Optimizing Pathways and Market Systems for Enhanced Competitiveness of Sustainable Bioenergy and Technologies in Europe

Deliverable 2.4

BIOENERGY PATHWAY SUSTAINABILITY ASSESSMENT IN FINLAND

Key activity: The sustainability of biomass-to-energy pathways

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1 Introduction

Bioenergy derived from different biomasses is an excellent renewable energy source with wide range of possibilities to decrease GHG emissions. However, unsustainable use of biomasses for bioenergy can in some cases even increase GHG emissions or other impacts, and may not be environmentally, socially or economically sustainable. There are already several existing methodologies for bioenergy sustainability assessment which take into account different sustainability aspects of bioenergy. Nevertheless, there was an aim to create more advanced sustainability assessment framework that could be applied to different kind of bioenergy pathways in different countries.

The BIOTEAM consortium, consisting of six EU countries (Finland, Germany, Italy, Lithuania, the Netherlands and Poland), has developed a sustainability assessment methodology: the so-called “Harmonized bioenergy pathway sustainability assessment framework”.[1] This sustainability assessment framework takes into account environmental, economic and social sustainability. The BIOTEAM consortium has made an effort to create an assessment framework that is sufficiently robust to be applied to different bioenergy pathways within different market contexts in different EU countries. The sustainability assessment framework aims at being applicable to a wide range of pathways and to provide room for inclusion of both objectively measurable and more qualitative sustainability impacts of specific pathways.

According to the sustainability assessment methodology developed in the BIOTEAM project, the sustainability assessments were executed by all six BIOTEAM countries. This report contains the results of sustainability assessments of six bioenergy pathways in Finland (two solid, two liquid and two gaseous). The solid pathways assessed in Finland were Eno Energy Cooperative, which produces district heating from wood chips, and Vapo Forssa plant, which produces heat and electricity from wood chips and peat in CHP plant. Liquid pathways were bioethanol production from barley (plant is not existing), and bioethanol production from straw (Suomen Bioetanoli Oy). Two gaseous pathways were biogas plants, which use waste and side streams to produce heat and electricity in CHP plant (Biovakka and Biokymppi).

2 Solid pathways

Finland is one of the leading countries of the world in the utilization of wood based energy and the development of biomass combustion technologies. Wood fuels contributed about 24.2% of the total primary energy consumption in 2012 (Statistics Finland 2012). The share of wood fuels has been recognized for the first time the biggest growth that became the most significant source of energy. The contribution of wood fuels in the final primary energy consumption has steadily increased over the past years. The use of forest chips rose to a new record level as 8.3 million m^3 which amounted 11% higher than the previous year. Forest chips are still a minor product among the solid wood fuels if we consider the total wood consumption (total round wood consumption in 2012 was 60 million m^3) in the country (Statistics Finland 2012). Small size trees from young forests, logging residues, bark and other industrial wood residues are the main sources of forest chips.

[1] Available online: http://www.sustainable-biomass.eu/index.php/publications

2.1 Pathway 1: Wood-based district heating

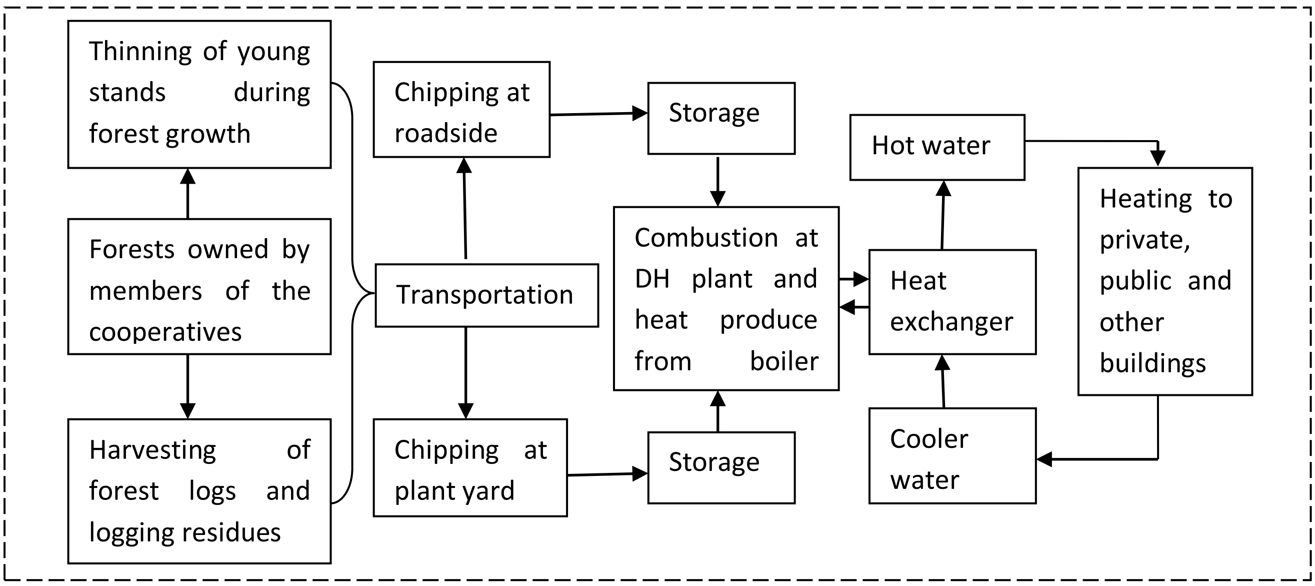
The Eno Energia Cooperative is operating three district heating (DH) plants. The DH plants are producing altogether about 15000 MWh thermal energy from local forest chips, which replacing about 1.8 million liters of light fuel oil annually. In case of Eno district heating plants the annual demand of forest chips is about 20000 to 22000 loose-m^3 of which 70% is supplied from small-sized trees from young trees (trees from thinning operation), 10% from logging residues and rest 20% from Uimaharju pulp mill (mostly bark). About 60% of all raw materials originate from the members of the cooperative. Mostly they carry out the wood materials from their own forest harvesting operations. However, the Eno DH plants also use peat and light fuel oil as backup.

The main data for making sustainability assessment of wood-based district heating pathway were obtained from interviewing one of the executive members of ENO Energia Cooperatives. In addition, several documents of the Cooperatives, as well as the previous bioenergy project documents (projects conducted by the University of Eastern Finland and Finnish Forest Research Institute) were explored for collecting the relevant information. The Statistical Yearbook of Finland (Statistics Finland 2012), EcoInvent database (environmental impacts), and relevant information from EU level were explored for gathering the information on baseline fuels.

2.1.1 *SYSTEM BOUNDARY AND ALLOCATION*

The system boundary of Eno wood-based DH plants includes all thinning, harvesting, transportation, chipping operations and storage of the forest raw materials as well as combustion process of forest chips in the heating plants (Figure 1). Re-enrichment of forest planting operations (if occur), construction of roads, construction and maintenance of DH plants and production of other machineries and equipments related to the DH plants operations are excluded. All emissions within system boundary were allocated to the produced energy.

Figure 1. System boundary of wood-based district heating pathway



2.1.2 Results

The results of wood-based DH pathway are shown in Tables 1-3. The wood-based DH pathway is better than light fuel oil in case of GHG emission, acidification and chemical use. However, burning of wood-based materials produces more particulate matter (PM_{10}) in comparison to baseline although the other air contaminants are higher. The feeding materials of the pathway are supplied from local forests where no irrigation is needed for its' growth. The rain water use for forest growth does not take into account for the consideration of water use as per the guidelines. Nutrient balance in bioenergy pathway is estimated to be negative for nitrogen as all nitrogen is lost in combustion (Motiva 2009). Phosphorus, however, remains in ash and would be brought back to forest and used for stands re-growth. Nitrogen is also lost in case of combustion of light fuel oil. The pathway provided great result than baseline in case of net energy balance.

Table 1. Results of environmental sustainability assessment of wood based district heating and light fuel oil for heating.

Environmental indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Greenhouse gas emissions	3.42	93.7	-90.28	g CO_2 eq/MJ output energy
Acidification	0.125	0.194	-0.069	g SO_2 eq/MJ output energy
Air quality	0.289	0.007	0.282	g PM10/MJ output energy
Chemical use	0	3[2]	-3	Points
Water use	0	1.38 E-04	-1.38 E-04	m^3/MJ output energy
Nutrient balance	-0.045 0	-0.0001 0	-0.0449 0	kg N/MJ output energy kg P/MJ output energy
Net energy balance	0.20	0.20	0	MJ/MJ output energy
Land use	0	2.6 E-10[3]	-2.6 E-10	ha/MJ output energy

Regarding the economic indicators, the internal rate of return (IRR) of the pathway (wood-based DH) plant is lower than the baseline plant (oil refinery). The main reason may be the indirect benefits derived from the pathway have not been taken into account. The repayment period is higher in pathway in comparison to baseline plant since the pathway plant is service oriented and has narrow business options. In the past ten years the price of forest land has increased over 50%, but it is not possible to say how much of the increase is due to energy production. In this study, the economic contribution from all existing DH plants in Finland's GDP in 2012 has considered as the contribution of national economy of the pathway. Still the integrated contribution of the wood-based DH pathway is far away from the baseline (contribution of light fuel oil to national economy). The product price to the end user would be lower in case of wood-based DH, but the production cost would be slightly higher. However, the production cost of light fuel oil does not take into account refining.

[2] A lot of different chemicals are used in refining, most of them are only slightly hazardous, but sodium hypochlorite is extremely dangerous to aquatic environment, and strongly irritating to skin and damaging eyes.

[3] Land used for oil extraction

Table 2. Results of economical sustainability assessment of wood based district heating and light fuel oil for heating.

Economic indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Internal rate of return	9.4	13[4]	-3.6	%
Repayment period	12	8	4	year
Land price change	4.5	0	4.5	%
Contribution to national economy	468	1050[5]	-582	ppm
Product price to the end user	0.021	0.031	-0.01	€/MJ
Production cost	0.019	0.018	0.001	€/MJ

Table 3. Results of social sustainability assessment of wood based district heating and light fuel oil for heating.

Social indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Employment	1.3 E-07	4.8 E-08	8.2 E-08	FTE/MJ (full-time equivalent)
Effect on the regional economy	85.1	50	35.1	%
Job quality	Forestry 43 Eno plant 0	Oil extraction 15 Industry 28	28 -28	Number of injuries per 1000 employed
	Forestry 0 Eno plant 0	Oil extraction 0.5 Industry 0.03	-0.5 -0.03	Number of fatal accidents per 1000 employed
	Energy sector in Finland 42000	Oil extraction 12900 Oil company 42000	29100	Level of wage, €/year
Property price change	1	-2[6]	3	Points
Change in environmental status and wellbeing (noise, smell, aesthetic)	1	3	-2	Points

All social indicators of the pathway gave promising results compared to baseline. The wood-based DH plant offers more jobs in comparison to baseline. It also puts great impact on regional economy in many forms such as raw material supply, providing jobs, and revenue generation. Although the light fuel oil has a small contribution in the regional economy particularly in the plant construction phases such as in the form of providing employment. So far no injury and fatal accident have been recorded in the present selected wood-based DH plant whereas in the industrial sector in Finland the frequencies of such incidences are higher (Statistics Finland 2011). In the other hand, forestry has more injuries compared to oil extraction, but less fatal accidents. However, the impact of wood-based DH pathway on property price has not been assessed but assumed that it has positive impact since the plant provides heating services to its' premises that is increase the living standard. In this concern, the impact of oil refinery particularly for oil drilling is

[4] Target for oil refinery
[5] All oil products in Finland 0.5% (Seppälä et al. 2009). Share of light fuel oil is about 21% from all oil products (Finnish Petroleum Federation).
[6] Oil extraction

negative. The wood-based pathway provided better results than oil refinery in cases of other environmental status (noise, smell and aesthetic), where the all the impacts are negative.

2.1.3 *Sensitivity analysis*

All emissions from this pathway were allocated to the energy. However, if ash could be classified as valuable fertilizer, there could be a possibility to allocate some emissions to the ash which would decrease the emissions of bioenergy. Currently, ash is brought back to forest but it is not classified as valuable fertilizer. Transportation distance of wood chips is very short, only 30 km, but if the distance would be much longer, that would increase the environmental impacts and decrease the profitability. Also, the more expensive feedstock price would decrease the profitability (production cost, IRR and repayment period).

2.2 Pathway 2: Wood-based CHP plant

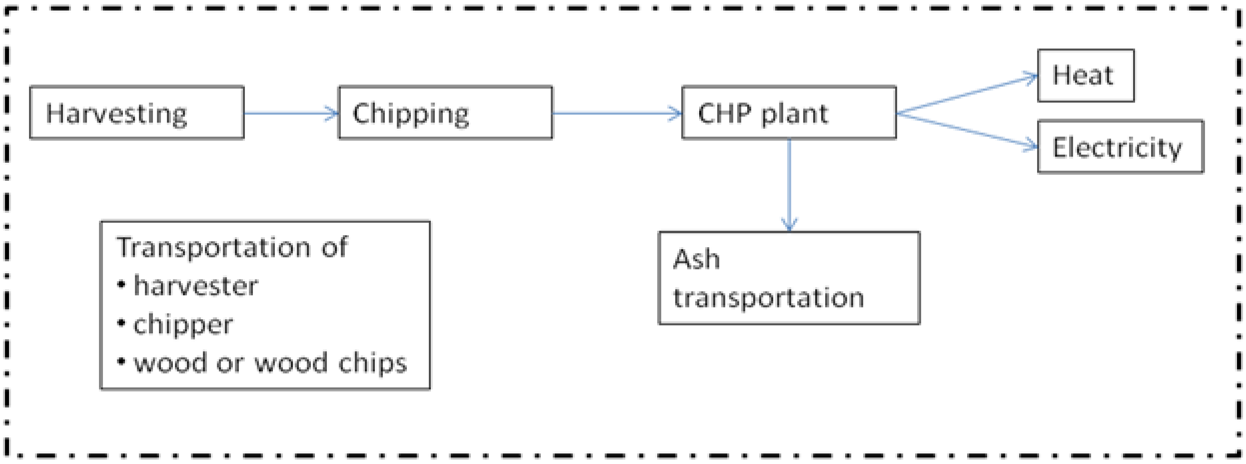
Vapo Forssa plant has a capacity of 17 MW electricity and 47 MW district heating, overall capacity is 300 GWh energy from wood chips and peat. Peat makes up 50% of the energy production. Wood raw materials are mainly pruned wood from forest thinning (45%), non-pruned wood small diameter wood (22%) and logging residues (26%). Rest raw materials could also be suitable to pulpwood, and they also could use very small amount of logs, but these have some defect that impede their use to more valuable purposes. They also use peat as a mixture, but this assessment takes into account only wood. Wood chips are made along the forest road and then the chips are transported to the plant. Average transportation distance is 100 km.

Baseline for Vapo plant is heavy fuel oil, because this kind of plant usually replaces use of heavy fuel oil in the similar plant. Information for environmental impact assessment is mainly based on plant specific information from Vapo. Also some economic and social indicator values were directly from stakeholder (repayment period, employment) or reports from stakeholder. Other indicators were assessed according to literature. For job quality, it is used values from Finnish industry, as there is not information from injuries and accidents in energy sector. Baseline assessment is based on EcoInvent database, and Finnish and international publications.

2.2.1 *System boundary and allocation*

System boundary of wood CHP plant includes transportation of harvester to forest, wood harvesting, transportation of wood to roadside storage, transportation of mobile chipper, chipping of wood in road side, transportation of wood chips to plant, energy consumed in CHP plant, and ash transportation back to forest (Figure 2). All emissions are allocated to the energy produced in CHP plant. Biogenic carbon is not taken into account in the assessment.

Figure 2. System boundary of wood chip CHP plant.



2.2.2 RESULTS

Following tables (Table 4-6) represent the results of pathway assessment with comparison to baseline. All environmental indicators have as good as or better result in case of bioenergy pathway compared to baseline, but land use is slightly bigger. However, most of the wood used in energy production is from forest thinning, which is essential that it is possible to get logs for non-energy purposes, or from logging residues, which would be left to forest if these are not used for energy. Greenhouse gas emissions are clearly lower when wood chips are used for district heat production compared to heavy fuel oil. Also in case of chemical use, bioenergy pathway performs much better, as there is no chemical usage in wood based bioenergy production, and in oil refining they could use very harmful chemicals. Nutrient balance in bioenergy pathway is estimated to be negative for nitrogen as all nitrogen is lost in combustion (Motiva 2009). Phosphorus, however, remains in ash and would be brought back to forest. Nitrogen is also lost in case of combustion of heavy fuel oil but not as much as in case of wood combustion per MJ. Net energy balance is better for bioenergy pathway, and there is no land use in bioenergy pathway as raw materials are mainly residues.

Internal rate of return is higher for wood-based DH. Repayment period of assessed bioenergy plant is within range of repayment period of oil refinery (3-14 years), but when using average value for biorefinery, wood-based DH has longer repayment period. Wood based district heating has bigger contribution to national economy compared to oil based district heating because there is more plants using wood than plants that use oil in Finland. In the past ten years the price of forest land has increased over 50%, but it is not possible to say how much of the increase is due to energy production. According to Finnish statistics (Energiateollisuus ry 2014a), district heating in Vapo plant has a slightly higher price for the end user compared to district heating plant that uses a great amount of heavy fuel oil. However, the production cost of heat produced from wood chips is lower compared to heat produced from heavy fuel oil, when it is assessed in the way that same plant would buy wood chips or heavy fuel oil to produce same amount of energy.

Table 4. Results of environmental sustainability assessment of wood based CHP plant and heavy fuel oil for heating.

Environmental indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Greenhouse gas emissions	1.83	94.7	- 92.87	g CO_2 eq/MJ output energy
Acidification	0.163	0.632	- 0.469	g SO_2 eq/MJ output energy
Air quality	0.0025	0.0478	- 0.0453	g PM10/MJ output energy
Chemical use	0	3[7]	-3	Points
Water use	0	7.31 E-05	-7.31 E-05	m^3/MJ output energy
Nutrient balance	-0.045 0	-0.0001 0	-0.0449 0	kg N/MJ output energy kg P/MJ output energy
Net energy balance	0.30	0.41	- 0.11	MJ/MJ output energy
Land use	0	2.6 E-10[8]	-2.6 E-10	ha/MJ output energy

Table 5. Results of economical sustainability assessments of wood based CHP plant and heavy fuel oil for heating.

Economic indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Internal rate of return	23	> 13[9]	<10	%
Repayment period	10	8[10]	2	year
Land price change	4.5	0	4.5	%
Contribution to national economy	2700	250[11]	2450	ppm
Product price to the end user	0.0205	0.0192	0.0013	€/MJ
Production cost	0.0086	0.0114	- 0.0028	€/MJ

Employment in this specific bioenergy pathway is slightly lower per produced energy compared to oil pathway, but the result is almost same. Injuries in forestry would be higher compared to injuries in oil extraction. However, there was not any fatal accident in forestry in Finland in 2010 (Statistics Finland 2011), while in oil extraction there were some accidents (United States Department of Labor). Accidents in power plant are estimated according to Finnish industry statistics (EK 2013), so there would not be any differences. Energy industry in Finland has a better level of wage compared to oil extraction. Oil refining in Finland would, however, have same wage level as other energy production. District heating plant is assumed to have no effect on property price, but oil drilling could have strong negative effect. Also, district heating plant or oil refinery in Finland is estimated to have only low impact on environmental status (noise, smell, aesthetic), while oil drilling could have high impact on environmental status.

[7] A lot of different chemicals are used in refining, most of them are only slightly hazardous, but sodium hypochlorite is extremely dangerous to aquatic environment, and strongly irritating to skin and damaging eyes.
[8] Land used for oil extraction
[9] Target for oil refinery
[10] Average for oil refinery
[11] All oil products in Finland 0.5% (Seppälä et al. 2009). Share of heavy fuel oil is about 5% from all oil products (Finnish Petroleum Federation).

Table 6. Results of social sustainability assessment of wood based CHP plant and heavy fuel oil for heating.

Social indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Employment	4.8 E-08	4.9 E-08	-1 E-09	FTE/MJ (full-time equivalent)
Effect on the regional economy	97.8	36	61.8	%
Job quality	Forestry 43 Industry 28	Oil extraction 15 Industry 28	28 0	Number of injuries per 1000 employed
	Forestry 0 Industry 0.03	Oil extraction 0.5 Industry 0.03	-0.5 0	Number of fatal accidents per 1000 employed
	Energy sector in Finland 42000	Oil extraction 12900 Oil company 42000	29100	Level of wage, €/year
Property price change	0	-2[12]	2	Points
Change in environmental status and wellbeing (noise, smell, aesthetic)	2	3	-1	Points

2.2.3 Sensitivity analysis

All emissions from this pathway were allocated to the energy as was the situation with wood-based district heating pathway. Also in this case, if ash could be classified as valuable fertilizer, there could be a possibility to allocate some emissions to the ash which would decrease the emissions of bioenergy. Transportation distance of wood chips is quite short, about 100 km, but if the distance would be much longer, that would increase the environmental impacts and decrease the profitability. Also, the more expensive feedstock price would decrease the profitability (production cost, IRR and repayment period).

3 Liquid pathways

3.1 Pathway 1: Bioethanol from barley

There are no grain ethanol plants for biofuel in Finland yet, but it is indicated that it is possible to build 2-3 of those in the future (Härmälä 2010). Accordingly, there are several initiatives for such plants. This assessment is based on one initiative for Uusikaupunki. The raw material of this plant is projected to be barley. The plant would produce 75 million litres of bioethanol annually. In addition, the plant would produce 80 million kg of dried distiller`s grain (DDGS) annually as a by-product, which is suitable for animal feed. The process energy would be produced in a wood chip CHP plant that would be built for the ethanol production. Excess electricity would be fed to the national electricity grid. Baseline for the bioenergy pathway is fossil gasoline, as bioethanol replaces the use of gasoline, when it is mixed with the gasoline fuel. The main data source for this assessment was the report that introduces the Uusikaupunki plant concept (Korpi 2011) and Finnish statistics. Barley cultivation is based on Finnish cultivation data gathered

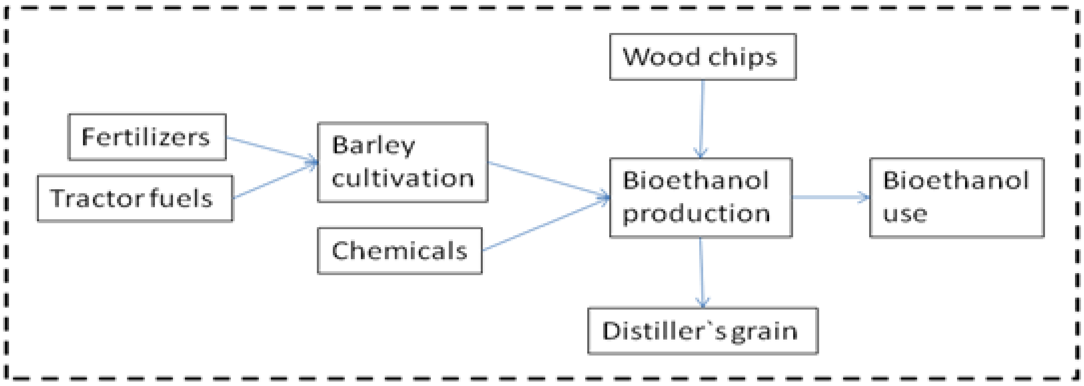
[12] Oil extraction

in previous projects in MTT. Information for baseline assessment is from EcoInvent database, and Finnish and international reports.

3.1.1 System boundary and allocation

System boundary includes all necessary inputs needed for barley cultivation and bioethanol production, transportations in the different phases, as well as bioethanol use in transportation (Figure 3). Production of machinery, roads and bioethanol plant is excluded. Also, direct land use change is assumed to be zero, as in Finland the total field area is bigger than the cultivated area, and it can be assumed that any extra area not needed for food or other production can be taken into cultivation of bioenergy crops, without and use change. Indirect land use change is left outside the system boundary for the same reason. In the base scenario the allocation method used is physical allocation according to lower heating values of ethanol and distiller`s grain as it is recommended in the BIOTEAM methodology guidance (D2.3). However, distiller`s grain is seldom combusted, so we will investigate the effect of different allocation in sensitivity analysis (see Chapter 0).

Figure 3. System boundary of bioethanol production. There are also transportations in different phases of the pathway.



3.1.2 Results

Following tables (Table 7-9) represent the results of pathway assessment with comparison to baseline. The bioethanol pathway causes less greenhouse gas emissions, is less harmful for air quality and uses less harmful chemicals, but causes more acidification and uses more water compared to fossil gasoline. The majority of the studied environmental impacts are caused by barley cultivation, except water use, which is only considered for the bioethanol plant, as the methodology does not take into account rain water, and cereals are not irrigated in Finland. Nutrient balance of bioethanol pathway is estimated according to fertilization rate when 1% of input nitrogen is volatilized directly and according the amount of nitrogen and phosphorus leached from field. Also, some small amounts of nutrients are lost with waste water from the bioethanol plant, but this is not taken into account. Majority of barley nutrients go to distiller`s grain which could be used as animal feed. In gasoline pathway, small amount of nutrients are lost in combustion as the nitrogen is emitted to the air as nitrogen oxides. Also net energy balance and land use performs better in case of gasoline pathway.

Table 7. Results of environmental sustainability assessment of bioethanol pathway and fossil gasoline.

Environmental indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Greenhouse gas emissions	69.9	84.3	-14.4	g CO_2 eq/MJ output energy
Acidification	1.04	0.63	0.41	g SO_2 eq/MJ output energy
Air quality	0.0078	0.01	-0.0022	g PM10/MJ output energy
Chemical use	2[13]	3[14]	-1	Points
Water use	4E-04	8 E-05	3.2E-04	m^3/MJ output energy
Nutrient balance	-2.4 E-04 -2.3 E-05	-1E-04 0	-3.4 E-04 -2.3 E-05	kg N/MJ output energy kg P/MJ output energy
Net energy balance	0.57	0.18	0.39	MJ/MJ output energy
Land use	3 E-05	2.6 E-10[15]	3 E-05	ha/MJ output energy

All economic indicators are worse for the barley ethanol pathway than for the fossil fuel pathway, except land price change, which is estimated to be same for both pathways. However, if there would be a plant that uses grain as raw material for ethanol, it would possibly raise the price of agricultural land. The contribution to the national economy is currently zero for bioethanol, because there are no bioethanol plants yet in Finland. However, if a plant like this would be built, effect to the national economy would be about 200 ppm. So, the contribution of one single plant would be quite small compared to contribution of fossil gasoline. Price of bioethanol would be a little higher for bioethanol as the energy content is lower compared to gasoline. Also production cost would be little bit higher (Korpi 2011).

Table 8. Results of economical sustainability assessment of bioethanol pathway and fossil gasoline.

Economic indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Internal rate of return	12.7	> 13[16]	> -0.3	%
Repayment period	16	8[17]	8	year
Land price change	0	0	0	%
Contribution to national economy	200	1000[18]	-800	ppm
Product price to the end user	0.030	0.028	0.002	€/MJ
Production cost	0.012	0.011	0.001	€/MJ

[13] Chemicals are used in different stages (barley cultivation, processing), some chemicals score 2 (hazardous)
[14] A lot of different chemicals are used in refining, most of them are only slightly hazardous, but sodium hypochlorite is extremely dangerous to aquatic environment, and strongly irritating to skin and damaging eyes.
[15] Land used for oil extraction
[16] Target for oil refinery
[17] Oil refinery
[18] All oil products in Finland 0.5% (Seppälä et al. 2009). Share of gasoline is about 20% from all oil products (Finnish Petroleum Federation).

Table 9. Results of social sustainability assessment of bioethanol pathway and fossil gasoline.

Social indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Employment	2.5 E-07	4.9 E-08	2 E-07	FTE/MJ (full-time equivalent)
Effect on the regional economy	93.4	70	23.4	%
Job quality	Agriculture 50, Industry 28	Oil extraction 15 Industry 28	35 0	Number of injuries per 1000 employed
	Agriculture 0.05 Industry 0.03	Oil extraction 0.5 Industry 0.03	-0.45 0	Number of fatal accidents per 1000 employed
	Energy sector in Finland 42000	Oil extraction 12900 Oil company 42000	29100	Level of wage, €/year
Property price change	0	-2[19]	2	Points
Change in environmental status and wellbeing (noise, smell, aesthetic)	2	3	-1	Points

Bioethanol production has higher employment effect compared to fossil fuel sector, which could be good in the view of social aspects but bad for the economic aspects. If a bioethanol plant would be constructed, it could have a clear positive effect on regional economy, whereas a fossil gasoline plant has only a small effect related to plant construction phase and further employment. It is not possible to assess job quality for plant that does not exist, so the agriculture is compared to oil extraction, when agriculture has more injuries but less fatal accidents. Bioethanol production is compared to oil refinery in Finland, but those have same results as the sources are same (Statistics Finland 2011, EK 2013). Property price change and change in environmental status are estimated to be similar in Finland in case of bioethanol and oil refinery, but oil extraction could have unwanted effects.

3.1.3 Sensitivity analysis

We made a sensitivity analysis where we assessed the impact of different allocation method to the results. In this approach we used system expansion when distiller`s grain replaces the direct feed use of barley. The assumption was that one kg of distiller`s grain would replace approximately one kg barley. In that case the greenhouse gas emissions would be 54.1 g CO2 eq/MJ (69.9 in base scenario). Also, acidification and air quality would be lower compared to the base case. Also economic allocation could be possible and would give different results. Other possible changes would be the inclusion of ILUC and change in the process energy from wood chip CHP to fossil energy. Both changes would increase the environmental impacts.

For economic indicators, the main effect would be in the price of feedstock effecting directly to the production cost, IRR and repayment period, and indirectly to the product price to the end user. If feedstock would be more expensive, the profitability of pathway would decrease and product price to the end user increase, and vice versa.

[19] Oil extraction

3.2 Pathway 2: Cereal straw based bioethanol

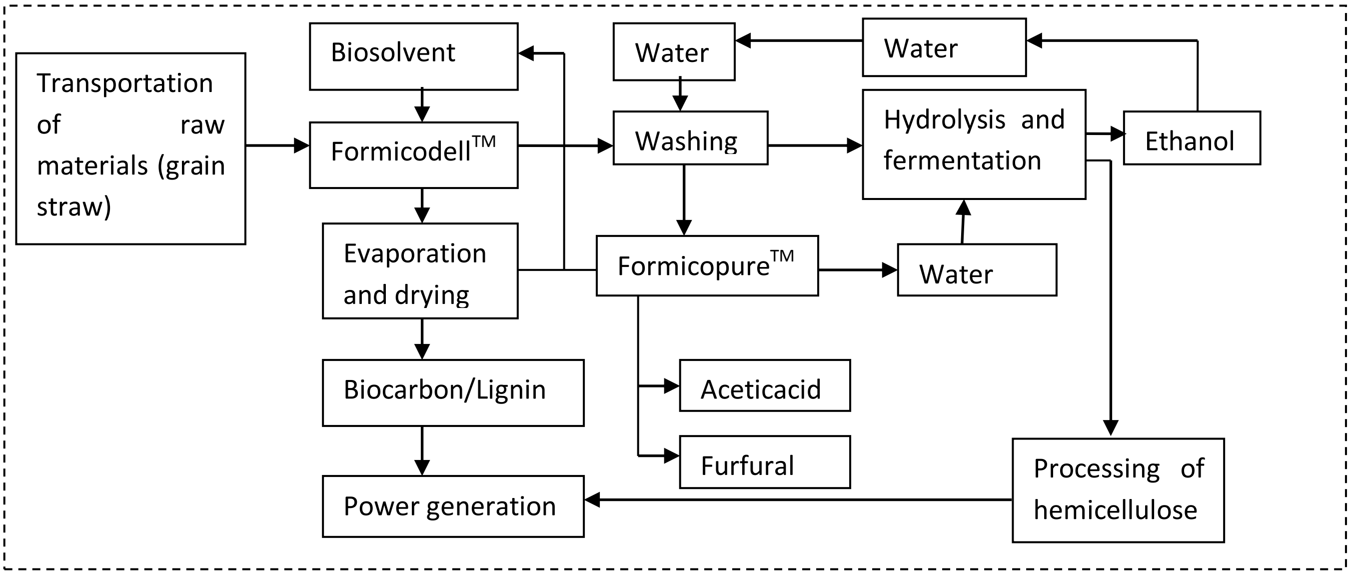
Bioethanol production from cereal straw and reed canary grass is quite promising for Finland (Pahkala et al. 2007). In fact, there is no such type of plant yet in operation in Finland. The present assessment has been made based on a proposed cereal straw based bioethanol plant at Myllykoski (former UMP Paper Mill site). The raw material is mainly straw from wheat and barley cultivation. The raw materials will be supplied from neighboring agricultural field covering of 185 000 ha. It has been speculated that 70% of the total harvested straw will be exploited as feeding material of the plant. The target of the proposed plant is to produce 60 000 tons of bioethanol from 330 000 tons of straw annually. In addition, the plant will also produce 172 000 tons of green coal (lignin contain substance) and 96 000 tons distillers which are exploitable for heat energy and animal feed respectively. For the plant operation, majority of required energy will be supplied from the nearest Myllykoski Bio-power Plant and rest will be fed from the national electricity grid. Chempolis Biorefining (FormicobioTM) Technology has been proposed to apply for raw material processing. Bioethanol from this proposed plant will replace the use of fossil gasoline as it is blended with gasoline to use in motor engine.

The primary data were obtained from interviewing one of the owners of the Suomen Bioetanoli Oy. The feasibility study report on 'Suomen Bioetanoli Oy' prepared by Neste Jacobs in 2013 was explored for making the grain straw-based bioethanol pathway. The Statistical Yearbook of Finland 2012 (Statistics Finland 2012), EcoInvent database (environmental indicators) and relevant information from EU level were explored for gathering the information on baseline fuels.

3.2.1 System boundary and allocation

The system boundary of the cereal straw-based ethanol pathway is presented in Figure 4. Since the raw materials are residues therefore, all inputs related to the crop cultivation were not considered in the estimation. However, the raw material purchasing cost including the transportation cost from field to the plant site is included. The system boundary includes all operations related to the processing of raw materials to bioethanol production. The use of chemicals, water, heat and electricity are also included. The costs for the existing infrastructures (building, road and network) are excluded from the system boundary. Allocation method used is physical allocation according to lower heating values of ethanol and distiller`s grain as it is recommended in the BIOTEAM methodology guidance (D2.3).

Figure 4. System boundary of the grain straw-based ethanol production



3.2.2 RESULTS

Tables 10-12 represents the results of cereal straw-based ethanol pathway in comparison to baseline. GHG emission and acidification indicators are better in bioethanol pathway than baseline. However, regarding air quality, the amount of particulate matter (PM_{10}) in the atmosphere is expected to be somewhat higher in bioethanol pathway than baseline. Regarding chemical use, the pathway plant showed better result than the baseline since in the baseline there are different hazardous chemicals are used of which some (i.e. polycyclic aromatic compounds) are susceptible for environment, animal and human health. Nutrient balance of the bioethanol pathway is seen to be negative, as the harvesting of cereal straw from cultivation land may deplete the soil nutrient. Nevertheless, for sustainability aspects, about 30% of the total cereal straw is recommended to leave at the cultivated site.

Some of the economic indicators of bioethanol pathway provide better results than baseline. In case of pathway, the higher IRR was due to the company is going to explore the existing infrastructures, which saving the investment cost about 15 million euro. It has been estimated that if the proposed bioethanol plant run according to its plan then the effect to the national economy (based on GDP of Finland in 2012) would be 520 ppm. Repayment period of straw ethanol plant would be higher compared to average for oil refinery. It is not possible to assess what would be the effect of straw collection to land price, but it could be positive, because farmer could have better profit from cultivation as nowadays straw is usually left to field. Product price to the end user would be slightly higher in case of bioethanol. Also, the production cost is higher in case of bioethanol compared to baseline.

Table 10. Results of environmental sustainability assessments of bioethanol pathway and fossil gasoline

Environmental indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Greenhouse gas emissions	6.62	84.3	-77.68	g CO_2 eq/MJ output energy
Acidification	0.126	0.63	-0.504	g SO_2 eq/MJ output energy
Air quality	0.0315	0.01	0.0215	g PM10/MJ output energy
Chemical use	2	3[20]	-1	Points
Water use	0.0013	0.00008	-0.019	m^3/MJ output energy
Nutrient balance	-0.00055 -0.00011	-0.001 0	-0.00045 -0.00011	kg N/MJ output energy kg P/MJ output energy
Net energy balance	0.10	0.18	-0.08	MJ/MJ output energy
Land use	0	2.6 E-10[21]	-2.6 E-10	ha/MJ output energy

Table 11. Results of economical sustainability assessment of bioethanol pathway and fossil gasoline.

Economic indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Internal rate of return	25.7	>13[22]	12.7	%
Repayment period	15	8[23]	7	year
Land price change	0	0	0	%
Contribution to national economy	520	1000[24]	-480	ppm
Product price to the end user	0.030	0.028[2]	0.002	€/MJ
Production cost	0.019	0.011	0.008	€/MJ

Based on the pathway plan, the effect of the regional economy is estimated about 70.37%. However, the job quality of the pathway has not been assessed. The number of injuries, number of accident and level of wage are considered on the average values of Finnish agriculture and industries sectors (Statistics Finland 2012). The results showed that the pathway could provide better than the baseline in all the parameters of job quality except for injuries which is higher in agriculture and industry sectors. In fact, there is no difference between the impact of pathway plant and oil refinery on land price changes, however, for oil drilling it has negative impact in this regard. Likewise, in case of environmental changes, no differences have been recognized between pathway plant and oil refinery but in case of oil drilling the impacts are negative.

[20] A lot of different chemicals are used in refining, most of them are only slightly hazardous, but sodium hypochlorite is extremely dangerous to aquatic environment, and strongly irritating to skin and damaging eyes.
[21] Land used for oil extraction
[22] Target for oil refinery
[23] Average for oil refinery
[24] All oil products in Finland 0.5% (Seppälä et al. 2009). Share of gasoline is about 20% from all oil products (Finnish Petroleum Federation).

Table 12. Results of social sustainability assessment of bioethanol pathway and fossil gasoline.

Social indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Employment	3 E-08	4.9 E-08	-1.9 E-08	FTE/MJ (full-time equivalent)
Effect on the regional economy	93.6	70	23.6	%
Job quality	Agriculture 50, Industry 28	Oil extraction 15 Industry 28	35 0	Number of injuries per 1000 employed
	Agriculture 0.05 Industry 0.03	Oil extraction 0.5 Industry 0.03	-0.45 0	Number of fatal accidents per 1000 employed
	Energy sector in Finland 42000	Oil extraction 12900 Oil company 42000	29100	Level of wage, €/year
Property price change	0	-2[25]	-2	Points
Change in environmental status and wellbeing (noise, smell, aesthetic)	2	3	-1	Points

3.2.3 *Sensitivity analysis*

In case of cereal straw based bioethanol, the main factor for its low environmental impact is that straw could be classified as residue. However, if it would be classified as a co-product from cereal cultivation and part of cultivation impacts would be allocated to straw, the environmental sustainability of cereal straw based bioethanol would decrease. However, this would improve the results of the barley ethanol pathway. Also in this case, other allocation methods, in addition to physical allocation, could be used. These could be system expansion and economic allocation. Both methods could give different results to the environmental sustainability. Also in this case, the feedstock price would have significant effect to the profitability (production cost, IRR and repayment period) and indirectly to the product price to the end user.

4 Gaseous pathways

Finland has long history on biogas production. Finnish Biogas Association has founded in 1991 as non-governmental organization with interest in the biogas field. Municipal Waste (MW) is a good option for biogas production. The amount of waste generation in 2011 was 96.6 million tons (Statistics Finland 2012) and this is a promising resource for energy options. The first MW based CHP plant established in Vaasa area in 1990 and till to the end of 2011, there are 18 MW based energy plants have been operating in the country.

[25] Oil extraction

4.1 Pathway 1: Biogas from wastes and residues

Biovakka Vehmaa plant was established in 2005. Its main business area is treatment of biodegradable waste and side products in biogas process and production of recycled nutrients, as all the nutrients in raw materials retain in the digestate. Capacity of Vehmaa plant is about 120 000 tons of raw materials per year. The raw materials consist of residues from enzyme industry, food industry and fish processing. It also uses a small amount of manure from partners' farms as a raw material. The Vehmaa plant produces electricity and heat with CHP plant. Part of the produced energy goes to own use and part is sold outside the plant. Electricity is sold to Finnish electricity grid and heat to a local greenhouse. There is no district heating network available, because the plant is located in the countryside. Therefore all produced heat cannot be used. Functional unit of the study is mainly MJ output energy in the present situation, when this excess heat is not taken into account. This leads to slightly worse results compared to situation where all heat could be utilized. In addition to energy, Vehmaa plant also produces recycled fertilizers, which are processed from the digestate.

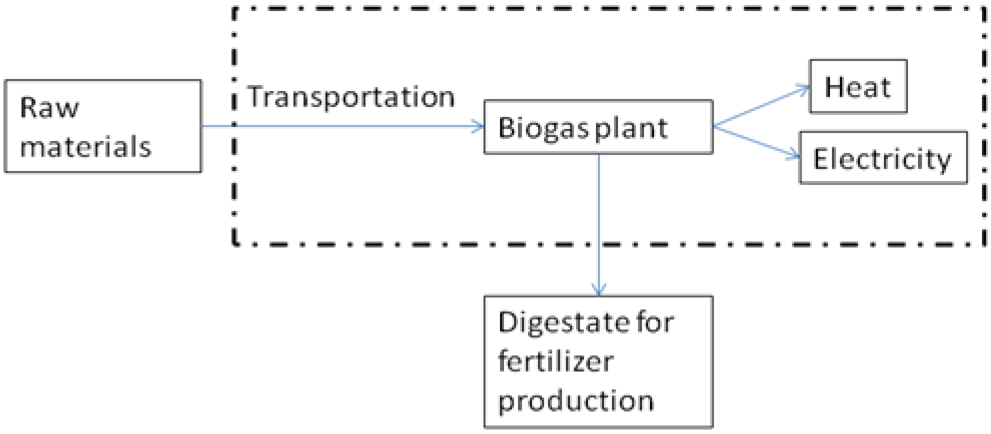
As the main energy output is electricity to Finnish electricity grid, the baseline is the Finnish average electricity, which consists of nuclear power (30%), hydro power (19%), natural gas (15%), coal (14%), wood (12%), peat (7%) and others (3%) (Yrjänäinen 2011). There are about 120 electricity production companies and about 400 power plants in Finland. Electricity production in Finland is quite distributed compared to many European countries. Due to this fact, it is quite difficult to assess some indicators in BIOTEAM sustainability assessment framework, in particular the economic indicators. Almost one third of electricity in Finland is produced in CHP plants, where as much as 90% of energy content can be utilized (Energiateollisuus ry 2014b). Data sources for baseline sustainability assessment were from EcoInvent database and Finnish national statistics.

Data for the environmental sustainability assessment was obtained from Biovakka. Also some other information that helped to estimate social impacts was from the stakeholder. Economic indicators and some social indicators were assessed according to literature (mainly MK Protech Oy 2005, Marttinen & Maaranen 2005). Although these references are quite old, they were the best sources that were available. Data for baseline assessment is based on EcoInvent database, and Finnish statistics and reports.

4.1.1 System boundary and allocation

System boundary starts from the transportation of the raw materials as they are wastes and residues when the production impacts could be excluded from the assessment (Figure 5). Processing of the digestate into recycled fertilizers is also left outside the system boundary in base scenario. In the sensitivity analysis, it is studied how the results would be affected in a case when digestate processing is included in the system boundary (Chapter 4.1.3). There is no allocation between energy and digestate, as the default allocation method is lower heating value and digestate has very low dry matter content and consequently its energetic value is close to zero. In other words, all emissions are allocated to energy sold out from biogas plant.

Figure 5. System boundary of biogas production.



4.1.2 RESULTS

Results of the pathway assessment are represented in the following tables (Table 13-15). Electricity from the biogas pathway performs better than Finnish average electricity in most of the environmental indicators. Only acidification effect is clearly bigger in case of biogas. This is due to emissions from biogas CHP (Kristensen et al.). Otherwise, the better results are mainly due to fact that biogas is produced from wastes and residues, so there are no emissions from cultivation, and e.g. land use is then zero. Chemical use in biogas production is zero, as chemicals are used only in digestate processing and it was left outside the system boundary in this base case. Nutrient balance is assumed to be close zero in case of biogas and baseline scenario as well. There is small nutrient loss in biogas plant through waste water, but majority of nutrients remain in digestate which is used as a fertilizer, so nutrients are recycled back to use. In electricity production, there are small nutrient losses in combustion of wood or fossil raw materials as the nitrogen is emitted to the air as nitrogen oxides.

In case of economic indicators, the biogas production performs better than the average electricity in internal rate of return, which could be quite different for different electricity production forms (nuclear 13%, gas 11.5%, coal 6.8%, peak plants negative (Vuorinen 2007)). Also the repayment period depends on electricity production form, and could be shorter or longer compared to biogas plant, but if using average values, biogas plant has shorter repayment period. Land price change for biogas is zero as the raw materials are wastes and residues. In the past ten years the price of forest land has increased over 50%, but it is not possible to say how much of the increase is due to energy production. Electricity production has a quite high contribution to national economy in Finland (Seppälä et al. 2009), but the contribution of all biogas plants that use waste materials as raw material has only a small share of that contribution. According to Finnish statistics, the price of green electricity is higher although the production cost of biogas from wastes and residues is lower than average electricity. The reason for such low production cost could be gate fees (the waste material is not just free, but the provider pays money for its processing in the plant).

Table 13. Results of environmental sustainability assessment of biogas pathway compared to Finnish average electricity.

Environmental indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Greenhouse gas emissions	23.4	93.1	-69.7	g CO_2 eq/MJ output energy
Acidification	0.61	0.24	0.37	g SO_2 eq/MJ output energy
Air quality	0.0018	0.0084	-0.0066	g PM10/MJ output energy
Chemical use	0	1[26]	-1	Points
Water use	0.0009	0.0026	-0.0075	m^3/MJ output energy
Nutrient balance	~ 0 ~ 0	~ 0 ~ 0	0 0	kg N/MJ output energy kg P/MJ output energy
Net energy balance	0.28	1.94[27]	-1.66	MJ/MJ output energy
Land use	0	1.12 E-05	-1.12 E-05	ha/MJ output energy

Table 14. Results of economical sustainability assessment of biogas pathway compared to Finnish average electricity.

Economic indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Internal rate of return	23.3[28]	10	13.3	%
Repayment period	12	18	-6	year
Land price change	0	4.5	-4.5	%
Contribution to national economy	34[29]	13700	-13666	ppm
Product price to the end user	0.0178	0.0147	0.0031	€/MJ
Production cost	0.0128	0.0133[30]	-0.0005	€/MJ

Biogas plant has higher employment rate compared to Finnish energy sector on average. High employment could be good in terms of social aspects, but not for competitiveness. Biogas plant has a significant effect to the regional economy. Also average electricity production has some positive effect as some plants use domestic wood or peat, and also they have domestic workforce in construction and operation. In Biovakka plant, there have been no recorded injuries or accidents. In Finnish industrial sector there was a small amount of injuries and accidents in 2010 (Statistics Finland 2011). The wage level was estimated to be same in both pathways according to Finnish statistics to energy sector (EK 2013). Also the property price change and change in environmental status and wellbeing were estimated to be low in both cases.

[26] Takes into account only sulphur hexafluoride that is used in electricity grid as energy carrier. It could exploit when subject to heat otherwise not hazardous.
[27] EU mix (Edwards et al. 2013). Finnish figure would be better due to significant amount of CHP
[28] Reference: MK Protech Oy 2005
[29] All co-digestion plants using waste materials in Finland in 2012 (value of energy compared to GDP)
[30] Reference: Vainio 2011

Table 15. Results of social sustainability assessment of biogas pathway compared to Finnish average electricity.

Social indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Employment	1.56 E-07	4.7 E-08	1.09 E-07	FTE/MJ (full-time equivalent)
Effect on the regional economy	87.8	51.3	36.5	%
Job quality	0	28	-28	Number of injuries per 1000 employed
	0	0.03	-0.03	Number of fatal accidents per 1000 employed
	42000	42000	0	Level of wage, €/year
Property price change	0	0	0	Points
Change in environmental status and wellbeing (noise, smell, aesthetic)	2	2	0	Points

4.1.3 SENSITIVITY ANALYSIS

We made a sensitivity analysis where we assessed the impact of different system boundary and allocation method. In this second approach, we took into account also the processing of digestate to fertilizers when the produced energy is lower, as part of energy is consumed to digestate processing. Also, there is chemical usage (sulphuric acid, sodium hydroxide) in digestate processing. In sensitivity analysis, we used a system expansion approach when the recycled fertilizers replace commercial fertilizers. Results of the sensitivity analysis show that greenhouse gas emissions would be negative, i.e. avoided emissions from fertilizer production would be higher compared to emissions from biogas pathway. Acidification and air quality emissions would be higher compared to base scenario, because emissions from sulphuric acid production are quite high. Also the net energy balance would be worse, 0.79 MJ/MJ. Also economic allocation between biogas and digestate could be possible calculating economic values for nutrients that digestate is containing. That would mean that more than half of emissions could be allocated to digestate. In case of mass allocation, almost all emissions could be allocated to digestate as mass of biogas is really low compared to digestate.

Effect of the different system boundary and allocation method to the economic or social indicators could not be assessed, as most of the results are based on generic data, not plant specific data. In case of plant specific data, e.g. employment, the value presented in base scenario includes digestate processing as it could not be excluded. However, the use of generic data would have a significant effect to the results, e.g. the assumption of gate fees has a clear effect to the profitability (production cost, IRR and repayment period).

4.2 Pathway 2: Municipal Waste based biogas

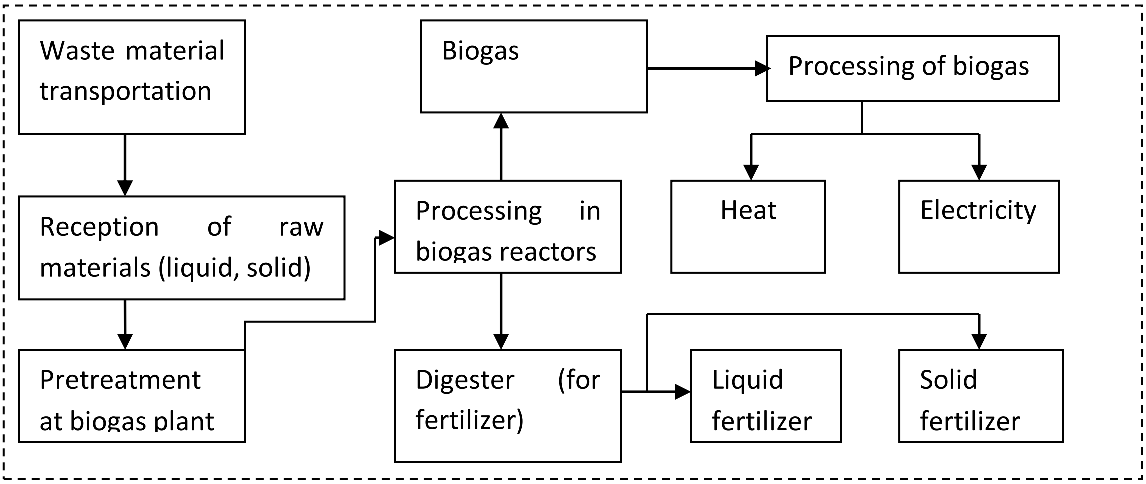
The 'Bio10 Biokymppi Oy' at Kitee was established in 2006 and started in operation from 2009. The main objectives of the company's business are to handle the waste materials generated from the neighboring municipalities and to explore the biodegradable waste materials for side products such as heat, electricity and fertilizer. The annual capacity of this plant is about 19000 tons. The raw materials are mainly municipal biowaste, wastewater treatment plant sludge, industrial biowaste, fatty sludge, animal dung and other vegetable based waste. The Biokymppi CHP plant produces about 10000 MWh consisting of 2000 MWh power, 8000 MWh heat and 18000 m^3 liquid fertilizers annually. Nearly half of the generated electricity is used for its' own use mainly for plant operation. Remaining electricity is sold to the national grid. Heat is sold to the Kitee Municipality through heating pipeline network. Liquid fertilizer is supplied with container truck (capacity 30 m^3) to the farmers' agricultural land. About 85% of the Biokymppi is generated from waste handling fees, 11% from heat selling, 3% from electricity selling and 1% from fertilizer. Lower price of green electricity and lack of governmental subsidies have been pointed the major obstacles for the promotion of biogas based electricity generation in case of Biokymppi.

The Bio10 Biokymppi Oy replaces mainly heavy fuel oil (HFO) since more than 80% of the final product is heat which is supplied to the inhabitants of the Kitee Municipality. On this account, heavy fuel oil is considered to be the baseline for the Biokymppi case. The primary data were obtained from interview of the Chief Executive of Bio10 Biokymppi Oy. In addition, several documents of the company were explored for making sustainability assessment of waste-based biogas pathway. The sources for heavy fuel oil are same as represented in section 2.2.1.

4.2.1 System boundary and allocation

Figure 6 represents the system boundary of biogas pathway which considered for the assessment in case of Biokymppi. The system boundary starts from raw materials transportation from the disposal sites to the plant yard. The pretreatment and processing of raw materials to the final products are included in the system boundary. However, the transportation of liquid fertilizer that produces from digestive process in the biogas reactor is excluded from the system boundary. Nevertheless, there is no allocation of energy in biogas digester since there is very low dry matter and their energy value is closed to zero. Importantly, the digestate processing is considered in the system boundary for sensitive analysis. The reason is that fertilizer produced from the pathway replaces the chemical fertilizers eventually the emission from chemical fertilizers is reducing by using of the fertilizer produced from the biogas pathway.

Figure 6. System boundary of municipal waste-based biogas pathway



4.2.2 RESULTS

Tables 16-18 represent the results of pathway and baseline. The biogas pathway provided better results than HFO in case of GHG emission, acidification and air quality. In fact, biogas that is produced from wastes has no emission because the raw materials are not directly subjected to land cultivation. In case of chemical use biogas pathway provided better results than baseline as very limited chemicals are used in biogas digestate whereas in oil refinery varieties of chemicals are used in oil refinery for processing of crude oil. There are small amount of nutrient loss in biogas pathway through wastewater but it does not have negative impact because majority portion of nutrient are remained in the fertilizer that produce through digestate processing and that is reused in the agricultural field. Regarding net energy balance, the biogas pathway provided far better results than baseline (heavy fuel oil).

The investigation showed that in most of the economic indicators, the biogas pathway did not have the promising results than the baseline (oil refinery). In case of pathway, the IRR is lower and the repayment period is higher than baseline. It has been noted that the existing waste-based biogas plant decreased the premises land prices; therefore, the net impact is negative. However, the company has initiated to reduce odor by introducing odor free appliances. Although the contribution of all waste based biogas plants in national GDP is remarkable but still the contribution is far behind than the baseline (HFO). Interestingly, biogas pathway provided better options than the baseline (HFO) in case of product price and production cost indicators. The reason of such low product price and low production cost are due to the bulk of income of this plant generates from waste handling fees.

Table 16. Results of environmental sustainability assessment of biogas pathway compared to heavy fuel oil for heating.

Environmental indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Greenhouse gas emissions	10.7	94.7	-84.0	g CO_2 eq/MJ output energy
Acidification	0.45	0.632	-0.182	g SO_2 eq/MJ output energy
Air quality	0.0009	0.0478	-0.0469	g PM10/MJ output energy
Chemical use	1	3[31]	-2	Points
Water use	8.3 E-05	7.31 E-05	-6 E-05	m^3/MJ output energy
Nutrient balance	~0 ~0	-0.0001 0	~0.0001 0	kg N/MJ output energy kg P/MJ output energy
Net energy balance	0.10	0.41	-0.31	MJ/MJ output energy
Land use	0	2.6 E-10[32]	-2.6 E-10	ha/MJ output energy

Table 17. Results of economical sustainability assessment of biogas pathway compared to heavy fuel oil for heating.

Economic indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Internal rate of return	10	> 13[33]	-3	%
Repayment period	8	8[34]	0	year
Land price change	0	0	0	%
Contribution to national economy	34[35]	250[36]	-216	ppm
Product price to the end user	0.009	0.036[37]	-0.027	€/MJ
Production cost	0.011	0.013	-0.002	€/MJ

Study also revealed that biogas pathway provided better results in employment than any other energy sector in Finland. Although it is not good for getting the net benefit but is good for social aspects. The pathway has implicit impact on regional development. It has also remarkable effect on the regional economy. The raw material collection, transportation, processing, services of the final products all are mostly restricted within the region. There were 2 minor injuries happened but still the severity is lower than the average of Finnish industrial sector (Statistics Finland 2011). No fatal accident occurred so far. The wage level was the same as Finnish energy sector (EK 3013). Since the waste-based biogas plant involves

[31] A lot of different chemicals are used in refining, most of them are only slightly hazardous, but sodium hypochlorite is extremely dangerous to aquatic environment, and strongly irritating to skin and damaging eyes.

[32] Land used for oil extraction

[33] Target for oil refinery

[34] Average for oil refinery

[35] All co-digestion plants using waste materials in Finland in 2012 (value of energy compared to GDP)

[36] All oil products in Finland 0.5% (Seppälä et al. 2009). Share of heavy fuel oil is about 5% from all oil products (Finnish Petroleum Federation).

[37] Based on import price of heavy fuel oil in 2012 (Statistics Finland 2012).

waste handlings and processing which are subjected to emitting bad smell. This cause negative impact on adjacent property prices such as land prices. It has been estimated that the present waste-based biogas plant decreased about 5-10% of the property values. Moreover the pathway put negative impact in smell that changes the environmental status. However, in other environmental status such as noise and aesthetic, the impact is minimal. On the other hand the impact of oil refinery and oil drilling put negative impacts in changing of environmental status. Therefore, in these regards, the difference (based on average value of the change environmental indicators) between biogas pathway and baseline is estimated as zero.

Table 18. Results of social sustainability assessment of biogas pathway compared to heavy fuel oil for heating.

Social indicator	Bioenergy pathway impact	Baseline impact	Net impact	Unit
Employment	1.67 E-07	4.88 E-08	1.182 E-07	FTE/MJ (full-time equivalent)
Effect on the regional economy	83	36	47	%
Job quality	20	28	-8	Number of injuries per 1000 employed
	0	0.03	-0.03	Number of fatal accidents per 1000 employed
	Energy sector in Finland 42000	Oil extraction 12900 Oil company 42000	29100	Level of wage, €/year
Property price change	-1	0	-1	Points
Change in environmental status and wellbeing (noise, smell, aesthetic)	2	3	-1	Points

4.2.3 Sensitivity analysis

In sensitivity analysis we assessed what would be the environmental performance of biogas pathway if nutrients in digestate replace commercial fertilizers. When digestate replaces commercial fertilizers the GHG emissions would be -2.65 g CO_2 eq, acidification would be 0.42 g SO_2 eq/MJ and air quality 0.0009 g/MJ. So, the allocation method would have a very big impact for greenhouse gas emissions as production of fertilizers emits a lot of N_2O emissions. For other emissions, the impact of allocation method is not significant. Also in this case, the economic allocation between biogas and digestate could be possible calculating economic values for nutrients that digestate is containing. That would mean that more than half of emissions could be allocated to digestate. In case of mass allocation, almost all emissions could be allocated to digestate as mass of biogas is really low compared to digestate.

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