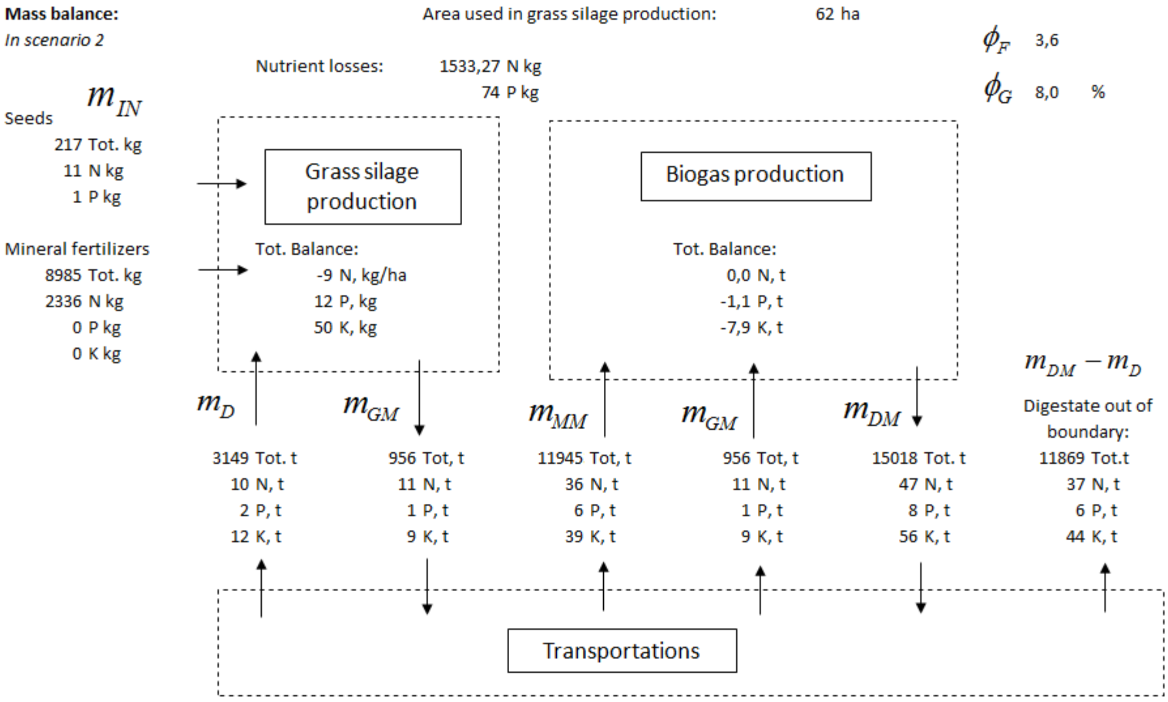


Figure 8.4: Mass balance in the LCA model.

2, less mineral fertilizers were needed in the grass renewing process than in scenario 1 when energy consumption in scenarios 2 and 1 were 33.9 GJ and 34.5 GJ, respectively. The total reduction of mineral nitrogen fertilizer from scenario 1 to scenario 2 was 2690 kg which is about 43 kg/ha, but direct machinery energy consumption increased 15 GJ from scenario 1 to scenario 2.

There was a nine kg/ha lack of nitrogen, but an excess of phosphorus and potassium of 12 kg/ha and 50 kg/ha, respectively. Nitrogen and phosphorus losses were 1533 kg and 74 kg, respectively. Nitrogen losses consisted of 1424 kg from leaches, 85 kg from N_2O-N dissipation and 24 kg from NH_3-N dissipation. Phosphorus losses of 74 kg were only considered from leaches.

Transportation

In slurry and grass silage transportation between the biogas plant and the farms, energy consumption was 356 and 31 GJ, respectively. Transportation distances were from 0.11 km to 6.22 km (table 8.2). Total transported loads from each farm were 11945 t slurry manure, 15018 t digestate and 955.7 t grass silage (table 8.2). Because the total field area in grass silage production for the biogas plant was 21 % from total field area, the digestate need (3149 t) in fertilizing would also be 21 % of the total available digestate. In total, farms could use 11869 t of digestate in their other fields. In slurry transportation, fuel consumption in a full load transportation was V_{TS} and in every second full load transportation V_{TSE}. In total, the fuel consumption in slurry transportation was 8273 kg which consisted of fuel consumption in slurry manure and digestate transportation (table 8.3). On average during the year, 733 slurry manure and digestate transportation loads were needed (table 8.2) to transport 11945 t of digestate to the farms and 11945 t of manure into the biogas plant. The rest of the 15018 t of digestate was 3072 t that was needed to transport to the farms in 183 loads. In grass silage transportation, the diesel fuel consumption was 712 kg when only full loads were transported. When direct CO_2 emissions were 24.71 t and 2123 kg in slurry and grass silage transportation respectively (table 8.3), the CO_2 equivalent emissions were 24.96 t and 2.14 t (figure 8.9) according to table 7.3. When grass silage and slurry were transported in totals of 956 t and 26964 t, respectively (table 8.2), the CO_2eqv. emission in slurry and grass silage transportation were 0.92 and 2.2 kgCO_2eqv./t respectively.

Table 8.2: Transportation in scenario 2 between farm i and the biogas plant.

		Slurry transportation				Grass silage transportation	
Farm, i ID :	d_{Ti} km	m_{Mi} t	m_{Di} t	n_{TSEi}	n_{TSi}	m_{Gi} t	n_{TGi}
1	6.12	3795	4771	58	232	301.3	29
2	6.22	1836	2309	28	113	101.2	10
3	2.06	1927	2422	30	118	218.5	21
4	1.01	2476	3113	38	152	105.8	11
5	-0.11	1449	1822	22	89	71.4	7
6	0.23	462	581	7	29	157.5	16
Tot.		11945	15018	183	733	955.7	

Table 8.3: Fuel consumption, CO_2 emissions and transportation work done in scenario 2.

		Slurry transportation			Grass silage transportation		
Farm, i ID :	d_{Ti} km	$V_{TSi} + V_{TSEi}$ kg	CO_2 t	W_{TSi} GJ	V_{TGi} kg	CO_2 kg	W_{TGi} GJ
1	6.12	3889	11.62	167.2	321	958	13.79
2	6.22	1915	5.72	82.4	112	334	4.81
3	2.06	1005	3.00	43.2	132	393	5.66
4	1.01	964	2.88	41.5	55	165	2.37
5	-0.11	362	1.08	15.5	26	77	1.11
6	0.23	138	0.41	5.9	66	196	2.82
Tot.		8273	24.71	355.7	712	2123	30.57

Biogas production

Annually, the biogas plant would produce 5002 GJ as heat and electricity when the plant operation required 325 GJ electricity. In mass balance calculations, it was assumed that the nitrogen mass balance is true.

Energy consumption in biogas plant operation consisted of the 1^{st} reactor heating and electricity consumption in mixing, pumping and minor energy device operation. Heat consumption of the 1^{st} reactor was an annual average of 1797 GJ (table 8.4) when the size of the reactor was 1094 m^3 and the grass silage and manure imported were 956 and 11945 t, respectively (figure 8.4). When one 7.5 kW and three 15 kW mixers were operating in this biogas plant, the annual energy consumption in mixing was 246 GJ. The functions of these mixers were described in more detail in section 6.4. Energy consumption in slurry pumping was assumed to be similar to water pumping when three pumps annually required 7.2 GJ of electric energy. There was also minor energy consumption in the plant totalling 72 GJ from the screw pump, two heat transfer liquid circulation pumps and four air pumps (table 6.1).

Methane productivity from feedstock volatile solids was predicted to be 282 m^3 (table 3.2). The volatile solid concentration of feedstock was 6.22 % of the feedstock wet weight as defined before in table 7.4. When the lower heating value of methane was 33.13 MJ/m^3 (chapter 6.1) and efficiency in electricity production was 36.6 % of the methane heat content (table 6.2), the electricity produced was 2743 GJ. So far the heat production efficiency was 54.1 % of the methane heat content, but the 1797 GJ heat needed in the 1^{st} reactor heating was reduced from the total heat produced from CHP. The net produced heat from the biogas plant was 2259 GJ (table 8.4).

As stated before in chapter 7.3, the biogas plant receives as much total nitrogen as it donates. From grass silage and slurry manure, the amounts of total nitrogen were 11 and 36 t when the total amount of total nitrogen in the digestate was 47 t (figure 8.4). This meant that the mass balance in the biogas plant is not correct, but the advantage of accumulated nitrogen in digestate could be better estimated for fertilizing purposes as noted in the previous grass silage production chapter. When it was assumed that the total nitrogen balance is true (Chapter 7.3) and the nitrogen concentration of digestate is 0.23 % of the wet weight (table 7.5), the total amount of digestate from the plant would be 15018 t (figure 8.4).

Table 8.4: One direct energy unit in gives 5.0 units out in scenario 2.

	Tot. Production GJ	Prod. In field GJ	Transportation GJ
Grass silage production:			
Spraying	-1.5	-0.9	-0.7
Lime spread	-5.3	-2.6	-2.7
Digestate spread	-100.0	-20.3	-79.7
Grass renewing	-33.9	-31.3	-2.6
Mineral fertilizer spread	-3.4	-1.7	-1.7
Harvesting	-151.1	-116.1	-35.0
Transportation:			
Energy needed in grass silage transportation	-31	GJ	
Energy needed in slurry transportation	-356	GJ	
Biogas production:			
Generated electricity	2743	GJ	
Generated heat	2259	GJ	
Energy consumption in mixing	-246	GJ	
Energy consumption in pumping	-7	GJ	
Minor device consumption	-72	GJ	
(1^{st} reactor heat consumption	-1797	GJ)	

8.3 Scenario 3

In scenario 3, one direct energy input into the system produced 5.5 energy units as heat and electricity (table 8.7). The plant was located when the energy consumption in slurry and grass silage transportations had minimum value. The requirement was that the total amount of grass silage should be 956 t which is same as in scenario 2. Additionally, the slurry manure and grass silage suppliers were chosen so that the maximum organic loading rate should be at most 3 kgVS/(m^{3}d). From these conditions it followed that the grass silage wet weight of the slurry manure wet weight ϕ_G was 29 % (figure 8.5 and figure 8.6). In total, the required field area in grass silage production was also 62 ha where digestate was used to replace mineral nitrogen fertilizer. The volume of the 1^{st} digester would be 1.3 times more than the volume of the 1^{st} digester ϕ_F in MTT's biogas plant in Maaninka.

Grass silage production

Two farms that had the lowest energy consumption in grass silage production were chosen to supply grass silage for the biogas plant. There were some differences in the energy consumption of grass silage production between farms, because each farm had different sized field blocks that were located differently (figure 8.7). The energy consumption was lowest on farms 4 and 5. Producing one ton of grass silage on farms

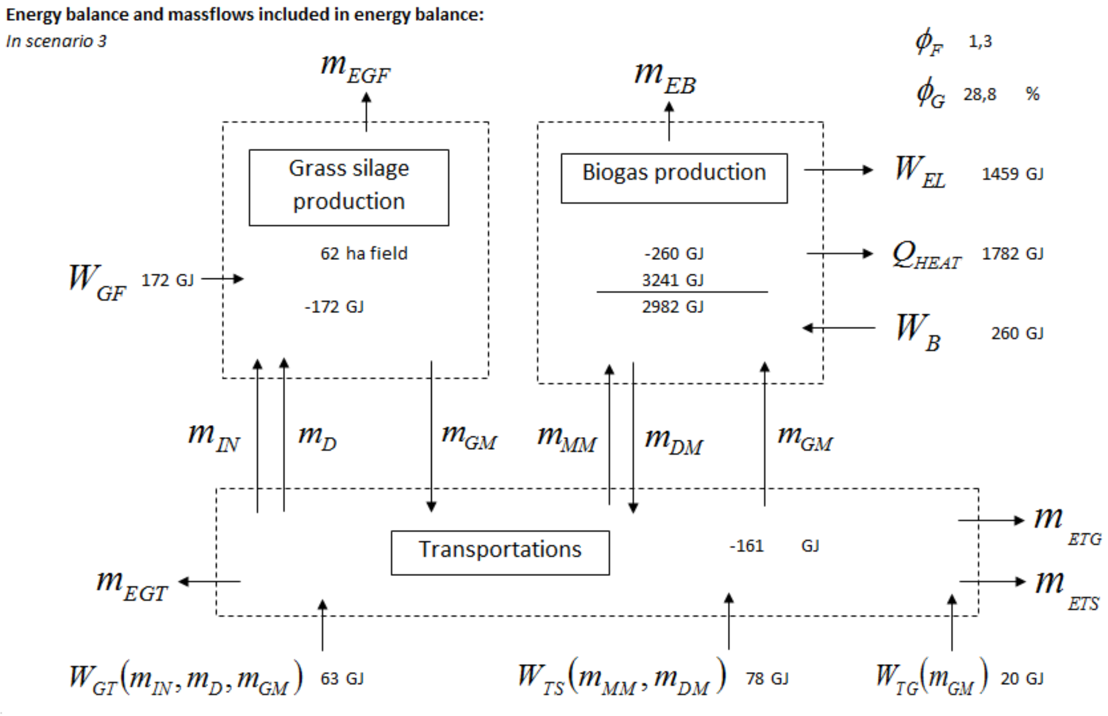


Figure 8.5: Energy balance in the LCA model.

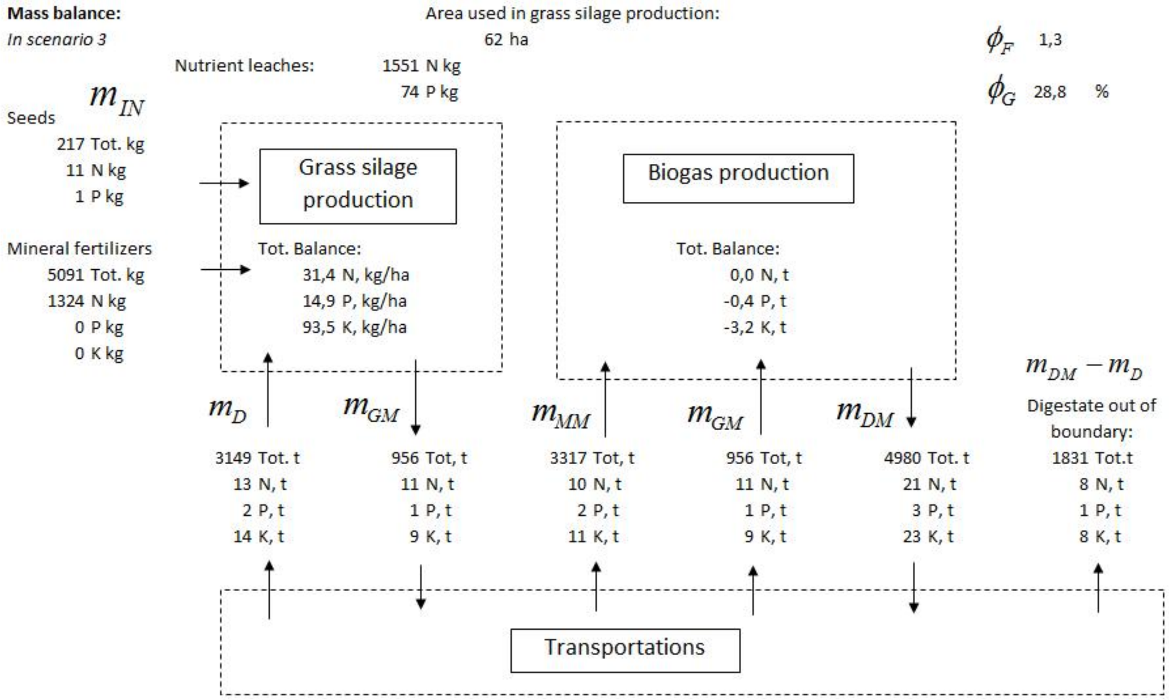


Figure 8.6: Mass balance in the LCA model.

4 and 5 required 278 and 201 GJ, respectively. When 571 and 385 t of grass silage were produced on farms 4 and 5 (table 8.5) and specific energy consumptions in grass silage production were 278 and 201 MJ/t in farms 4 and 5, respectively, the total energy consumption in grass silage production was 235 GJ. Total energy consumption in the field and on the road were 172 and 63 GJ (table 8.7).

Farms 4 and 5 should increase their grass silage field area by 13 % to produce 959 t of grass silage for the biogas plant. Total grass silage field areas on farms 4 and 5 were 32.7 and 22.0 ha. As described in table 4.4, grass yield per harvest Y_G was 8.82 t/ha. Seven harvests occurred during the four year cultivation period, so the annual average grass yield was 15.43 t/ha. When farms 4 and 5 increase their field areas up to 37 and 25 ha and annual average harvest yield during four year is 15.43 t/ha, they can produce 956 t of grass silage for the biogas plant.

There were excess nutrients in the field that were used in energy crop production (figure 8.6). Total fertilized nitrogen was about 230 kg/ha, still inside the limit of the nitrate directive [45]. There were 3 t more nitrogen available from digestate than in scenario 2, which would decrease the need for mineral nitrogen fertilizer from 2336 kg to 1324 kg. Nitrogen losses consisted of nitrogen leaches of 1424 kg, nitrogen dissipation of 103 kg from digestate in the form of nitrous oxide, and nitrogen dissipation of 24 kg in the form of ammonia. Phosphorus losses were considered only from leaches.

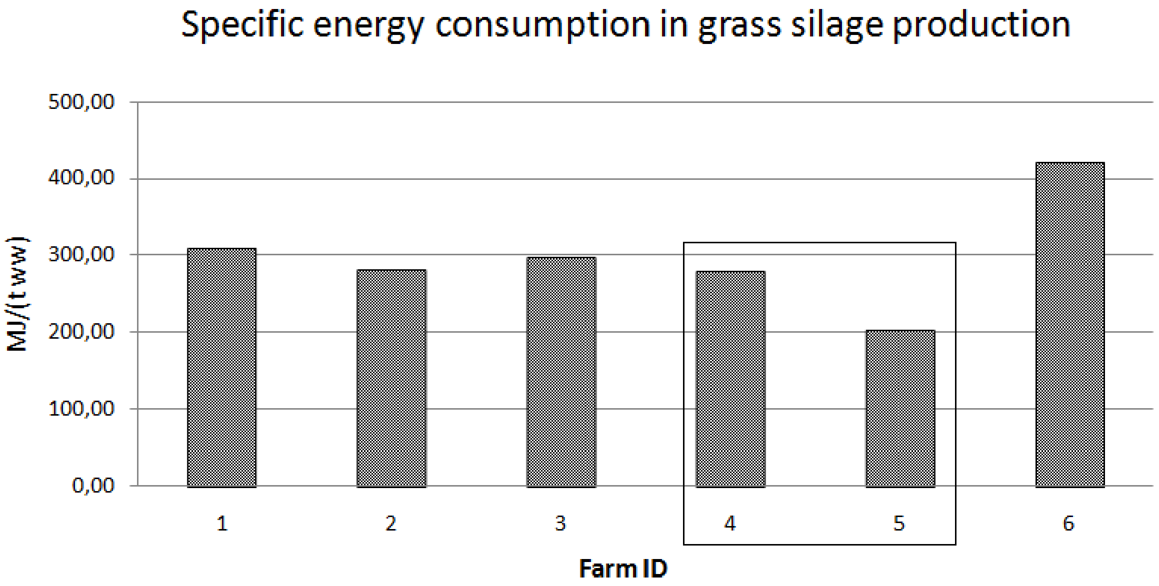


Figure 8.7: The average annual energy consumption per mass unit on each farm.

Table 8.5: In scenario 3 the distances from farms into the biogas plant are $d_0 - d_{Ti}$.

Farm, i	d_{Ti}	m_{Gi}	m_{Mi}	m_{Di}	w_i	$w_i d_{Ti}$	$\lvert d_0 - d_{Ti} \rvert$	n_{TSEi}	n_{TSi}	n_{TGi}
ID :	km	t	t	t	kg^2/h	(kg^{2}km)/h	km			
1	6.12		928		34735	212511	4.45	57		
3	2.06		1927	1831	83776	172639	0.39	6	112	
4	1.01	571		1880	87271	87825	0.66	114		55
5	-0.11	385		1269	58884	-6470	1.78	77		37
6	0.23		462		17309	4039	1.44	29		
Tot.		956	3317	4980	281975	470544				

Transportation

The biogas plant was located where energy consumption in feedstock and digestate transportation was minimum. First, two farms (4 and 5) that had the lowest energy consumption in grass silage production were chosen to supply grass silage for the biogas plant. Farms that would supply slurry manure were chosen so that the energy consumption would be minimal for slurry and grass silage transportation when the maximum organic loading rate in the biogas plant was allowed to be 3 kgVS/(m^{3}d). The selection of farms and positioning of the plant was done by using the biogas plant positioning algorithm in chapter 5.1. As a result, the optimal place for the biogas plant was found 1.67 km (the right) from the heat buyer **HB** (figure 5.1). All slurry manure would be transported from farms 3 and 6 (table 8.5). To obtain the organic loading rate of 3 kgVS/(m^{3}d), 928 t of slurry manure was still needed from farm 1. Transportation distances changed from 0.66 to 4.45 km into the biogas plant (table 8.5). Digestate was transported from the biogas plant to the farms 4 and 5 with 114 and 77 loads, respectively and grass silage was transported from farms 4 and 5 with 55 and 37 loads, respectively. Slurry manure and digestate transportation was done 112 times between farm 3 and the biogas plant, but six loads were still needed for digestate transportation to farm 3. Digestate would not be transported to farms 1 and 6. Energy consumption in slurry and grass silage transportation was then 77.6 and 20.3 GJ, respectively (table 8.6). From table 8.5 and figure 8.9 it can be seen that CO_2 emissions in slurry and grass silage transportation were 0.66 and 1.5 kgCO_2eqv./t, respectively.

Biogas production

Annually, the biogas plant would produce 3241 GJ as heat and electricity when the plant operation requires 260 GJ electricity. It was also noticed that metabolic heating

Table 8.6: Fuel consumption, CO_2 emissions and transportation work done in scenario 3.

		Slurry transportation			Grass silage transportation		
Farm ID :	$\lvert d_0 - d_{Ti} \rvert$ km	$V_{TS} + V_{TSE}$ kg	CO_2 t	W_{TS} GJ	V_{TGi} kg	CO_2 t	W_{TGi} GJ
1	4.45	489	1.46	21.0			
3	0.39	515	1.54	22.2			
4	0.66	331	0.99	14.2	253.7	0.76	10.9
5	1.78	352	1.05	15.1	219.5	0.66	9.4
6	1.44	118	0.35	5.1			
Tot.		1805	5.39	77.6	473.2	1.42	20.3

also has an effect on biogas reactor heating. It was assumed in scenario 3 that the nitrogen mass balance is true in the biogas plant.

Energy consumption in the biogas plant operation consisted of the 1^{st} reactor heating and electricity consumption in mixing, pumping and minor energy device operation. Heat consumption of the 1^{st} reactor was an average of 615 GJ during the year (table 8.7) when the size of the reactor was 379 m^3 and grass silage and manure imported were 956 and 3317 t, respectively (figure 8.6). When four 7.5 kW mixers were operating in this biogas plant, the annual energy consumption in mixing was 220 GJ. The functions of these mixers were described in more detail in section 6.4. Energy consumption in slurry pumping was assumed to be similar to water pumping, when three pumps would require annually 2.5 GJ of electric energy. There was also a total of 37 GJ in minor energy consumption in the plant from the screw pump, two heat transfer liquid circulation pumps and four air pumps (table 6.1).

A misleading result was noticed in the 1^{st} reactor heat consumption, because the surface heat loss term was negative in equation 6.25. From equation 6.19 the total heat loss from the biomass surface is

$$q_{LT} = q_T + (\dot{m}h)_{MT} + (\dot{m}h)_{GT} - (\dot{m}h)_{DT} = -3.8 \text{ kW}.$$

This would mean that the 1^{st} reactor receives heat from its surroundings, which is not true. During one year the 1^{st} reactor emits heat because the temperature inside the reactor is higher than its surroundings. The misleading error from surface heat q_{LT} could be at least partly fixed by using input data from the same time period in equations from 6.19 to 6.24. Metabolic self heating can also explain the negative value from the previous equation. If it is assumed that mass flows and mass flow properties are exactly correct, it can be determined that metabolic heating has at least a value

Table 8.7: One direct energy unit in gives 5.5 units out in scenario 3.

		Energy consumption GJ
Grass silage production:	Production in field	-172
	Transp. in production	-63
Transportation:	Grass silage transp.	-20
	Slurry transp.	-78
Biogas production:	Generated electricity	1459
	Generated heat	1782
	Mixing	-220
	Pumping	-2
	Minor device consumption	-37
	(1st reactor heat consumption	-615)

of 3.8 kW in the biogas reactor with a volume of 300 m^3. If that biogas reactor were perfectly insulated, the surface heat flow would be zero. Then in that reactor the metabolic self heating would have a value of 3.8 kW. Anyway, in this LCA model the effect of metabolic heating is taken into account by assuming that almost similar substances in the biogas reactor would have similar metabolic heating effects.

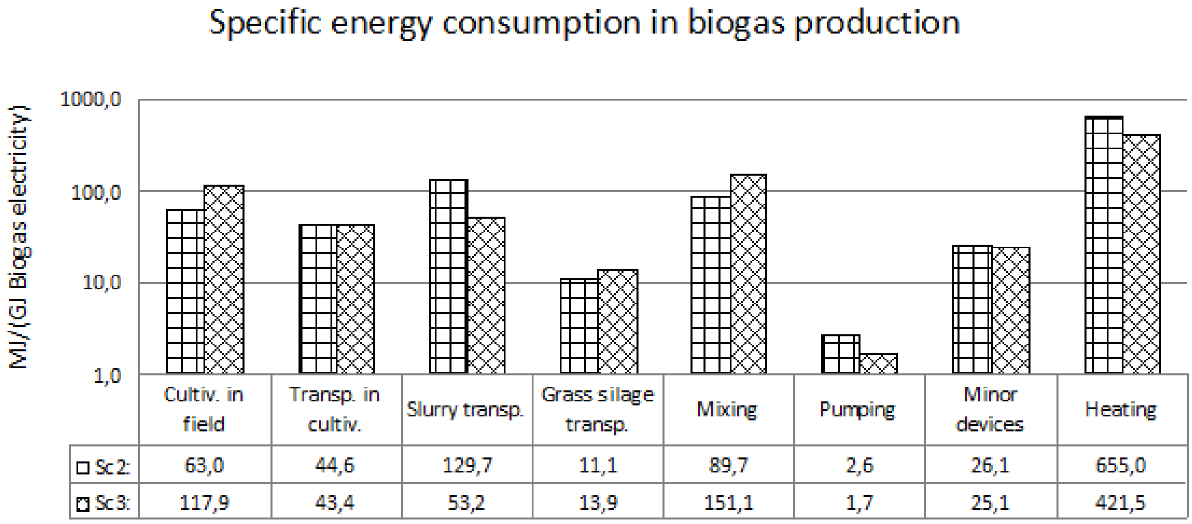
Methane productivity from feedstock volatile solids was predicted to be 309 m^3 (table 3.2). The volatile solid concentration of feedstock was 9.72 % of the feedstock wet weight as defined before in table 7.4. When the lower heating value of methane was 33.13 MJ/m^3 (chapter 6.1) and efficiency in electricity production was 34.3 % of the methane heat content (table 6.2), the electricity produced was 1459 GJ (table 8.7). So far the heat production efficiency in CHP was 56.4 % of the methane heat content. The need of 1st reactor heat of 615 GJ was subtracted from the total heat produced from CHP. The net heat produced from the biogas plant was then 1782 GJ (table 8.7).

As stated before in chapter 7.3, the biogas plant receives as much total nitrogen as it donates. From grass silage and slurry manure the amounts of total nitrogen were 11 and 10 t respectively when the total amount of total nitrogen in digestate was 21 t (figure 8.6). This meant that the mass balance in the biogas plant is not correct, but the advantage of accumulated nitrogen in digestate could be better estimated for fertilizing purposes as noted in the previous grass silage production chapter. When it was assumed that the total nitrogen balance is true (Chapter 7.3) and the nitrogen concentration of digestate was found to be 0.26 % of the wet weight (table 7.5) the total amount of digestate from the plant would be 4980 t (figure 8.6).

8.4 Energy consumption in biogas production

Energy consumption in biogas production was about the same as electricity production from the biogas plant in both biogas scenarios. When energy inputs were compared to produced electricity, it came out that in scenario 2 as much electricity was produced as the production required (figure 8.8). It came out also in scenario 3 that energy inputs were significant, in total about 83 % of the produced electricity. These results differ from the annual energy balance results that were calculated in the CropGen project where methane energy content was 49.9 GJ and the total energy requirement was 9.6 GJ [7]. If electricity production efficiency is 34.4 % of the methane heat content, the energy requirement is 56 % from produced electricity.

In general, energy consumption consisted of grass silage production, transportation between farms and the biogas plant, and both electricity and heat consumption in the plant. Machinery energy consumption in grass silage production was 11 and 16 % of the produced electricity in scenarios 2 and 3 respectively, because the grass silage of the feedstock was greater in scenario 3 than in scenario 2. Energy consumption in feedstock and digestate transportation was 14 and 7 % from produced electricity in scenario 2 and 3 respectively, because the location of the biogas plant was optimized and the slurry manure of the feedstock was decreased. Electricity consumption in the biogas plant was 12 and 18 % of the produced electricity in scenarios 2 and 3, respectively. The electricity consumption in pumping was greater in scenario 2 than in scenario 3 of the produced electricity, because in scenario 2 relatively more biomaterials that had a lower energy content were pumped than in scenario 3. The energy consumption of the produced electricity was greatest in the 1^{st} reactor heating in both biogas production scenarios (figure 8.8). The heat consumption was 66 and 42 % of the produced electricity in scenarios 2 and 3, respectively. The heat consumption of the produced electricity was greater in scenario 2 than in scenario 3, because more methane was produced from volatile solid feedstock in scenario 3.



	Cultiv. in field	Transp. in cultiv.	Slurry transp.	Grass silage transp.	Mixing	Pumping	Minor devices	Heating
☐ Sc2:	63,0	44,6	129,7	11,1	89,7	2,6	26,1	655,0
▨ Sc3:	117,9	43,4	53,2	13,9	151,1	1,7	25,1	421,5

Figure 8.8: Energy consumption per produced electricity unit during one year.

8.5 Greenhouse gas emissions

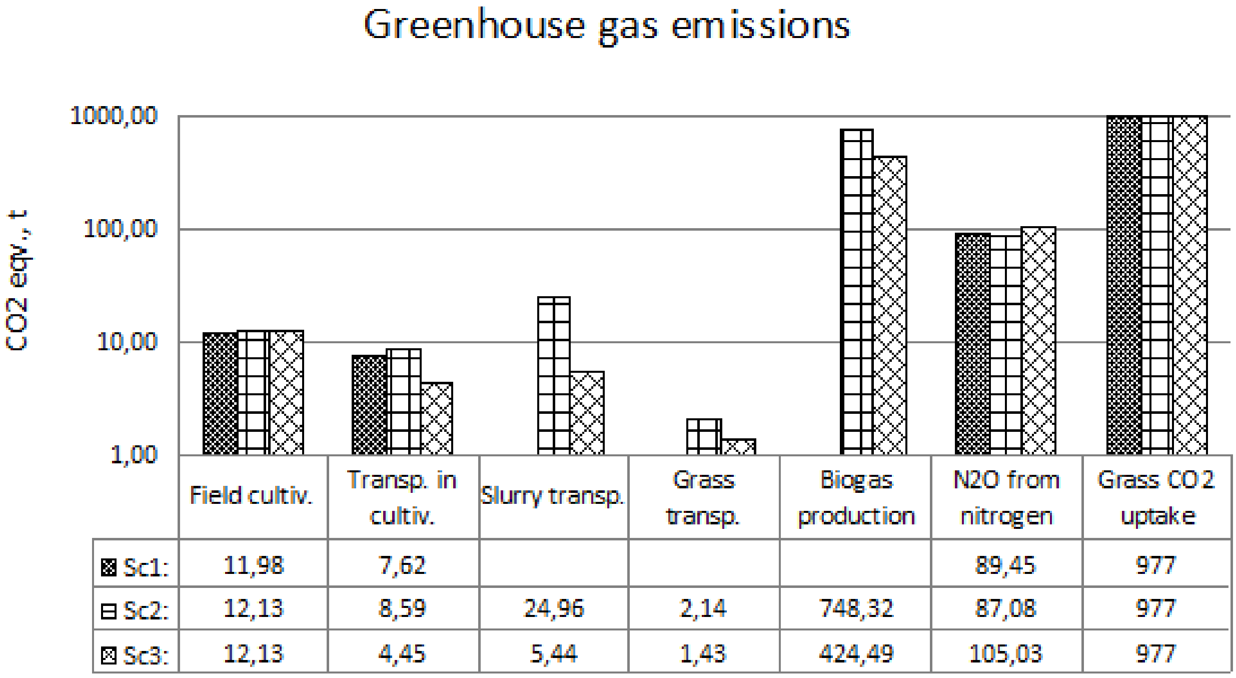
According to greenhouse gas emission (GHG) calculations, no GHG emissions would occur. The reason for this was that grass silage was assumed to bind at least all carbon dioxide that is released from electricity production from biogas. The amount of binded carbon dioxide in grass silage was estimated assuming that volatile solids in grass silage consist only of carbon. Volatile solid concentrations in each scenario were 27.9 % of the wet weight (table 7.4). When grass binds one mass unit of CO_2, it binds 0.273 mass unit of carbon according to molar mass ratio [22]. If volatile solids in harvested grass silage of 955.7 t are assumed to contain only carbon, the amount of bound CO_2 from air would be 977 t of CO_2 in each scenario. In total, the GHG emissions in scenarios 1, 2 and 3 were 109 t of CO_2, 883 t of CO_2 and 553 t of CO_2, respectively (figure 8.9). If grass silage can bind 977 tons of carbon dioxide in each scenario, there would be no CO_2 emissions in each scenario.

The biggest GHG source was biogas combustion (figure 8.9). In the second scenario, 407 t of CO_2 came directly from biogas combustion and 341 t of CO_2 were already in biogas when total GHG emisions were 748 t. In the third scenario, 231 and 193 t of CO_2 came from biogas combustion and biogas itself, respectively.

There were some differences in GHG emissions from N_2O between scenarios (figure 8.9). It was assumed that N_2O emissions were directly proportional to the amount of fertilized nitrogen. Total fertilized nitrogen was 12.55, 12.22 and 14.74 t in scenarios 1, 2 and 3, respectively when the total cultivated field area of grass silage production was 61.92 ha in each scenario. Total nitrogen concentrations were 0.30, 0.31 and 0.43 per cent of the slurry wet weight in scenarios 1, 2 and 3, respectively (table 7.4 and table 7.5). Slurries were spread 40, 51 and 51 t/ha in scenarios 1, 2 and 3, respectively. The higher concentration of total nitrogen in scenario 3 also increased the N_2O emissions compared to scenario 2 when direct N_2O emissions were 281 and 339 kg in scenarios 2 and 3, respectively. In scenario 1, 2 and 3 5.0, 2.3 and 1.3 t of mineral nitrogen fertilizers were used. It must be remembered that in all scenarios the total fertilized soluble nitrogen was 154 t/ha and mineral fertilizers were used to fulfill the nitrogen fertilizing requirement. In the calculations it was assumed that mineral nitrogen fertilizers consist of only soluble nitrogen. As a result there were differences in total fertilized nitrogen in the same sized 61.92 ha area. Differences in total fertilized nitrogen also explain the differences in direct N_2O emissions.

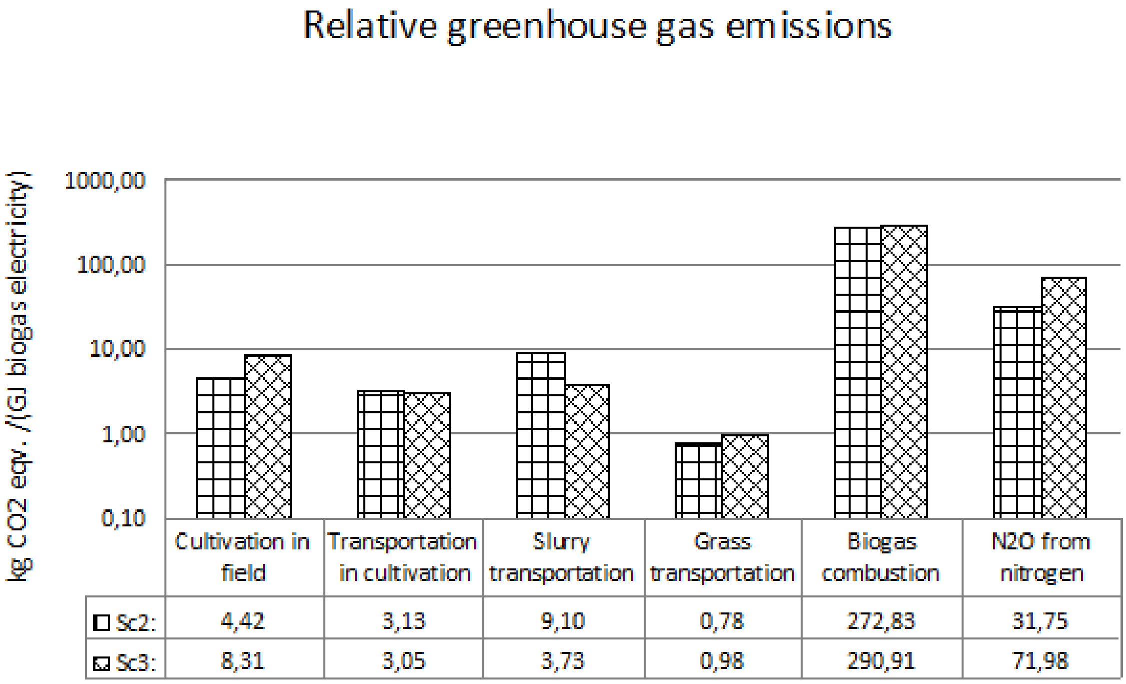
Smaller GHG emissions came from diesel fuel combustion in field cultivation and transportation (figure 8.9). GHG emissions were halved in scenario 3 compared to scenario 2, because farms producing the same amount of grass silage were chosen optimally in scenario 3. When the biogas plant was located optimally, GHG emissions in grass silage tranportation decreased from 2.14 t of CO_2 in scenario 2 to 1.43 t of CO_2 in scenario 3. In slurry transportations, GHG emissions decreased from 25 t of CO_2 in scenario 2 to 5 t of CO_2 in scenario 3. When in addition the total amount of transported slurries were 26964 t and 8297 t in scenarios 2 and 3, respectively the CO_2 emissions were 926 g of CO_2 and 656 g of CO_2 per transported ton of slurry. Because the biogas plant was located optimally in scenario 3, the CO_2 emissions in slurry transportation decreased by 29 % from those in scenario 2. In grass silage transportation in scenario 3, the CO_2 reduction was 33 % less than the CO_2 emissions in scenario 2.

In total, the direct relative CO_2 emissions were 322 and 379 kg of CO_2 per one GJ of produced electricity in scenarios 2 and 3, respectively (figure 8.10). Because in scenario 3 the grass silage of the slurry manure (29 %) was greater than in scenario 2 (8 %), relatively more land area and more machinery work were needed to produce electricity from grass silage. Increasing the grass silage of the feedstock increased the relative carbon dioxide emissions per produced electricity unit. Slurry manure was considered a waste because no energy inputs are required for production and no CO_2 emissions would occur. Relative CO_2 emissions per produced electricity unit could be decreased, if the amount of waste materials from feedstock could be increased.



	Field cultiv.	Transp. in cultiv.	Slurry transp.	Grass transp.	Biogas production	N2O from nitrogen	Grass CO2 uptake
▩ Sc1:	11,98	7,62				89,45	977
⊟ Sc2:	12,13	8,59	24,96	2,14	748,32	87,08	977
⊠ Sc3:	12,13	4,45	5,44	1,43	424,49	105,03	977

Figure 8.9: Greenhouse gas emissions in terms of CO_2 equivalents.



	Cultivation in field	Transportation in cultivation	Slurry transportation	Grass transportation	Biogas combustion	N2O from nitrogen
☐ Sc2:	4,42	3,13	9,10	0,78	272,83	31,75
⊠ Sc3:	8,31	3,05	3,73	0,98	290,91	71,98

Figure 8.10: Relative greenhouse gas emissions in terms of CO_2 equivalents per produced electricity unit.

9 Conclusions

Energy inputs from outputs depended on the possibility of utilizing heat from the biogas plant. If heat can be utilized from the biogas plant, the energy inputs from produced heat and electricity can be from 5.0 to 5.5. Energy inputs from outputs decrease to near one, if heat cannot be utilized from the biogas plant. This study determined that only electricity production from biogas would require about the same amount of energy inputs. This means that heat utilization from the biogas plant determines whether the total energy balance is reasonable or not.

Direct greenhouse emissions can be decreased even if the production of electricity and heat from biogas would not produce more CO_2 equivalent emissions than grass can bind during its growing period. By choosing farms in an energy efficient way in the farm cluster, the machinery energy consumption and direct CO_2 equivalent emissions from machinery work could be decreased by 20 %. Unfortunately, this would not decrease greenhouse gas emissions from the second biggest source - nitrous oxide dissipation from nitrogen fertilizing. When the biogas plant was located optimally, the direct CO_2 emissions could be decreased by one third. This would mean that the biogas plant would not be located directly in the place where the heat can be utilized. Relative CO_2 equivalent emissions per produced electricity unit could be decreased if the amount of waste materials of the feedstock could be increased. This would not change the fact that the biggest CO_2 equivalent emissions came from biogas combustion in the biogas plant.

As a final conclusion, it can be stated that energy savings could be done in many processes in biogas production. Farms should divide their field blocks so that the transportation distances in grass silage production decrease. Instead of electricity and heat, vehicle fuel production from biogas could give even better energy balance. Heat is not produced in vehicle fuel production which means that the location of the biogas plant could be optimized. The energy consumption in feedstock and digestate transportation can be minimized if there is no need to bind the location for the biogas plant based on heat consumption. The volume of the biogas reactor and feedstock material mass flows should be chosen so that heat consumption in an aerobic digestion has the minimum value of the produced biogas. Also, each substance should be experimentally tested to determine the optimal values for mixer impeller diameter and input voltage signal frequency.

9.1 Grass silage production

The need for mineral fertilizers was decreased by using digestate instead of slurry manure. Feedstock mass proportions had an effect on nitrogen accumulation in digestate, resulting in a decreased need for mineral fertilizers. When grass silage mass of the slurry manure wet weight was 8 %, the use of digestate could halve the need for mineral fertilizers. So far, by increasing the grass silage of the slurry manure from 8 % to 29 %, the use of digestate would decrease the need for mineral fertilizers by 40 %. In total, the use of digestate could decrease the need for mineral fertilizers by 70 %.

The work done for grass silage production in field cultivation in the CropGen project was quite similar to the field work done in this LCA model [51]. This model opened a new window by also calculating the machinery energy consumption in road transportations. The result was that in the farm cluster in this study, the machinery energy consumption in road transportation could be more than half of the machinery energy consumption in the field.

9.2 Transportation

If heat could be utilized from the biogas plant, the machinery energy inputs and direct CO_2 emissions could be decreased by one third per transported mass unit. Direct GHG emissions were decreased in grass silage transportation from 0.92 to 0.66 $kgCO_2eqv./t$. In slurry manure transportation $CO_2eqv.$, emissions were decreased from 2.2 to 1.5 $kgCO_2eqv./t$. If transportation plays a key role in energy balance calculations, a reasonable use for heat produced from the biogas plant should be devised.

9.3 Biogas production

The heat consumption of the 1^{st} reactor consisted of heat loss from biomass surface, heat loss from mass flows and metabolic self heating. When the volume of the biogas reactor is doubled, the surface heat flow from the reactor increases just 1.6 times. When the feedstock mass flows are doubled, the heat requirement from mass flows is also doubled. This means that increasing the enthalpy difference between feedstock and digestate would also increase the heat requirement. Usually this enthalpy difference is increased when the total solid concentration of the feedstock is decreased. If the biogas reactor were perfectly insulated, the metabolic heating power would be at least 3.8 kW in the 300 m^3 reactor.

This study also produced new results for heat consumption in anaerobic digestion.

In the CropGen project, the annual heat consumption in the 2000 m^3 digester was reported to be 2133 GJ [7]. About 1.07 GJ would be needed to heat one cubic metre of the reactor volume. In MTT's biogas plant, the average heat power consumption in the 300 m^3 digester was 14 kW. It would require 1.47 GJ to heat one cubic metre of the reactor volume.

Energy consumption in mixing depends on the diameter of the impeller and the electric signal input frequency. If there were no force resisting the rotation of the impeller axis, the revolution speed of the axis would be the same as the input signal frequency. In this study, it was only proven that the input signal frequency can contribute to the mixing energy consumption. Energy consumption in mixing can increase by input signal frequency to the third power. In dimensional analysis it was found that the diameter of the impeller can contribute to energy consumption in mixing, which is impeller diameter to the fifth power. Because impeller diameter and input signal frequency have an exponential contribution to the mixing energy consumption, those parameters should be chosen very carefully for each substance.

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