

A Life Cycle Inventory of existing biomass import chains for “green” electricity production

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Abstract

Essent Energie, a Dutch utility company, recently initiated the import of clean biomass for co-firing purposes in its coal plants. Key reasons for import are the fact that the availability of biomass with good co-firing properties in the Netherlands is limited and imported biomass can be competitive with biomass available in the Netherlands. In order to verify whether a certain biomass source meets formulated sustainability criteria, Essent Energie strives to create a certification system for biomass import. This study is set up to support the creation of such a certification system, by performing a Life Cycle Inventory (LCI) on biomass import chains. An LCI describes and quantifies the inputs (resources) and outputs (emissions) for each component of the biomass import chain, from biomass production to conversion. In doing so, the environmental performance can be determined.

Objective

The main objective of this study is to carry out a LCI on 2 existing biomass import chains to provide a basis for judging the overall environmental impact of biomass import and its application as fuel in coal plants to generate electricity by co-firing.

Approach

In this study, the import of wood pellets from Canada and palm kernel shells (PKS) from Malaysia are considered, 2 existing biomass import chains. The biomass is co-fired in the Amer 9 unit, a 600 MW_e coal fired power plant. For several components of the chain, case specific data provided by actual companies involved in the biomass import chain were used. If no such data were available, data from scientific publications and LCA databases were used.

A mass and energy balance is set up to calculate the net avoided primary energy and the emissions of the most important greenhouse gasses, NO_x, SO₂, particulates and several heavy metals are quantified. The energy use and emissions related to biomass import and co-firing are compared to several reference situations for electricity/heat production (a coal plant in the Netherlands and the average Dutch fuel mix), in which the biomass fate when it would not have been used for energy purposes is accounted for as well. Also the use of biomass in the country where it is produced in stand-alone combustion systems is considered. Finally, the net avoided primary energy and emissions of biomass import and co-firing is compared to the reference systems and the use of biomass as fuel in the country where it is produced.

Results

As can be concluded from figure A-1 and A-2, biomass import and co-firing in coal fired plants in the Netherlands is an efficient way to reduce fossil fuel use and greenhouse gasses in comparison to power production from 100% coal or the average Dutch fuel mix. The emission of SO₂, particulates (figure A-3) and heavy metals (figure A-4) of biomass co-firing are also lower in comparison to emissions caused by power production from fossil fuels. This is mainly explained by the fact that coal mining and transport to the Netherlands is an energy consuming process causing high emissions of especially CH₄, SO₂, particulates and heavy metals. Also the avoided emissions of CH₄ caused by decomposition of wood residues at landfills in Canada and CH₄, N₂O, SO₂ and particulate emissions caused by palm kernel shells burning in the open air in Malaysia contribute to the positive impact of biomass import and co-

firing. According to the results of this study, biomass import and co-firing has some less desired impacts as well. NO_x emissions (figure A-3) might increase when importing and co-firing of wood pellet. Co-firing the biomass sources considered in this study will also lead to an increase in heavy metal content of the ash, due to the high quantities of mainly Mn in both wood pellets and palm kernel shells. This could hamper the return of the ash to the country where the biomass was produced. Ash contains significant quantities of nutrients required for biomass growth, so it would be desirable to recycle the ash to the forest in Canada or to the palm oil plantations in Malaysia.

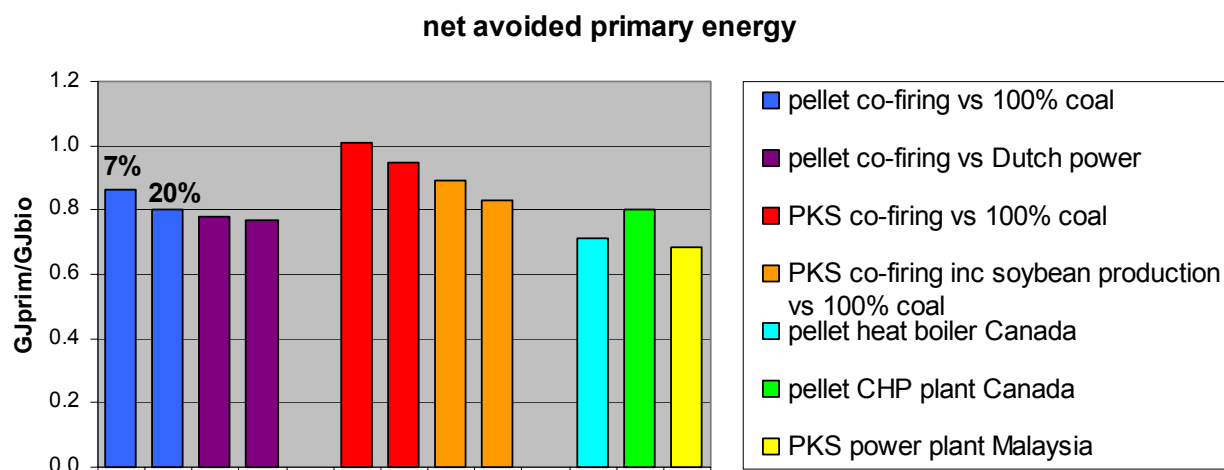


Figure A-1: Net avoided primary energy per unit biomass energy of pellet and palm kernel shells (PKS) import and co-firing and use in stand-alone combustion systems in the country where the biomass is produced. Different co-firing shares were accounted for; the left column of each series refers to 7% (on mass basis) and the right column to 20%. The stand-alone combustion systems included in the analysis are local boilers for heat production and a small-scale CHP unit in Canada and a small-scale power plant in Malaysia. Different reference systems were used in the calculations. Dutch power refers to electricity generation from the average Dutch fuel mix. The application of PKS as co-firing fuel might compete with its application as resource for fodder production in the Netherlands. Therefore, the production and transport of an alternative resource (soybeans from the USA) is included as reference.

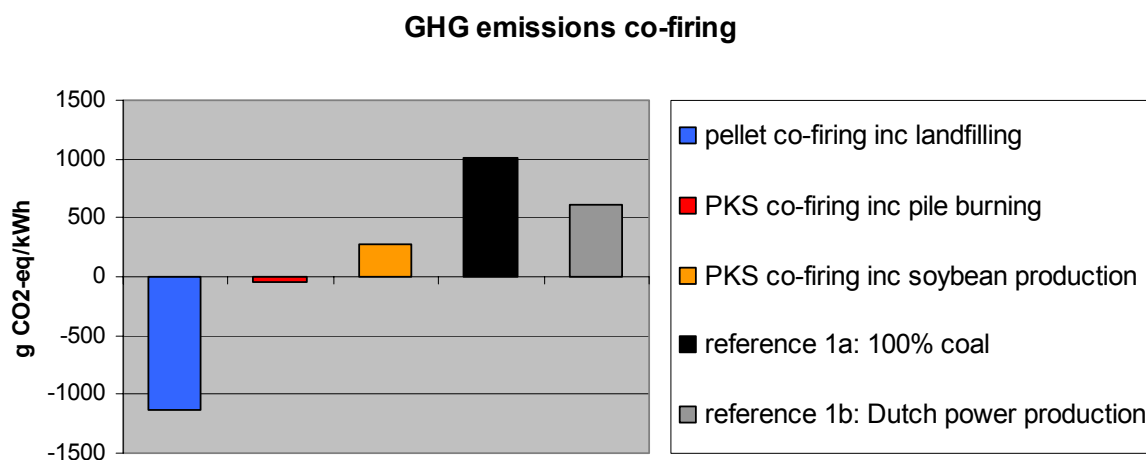


Figure A-2: GHG emissions of pellet and PKS import and co-firing in the Amer plant (g/kWh bio) in comparison to reference power production (g/kWh fossil).

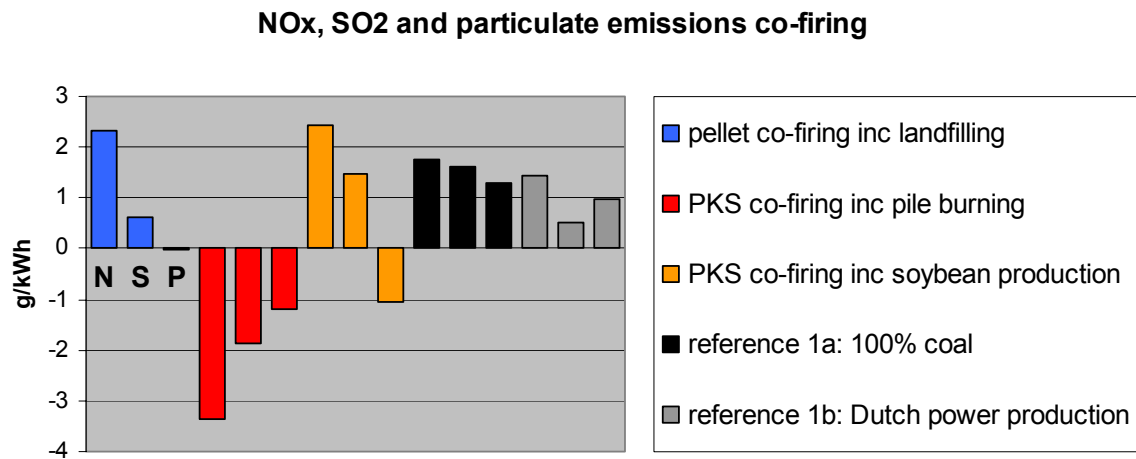


Figure A-3: NO_x (N), SO₂ (S) and particulate (P) emissions of pellet and PKS import and co-firing in the Amer plant (g/kWh bio) in comparison to reference power production (g/kWh fossil).

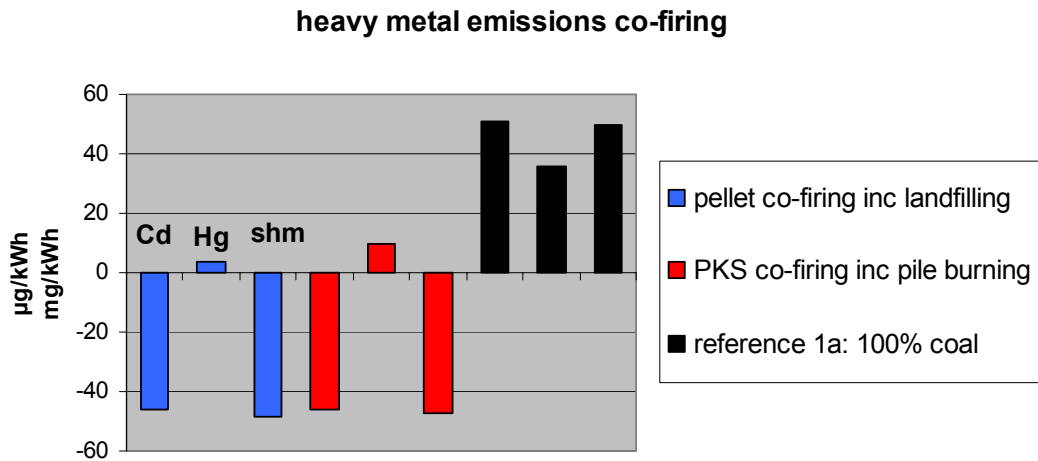


Figure A-4: Heavy metal emission of pellet and PKS import and co-firing in the Amer plant in comparison to reference power production (µg/kWh fossil). The emissions of Cd and Hg are given in µg/kWh bio and the sum of other heavy metals (shm) is given in mg/kWh bio.

The prospects of pellet and palm kernel shell utilization as fuel in stand-alone combustion systems in the country where the biomass is produced is less promising than transporting the biomass to the Netherlands for co-firing, in spite of energy use and emissions caused by sea transport over a large distance. This is explained by the lower efficiency of those relatively small-scale systems in comparison to the Amer plant considered for co-firing. Secondly, the relatively high energy use and emissions of coal mining and transport to the Netherlands are avoided when co-firing biomass. A third reason that makes export preferable above intern use for these specific cases, is the larger share of renewables in the electricity mix of especially Canada, in which 60% of the electricity is produced in hydro-electric plants. Consequently, avoided emissions of biomass use are lower than when used in the Netherlands.

Conclusions

This study has shown that the choice of the biomass resource, origin and reference system is very important for the environmental performance of biomass import and co-firing. The country/region of interest where a biomass potential exists, local conditions and market effects of biomass trade should be considered with care. Crucial aspects are the type of biomass, the fate of the biomass when it is not exported, the local/regional demand, competition with other applications and the energy system of a country. In conclusion, not only the availability, composition and price of biomass should be decisive, but also the context in which biomass production and trade occurs.

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Abbreviations

BIJSTER	Model to determine several emissions in coal fired power plant
BOO	Model to determine impact of co-firing on efficiency
CHP	Combined heat and power production
EFB	Empty fruit bunches
ESP	Electrostatic precipitators
FFB	Fresh fruit bunches
FGD	Flue gas desulphurisation
GEMIS	Global emission model for integrated systems, LCA software and database
GHG	Greenhouse gas
GWP	Global warming potential
HFO	Heavy fuel oil
kt	kilo tonne
ktdm	kilo tonne dry matter
ktfw	kilo tonne fresh weight
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower heating value
Mt	mega tonne
PKS	Palm kernel shells
REB	Regulerende Energie Belasting (Regulatory Energy Tax, tax exemption for electricity from renewable energy sources)
SIMAPRO	LCA software and database
SOTA	State of the art
tkm	tonne kilometer
WWT	Waste water treatment

1 Introduction

In the Netherlands, the import of biomass from other countries for energy purposes is taking place and expected to grow. The main reason is to increase the share of renewable energy in the energy supply system in order to reduce the emission of greenhouse gasses. The Dutch government set a target in the 3rd energy paper, which implies that 10% of the primary energy demand in 2020 should be generated from renewable sources. Biomass (consisting of a wide variety of forestry and agricultural residues, organic waste and dedicated energy crops) is considered to play a key role in the realisation of this target; about 40% of the renewable energy should be produced from biomass.

The energy sector will play a key role in the realisation of this target. In order to stimulate the production of renewable energy, the Dutch government introduced an incentive for the production of “green” (renewable) electricity. Green electricity is certified and the owner of the green certificate (often the distribution companies) is exempted from the so-called “regulerende energie belasting” (REB) for each MWh of green electricity sold, which makes green electricity economically attractive and competitive with electricity produced from fossil fuels/nuclear power. Moreover, the electricity producer directly receives an allowance for each green MWh produced.

Essent Energie is one of the utility companies, which strives to increase its market share of green electricity. One of the activities they recently undertook to increase the share of green electricity is the import of clean biomass from other countries, which is co-fired in its coal plants. Wood pellets (from Canada and Latvia), palm kernel shells (from Malaysia, Indonesia and Nigeria) and citrus pulp (from Brazil) were purchased and co-fired. Furthermore, there are plans to import olive oil from Spain and palm oil for co-firing purposes.

There are several reasons to import biomass instead of using biomass available in the Netherlands itself. Key reasons are amongst others availability, contractability, fuel quality (availability of biomass with good co-firing properties in the Netherlands is limited) and price (imported biomass can be competitive with biomass available in the Netherlands).

Since green electricity has a high market value, strict requirements are set on the environmental and socio-economic impact of the product. In order to be sold as green electricity, the sustainability of biomass production and import should be guaranteed. This is a complicated task, since the production, harvesting and transport of the biomass takes place in another country, which makes it very hard to introduce and regulate rules with regard to sustainable production of biomass specific for the Netherlands. Especially large-scale, intensive biomass cultivation may have environmental and socio-economic impacts, which might not be in line with sustainability criteria.

Essent Energie strives to create a certification system, allowing to verify whether a certain biomass source meets formulated criteria. This study is set up to facilitate the creation of such a certification system. The work consists of two key parts: a Life Cycle Inventory (LCI) is set up and an inventory is made of certification systems.

This report will focus on the first step. In basic terms, an LCI describes and quantifies the inputs (resources) and outputs (emissions) for each component of the chain, from fuel production to conversion. By doing so, the net avoided primary energy and the overall emissions of a product (which can be either biomass or electricity) can be determined for the complete biomass import and co-firing chain studied.

Objective

The objective of this study is to carry out a LCI on 2 biomass import chains to provide a test case and a basis for judging the overall environmental impact of biomass import and its application as fuel in coal plants to generate electricity by co-firing.

In order to obtain results for the actual situation, the LCI is performed on 2 *existing* biomass import and co-firing chains: wood pellets from Canada and palm kernel shells from Malaysia.

Approach

A mass and energy balance is set up and the emissions of the most important greenhouse gasses, NO_x, SO₂, particulates and several heavy metals are determined. Nutrients are considered in a more general way. The complete chain is considered, including biomass production/collection, pre-treatment, local and international transport and conversion of the biomass into electricity. The energy use and emissions related to biomass import and co-firing are compared to several reference situations for electricity/heat production (a coal plant in the Netherlands and the average Dutch fuel mix). The fate of biomass when it would not have been used for energy purposes (dumping at landfills, burning, fodder production) is accounted for as well in energy use and emissions. Also the use of biomass in the country where it is produced in stand-alone combustion plants is considered. Finally, the net avoided primary energy and emissions of biomass import and co-firing is compared to the reference systems and the use of biomass in the country where it is produced/becomes available. From this comparison it can be concluded whether international biomass trade is a desirable strategy for currently available biomass resources, considering net avoided primary energy and emissions.

In chapter 2, the methodology to determine net avoided primary energy and net emissions is discussed. Chapter 3 will describe the considered biomass import chains, including the data used for the analysis, from which the results are given in chapter 4. The results will be discussed more extensively in chapter 5 and conclusions will be drawn in the final chapter.

2 Methodology

In the first paragraph of this chapter, the different steps and relevant issues of a LCI are explained. The second paragraph gives an overview of the different chains to be compared in this study. A mass and energy balance is set up for each chain, which is explained in more detail in paragraph 3. In paragraph 4, the methodology to determine the emissions occurring in the entire chain is discussed and in paragraph 5, the nutrient issue is described.

2.1 Life Cycle Inventory

A Life Cycle Inventory (LCI) is the second step in a Life Cycle Assessment (LCA), which consists of 4 phases (CML 2001):

1. Goal and scope definitions
2. Inventory analysis (LCI)
3. Impact assessment
4. Interpretation

In the first phase, the goal of the study is formulated in terms of the exact question, target audience and intended application. The scope of the study is defined in terms of temporal, geographical and technological coverage, and the level of sophistication of the study in relation to its goal. The inventory analysis is the phase, in which the product system(s) is defined: the system boundaries are set, the flow diagrams with unit processes are designed, data are collected for each process and allocation rules (when dealing with by-products) are performed. This results in an inventory table listing the quantified inputs and outputs to the environment associated with the functional unit. Energy and raw material requirements, emissions, effluents and solid waste are quantified for each process, from resource extraction to final product use and disposal (Cradle-to-the-Grave approach). In the impact assessment, the set of results of the Inventory analysis is further processed and interpreted in terms of environmental impacts and societal preferences. A list of impact categories is defined, and models for relating the environmental interventions to suitable category indicators for these impact categories are selected. Finally, the category indicator results can be grouped and weighted to include societal preferences of the various impact categories. Interpretation is the phase, in which the results of the analysis and all choices and assumptions made during the course of the analysis are evaluated, and overall conclusions are drawn (CML 2001).

In this study, the impact assessment (phase 3) will not be performed. In the introduction, the goal and scope were already defined. This chapter will first consider the considered product system, the emissions to be considered, the type of data and the issue of allocation.

The product system

When performing an LCI, a distinction should be made between the economy (product system) and the environment by defining an economy-environment border. In the LCI, energy flows and emissions crossing this border are quantified. In this study, the choice of the boundary between the product system and environment system is done according to the guidelines for detailed LCA given in (CML 2001).

Human control over processes is the main criterion for regarding a process as a unit process and hence include it in the product system.

The product system considered in this study includes a biomass import chain and several reference systems. The biomass import chains consist of production and transport of biomass and fossil fuel and the conversion into electricity/heat. These chains are then compared to different reference systems, which include an alternative electricity/heat production system and the fate/application of biomass when it is not exported for co-firing purposes.

Only 1st and 2nd order energy inputs (based on LHV) are accounted for in the energy balance; 3rd order energy inputs (for construction and dismantling of capital goods) are not considered, which is justified considering the very small contribution to the total energy use. This is confirmed in several LCA studies, e.g. in a LCA study for an integrated coal gasification combined cycle from Smit (1994). Another reason not to include 3rd order energy inputs is that these are rather similar for comparable chain types.

Emissions to air

In this study, the most important greenhouse gases (CO₂, CH₄ and N₂O), NO_x, SO₂, particulates and heavy metals are considered. Although the emission of CH₄ and N₂O are generally small in comparison to CO₂ emissions, they are accounted for, since the greenhouse warming potential of these compounds is much higher than for CO₂. NO_x and SO₂ emissions cause acid rain and the former also stimulates the formation of smog. Fine particles have proven to cause serious health problems. Air emissions of Cd, Hg and other heavy metals combined (As, Co, Cr, Cu, Mn, Ni, Pb, Sb and V) occurring during production, transport and conversion of the fuels are estimated as well. Cd and Hg are considered separately, since these metals are extremely toxic. In analysing heavy metal emissions, emphasis is put on the conversion part.

Nutrients

Nutrient flows of biomass export and conversion are quantified in a more general way. It is determined how much nutrients are removed from the production sites and how much can theoretically be recovered and returned to the fields in the form of ash.

Type of data

In this study, data used to perform the LCI can be divided into 3 categories, ranging from very accurate and specific to very rough and general.

1. Case specific data provided by actual companies involved in the biomass import chain.
2. Data from scientific publications or quotes from experts.
3. Data from LCA databases and energy statistics.

If possible 1st category data were used and verified by comparing them with scientific literature. If no specific data on chain components were available, data from scientific publications and LCA databases were used.

Allocation

In this study, several allocation problems will arise. For residues, the energy use and emissions caused by the cultivation/harvesting of the main crop might be divided over different products. In that case, allocation of energy use and emissions is required. Different possibilities exist for allocation; it can be done on the basis of the mass,

economic value, energy and exergy content of the product. It was decided to allocate energy use and emissions on mass base, the method traditionally used in energy analysis. Allocation is also required to assess which part of the emissions is attributed to electricity and which to heat when the considered conversion system is a CHP plant. In this study, emissions are allocated to the exergy content of heat and power. This method will be explained in more detail in paragraph 2.4.

2.2 Overview considered chains

As mentioned before, different chains will be considered in this study: import and co-firing of biomass and the use of biomass in the country where it is produced as a fuel in different stand-alone combustion systems. Each chain is compared to one or more reference systems, which represent the operations that will be avoided when (co-) firing biomass. In the figures below, the considered chains, including the reference systems, are summarised.

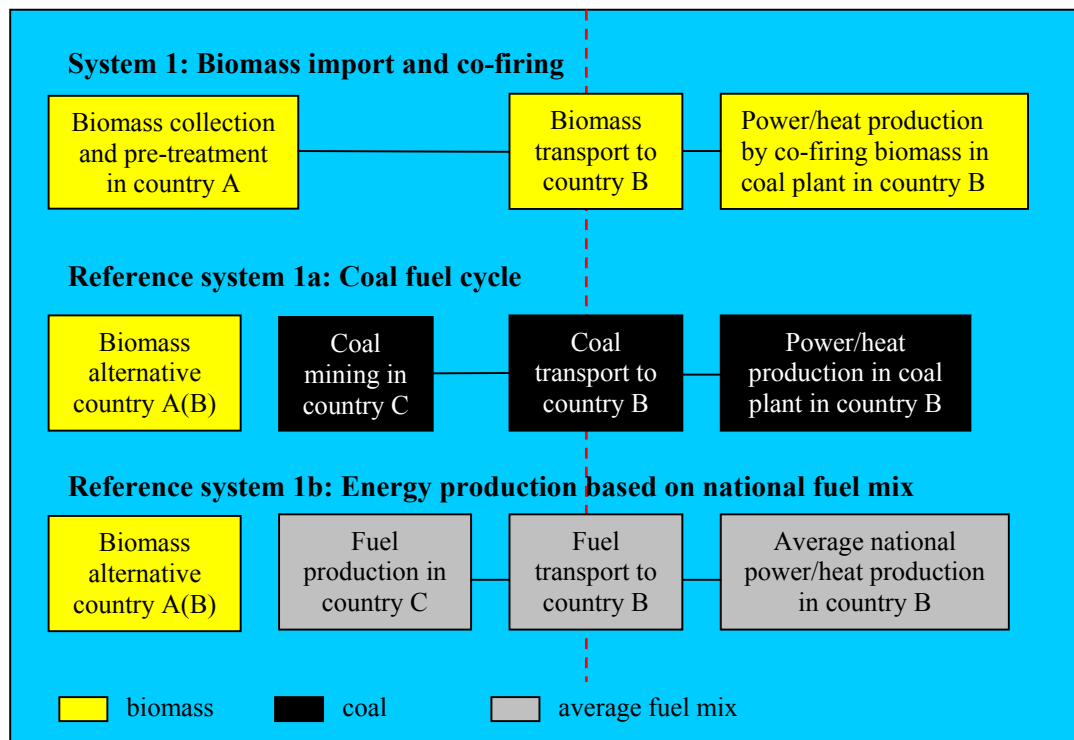


Figure 2-1: Biomass import and co-firing in the Netherlands with reference systems

Country A = biomass exporting country (Canada/Malaysia)

Country B = biomass importing country (Netherlands)

Country C = coal/gas/oil producing country, can be country B

System 1 includes the production and transport of biomass from Canada/Malaysia to the Netherlands, where it is co-fired in a coal-fired power plant. The dashed line distinguishes the operations performed in the country where biomass/fossil fuel is produced from the operations, which occur in the Netherlands, where the biomass is co-fired. As mentioned before, the reference system consists of a system for power/heat generation from fossil fuels and a system that considers the fate of biomass when it is not exported as co-firing fuel.

The most logical reference for the generation of electricity/heat by co-firing is the same coal-fired power plant without co-firing; the co-fired biomass in fact replaces a part of the coal. It was decided to consider the average electricity/heat production based on the Dutch fuel mix as well. The reason to include this reference system is because it can be argued that the electricity produced by co-firing biomass in a coal-fired power plant replaces an equivalent electricity from the grid (a reservoir with electricity produced by different plants and fuels).

The fate of biomass depends on the resource and the country. It is plausible that if residues will not be used, they are burned in the open air or disposed at a landfill. For palm kernel shells, the situation is more complicated, since this residue is used as fuel in the local palm oil industry. It might also be used as a resource for the production of fodder in the Netherlands. If a growing demand of palm kernel shells for energy purposes abroad is created, competition may occur with local energy application and fodder production. Since this study deals with the excess, competition with local energy application is not considered. When palm kernel shells are indeed used as resource for fodder production, the energy use and emission associated with the production and transport of an alternative resource for fodder production (e.g. soybeans) should be accounted for. It was decided to consider a best case (burning of palm kernel shells in the open air) and worst case (fodder production of palm kernel shells) scenario, to get insight in the ranges of the overall environmental impacts.

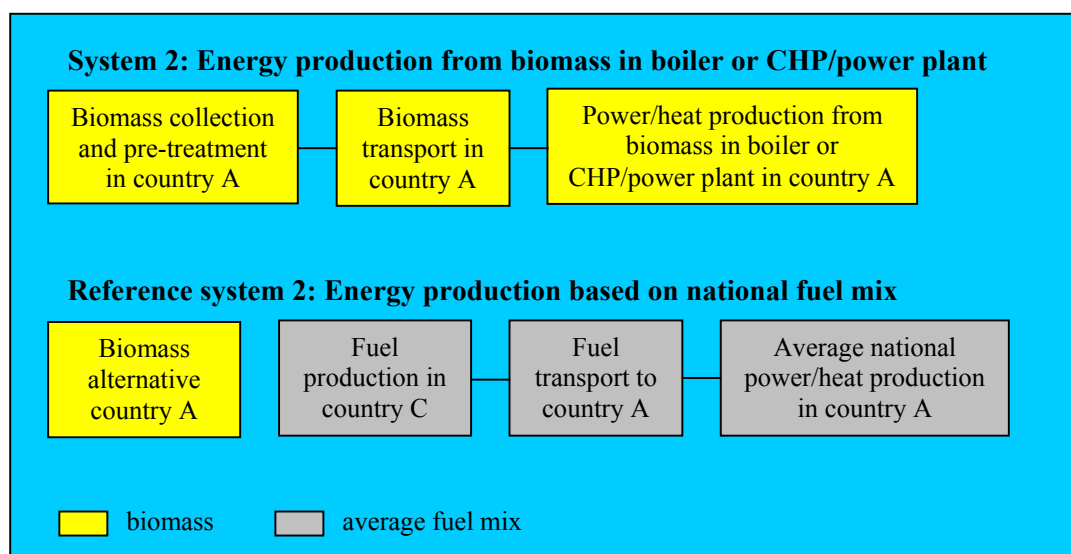


Figure 2-2: Energy production from biomass in the country where biomass is produced with reference system

Country A = biomass exporting country (Canada/Malaysia)

Country C = coal/gas/oil producing country, can be country A

System 2 investigates the option to use the biomass in the country where it is produced in a boiler or CHP/power plant fuelled with 100% biomass. The reason to include these systems in this study is to investigate the overall efficiency of a biomass trade system from a broader point of view. From the perspective of avoiding CO₂ emissions, it might be more efficient and environmental benign to use the biomass in the country where it is produced/becomes available in a boiler or CHP/power plant fuelled on biomass instead of transporting it to the Netherlands and use it as co-firing fuel. In Canada, basically 2 options can be distinguished. The pellets can be used as fuel in a stand-alone CHP plant. Pellets can also be used as a fuel for boilers to

produce heat in detached houses. Another option is to use the forestry residues (bark, sawdust and shavings) directly in the place where they are produced (chip mills or sawmills), replacing the electricity required in the production of chips, timber wood. This option is not considered in this study. It must be noted that the electricity in Canada is generated to a large extent by hydro-electric plants, so the emission reduction potential will be limited. In Malaysia, it is not probable that biomass is used to produce heat for district heating. There might be a heat demand in the industry, but this is not considered in this study. For Malaysia, we consider production of electricity in a stand-alone biomass fired power plant.

2.3 Mass and energy balance

The first step in the LCI is to set up a mass balance, which is the basis for the energy balance and is also relevant for quantifying the emissions. An important element for biomass import in the mass balance is to account for dry matter losses occurring in the biomass supply chain. The moisture content of the biomass is another important parameter, because it changes along the chain and thus influences the total required capacity of logistic facilities.

The energy balance is set up to determine primary energy inputs for each system component in order to calculate the amount of primary energy, which can be avoided by the replacement of coal by biomass. The net avoided primary energy and avoided emissions can be attributed to a GJ of biomass or a kWh of produced electricity/heat. The formulas and assumptions made to calculate the avoided primary energy are discussed below.

Net avoided primary energy

In order to calculate the net avoided primary energy per unit biomass energy for co-firing, the energy content of the avoided coal should be corrected for:

- Primary energy use to produce and transport the biomass.
- Effects of co-firing on the electric efficiency
- Primary energy involved with avoided operations that would have taken place if the biomass had not been co-fired.

Primary energy inputs for biomass production and logistics

The energy inputs for the production, pre-treatment and transport of the biomass are determined and normalised with respect to the amount of dry tonnes of biomass before conversion into electricity. For residues (e.g. palm kernel shells and the raw material for pellet production), it is reasonable not to account for energy use and emissions caused by the cultivation/harvesting of the main crop, because the residues can be considered as a waste stream. On the other hand, it can also be argued that the energy use for the residues should be accounted for by allocation, since the residues are effectively used. In this study, both cases are included in the calculations. As mentioned before, allocation of energy use and emissions is performed on mass base.

Co-firing biomass in the CHP plant

The electricity and heat production is calculated assuming a certain co-firing share of biomass on mass base. When co-firing biomass, the electricity and heat output can decrease for several reasons:

- The power consumption of coal mills might increase when biomass is added to the coal mixture, because biomass has a different structure than coal (which affects the sizing) and eventually by the higher total mass throughput when co-firing (see last point).
- Biomass has a different chemical composition, so the gas stream might have a different heat exchange coefficient, influencing the boiler efficiency.
- With increasing biomass portion, a slight decrease of carbon burnout could occur (Hamelinck and Faaij 2001).
- The biomass has a lower calorific value than coal and therefore the total mass input has to be increased to keep the heat input equal to 100% coal when co-firing biomass. This compensation can often be executed at low co-firing shares. However, at higher co-firing shares, relatively more air is required to burn the fuel mix in comparison to coal only. This causes a higher throughput of flue gas through the boiler, which may result in a lower heat transfer for steam production (more heat will be lost through the chimney). This effect will depend on the design of the boiler. When the boiler is designed for a maximum gas volume, the fuel input must be reduced, which results in a lower steam production. This is also referred to as de-rating and will be discussed in detail in section 3.4.2 for the coal plant considered.

Avoided operations

Operations that are avoided when co-firing biomass include mining and transport of the avoided coal and burning/decomposition of the biomass. When biomass is disposed at a landfill when it is not exported for energy purposes, CO₂ and CH₄ will be formed during decomposition. The latter can be collected to produce electricity in a gas-engine and this is accounted for in the net avoided primary energy (landfill gas utilisation). When palm kernel shells are used for fodder production, the primary energy use to produce and transport an equivalent amount of an alternative resource for fodder should be accounted for.

To calculate the net impact (in energy terms) of co-firing biomass, the eventual loss in electricity/heat production caused needs to be expressed in net terms per unit of co-fired biomass. The avoided primary energy per unit biomass energy in comparison to a conventional coal fired power plant (reference system 1a) can be calculated by means of the formula below:

$$\eta = \frac{\left(\frac{(\%_{biomass} \times E_{coal})}{\eta_{coal\ supply}} - \frac{(E_{coal} \times \eta_{e,coal} - E_{cofiring} \times \eta_{e,cofiring})}{\eta_{e,average}} - E_{bio\ supply} - E_{alternative} \right)}{E_{biomass}}$$

in which:

η = net avoided primary energy per unit biomass energy (MJ_{prim}/MJ_{biomass})

$\%_{biomass}$ = biomass co-firing share on energy base

E_{coal} = energy input 100% coal (MJ_{prim})

$E_{cofiring}$ = energy input co-firing (coal and biomass) (MJ_{prim})

$\eta_{coal\ supply}$ = efficiency coal production and transport

$\eta_{e\ coal}$ = electric efficiency 100% coal

$\eta_{e\ cofiring}$ = electric efficiency co-firing

$\eta_{e, average}$ = average electric efficiency Dutch fuel mix

$E_{biosupply}$ = energy required for the production and transport of the biomass (MJ_{prim})

$E_{alternative}$ = energy use/production of alternative fate biomass, which is either dumping at landfills or fodder production (MJ_{prim})

$E_{biomass}$ = biomass input co-firing (MJ_{bio})

The first term in the numerator represents the energy content of the avoided coal when co-firing, including coal mining and transport. The second term gives the energy penalty caused by lower efficiency when co-firing and de-rating. When de-rating is applied at the considered plant, the fuel input (and hence the energy input) is reduced in comparison to the 100% coal situation, decreasing the net avoided primary energy. When the average Dutch power and heat production are used as reference (reference system 1b), it is assumed that an equivalent amount of electricity and heat should be delivered by the Dutch electricity production system and gas fired boilers, respectively. In formula:

$$\eta = \frac{\left(\frac{E_{cofiring} \times \eta_{e,cofiring} \times \%_{biomass}}{\eta_{e,average}} + \frac{E_{cofiring} \times \eta_{th,cofiring} \times \%_{biomass}}{\eta_{th,average}} - E_{biosupply} - E_{alternative} \right)}{E_{biomass}}$$

in which:

η = net avoided primary energy per unit biomass energy ($MJ_{prim}/MJ_{biomass}$)

$E_{cofiring}$ = energy input co-firing (coal and biomass) (MJ_{prim})

$\eta_{e,cofiring}$ = electric efficiency co-firing

$\eta_{th,cofiring}$ = thermal efficiency co-firing

$\eta_{e,average}$ = average electric efficiency Dutch fuel mix

$\eta_{th,average}$ = average thermal efficiency

$\%_{biomass}$ = biomass co-firing share on energy base

$E_{biosupply}$ = energy required for the production and transport of the biomass (MJ_{prim})

$E_{alternative}$ = energy use/production of alternative fate biomass, which is either dumping at landfills or fodder production (MJ_{prim})

$E_{biomass}$ = biomass input co-firing (MJ_{bio})

When the biomass is not transported to the Netherlands for co-firing purposes, but is used in the country where it is produced as a fuel in biomass dedicated CHP plant, the equation given below is used to calculate the net avoided primary energy per unit biomass energy.

$$\eta = \frac{\left(\frac{E_{biomass} \times \eta_{e,CHP}}{\eta_{e,average}} + \frac{E_{biomass} \times \eta_{th,CHP}}{\eta_{th,average}} - E_{biosupply} - E_{alternative} \right)}{E_{biomass}}$$

in which:

η = net avoided primary energy per unit biomass energy ($MJ_{prim}/MJ_{biomass}$)

$E_{biomass}$ = biomass input ($MJ_{biomass}$)

$\eta_{e,CHP}$ = electric efficiency biomass dedicated CHP

$\eta_{th,CHP}$ = thermal efficiency biomass dedicated CHP

$\eta_{e \text{ average}}$ = average electric efficiency Dutch fuel mix

$\eta_{th \text{ average}}$ = average thermal efficiency

$E_{\text{biosupply}}$ = energy required for the production and transport of the biomass (MJ_{prim})

$E_{\text{alternative}}$ = energy use/production of alternative fate biomass, which is either dumping at landfills or fodder production (MJ_{prim})

When considering a power plant fuelled with biomass as alternative system, the net avoided primary energy per unit biomass energy can be calculated with this formula as well, using the electric efficiency of the CHP plant without heat production and setting the heat terms at 0. Moreover, the average electric efficiency of the country where the biomass is produced must be used. For the calculation of the net avoided primary energy when using pellets to produce heat in household boilers (Canada), this equation can also be applied, using the thermal efficiency of such boilers and the average Canadian electric efficiency and setting the electricity terms at 0.

2.4 Emissions

Emissions are quantified and attributed to a kWh power/heat. For a power plant fired with 100% coal, all the emissions can be attributed to the coal. In the co-firing systems and the systems in which heat/power is produced with 100% biomass, emissions are determined for a kWh of power and heat from biomass ($\text{kWh}_{e,\text{bio}}$ and $\text{MJ}_{th,\text{bio}}$), because after all, we focus on the emissions of a “green kWh”. Hereto, it must be determined which part of the produced power/heat is attributed to biomass in order to define a kWh from biomass. This is done on the basis of the energy input. Allocation is required to assess which part of the emissions is attributed to heat and which to coal when the considered system is a CHP plant. As mentioned earlier, emissions occurring at CHP plants are allocated to the exergy content of heat and power. In formula:

$$X_E = \frac{E}{E + \beta H} X \quad X_H = \frac{\beta H}{E + \beta H} X$$

in which:

X_E = emission of compound X allocated to electricity production

X_H = emission of compound X allocated to heat production

X = total emission of compound X

E = net electricity production of the CHP plant (enthalpy basis)

H = net heat production of the CHP plant (enthalpy basis)

β = the ratio between the exergy and enthalpy of the heat produced. For electricity this ratio is unity. For heat flows the value is much lower depending on the temperature of the steam. Typical values for β are 0.4 for process steam and 0.2 for hot water in district heating systems (Blok 2001).

In the figure below, the different conversion systems with the formula to calculate the emissions occurring during conversion are given.

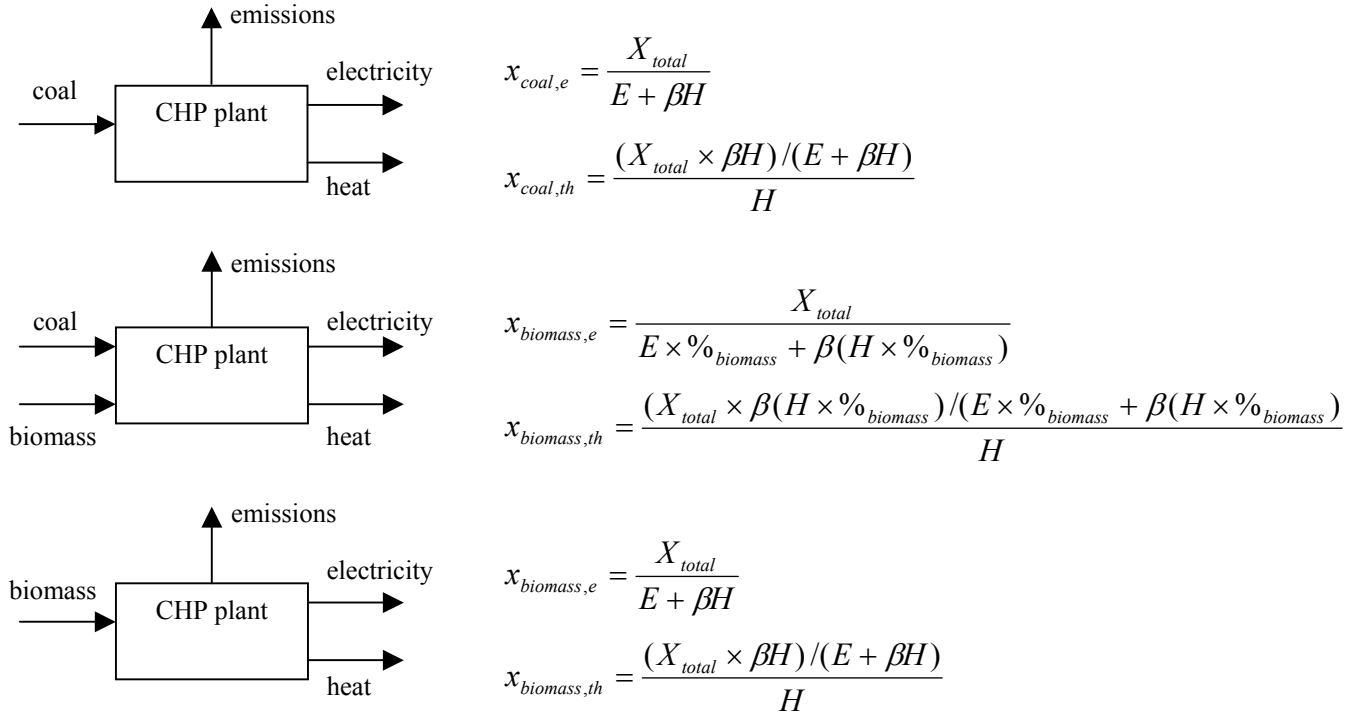


Figure 2-3: Emissions related to different conversion systems

$x_{coal,e}$ = emission of compound X for 100% coal allocated to electricity (g/kWh_e)

$x_{coal,th}$ = emission of compound X for 100% coal allocated to heat (g/MJ_{th})

$x_{biomass,e}$ = emission of compound X allocated to electricity produced from biomass (g/kWh_e)

$x_{biomass,th}$ = emission of compound X allocated to heat produced from biomass (g/MJ_{th})

X_{total} = total emission of compound X (g)

E = net electricity production of the CHP plant (kWh_e)

H = net heat production of the CHP/heat plant (MJ_{th})

β = ratio between the exergy and enthalpy of the heat produced

$\%_{biomass}$ = biomass co-firing share on energy base

In order to calculate the net emissions per kWh, the emissions from avoided operations should be subtracted from the emissions occurring during production, transport and conversion of the biomass. When palm kernel shells are applied as resource for fodder production, the emissions related to the production and transport of an alternative resource should be added to the emissions occurring during production, transport and conversion of the biomass. Below, the emission of each compound in the various stages of the chain and of the avoided operations is discussed.

CO₂ emissions

CO₂ emissions occur in various stages: during mining and transport of coal, collection and transport of biomass, but mainly during combustion of coal/biomass. CO₂ emissions caused by either the use or the decomposition of biomass are assumed to be zero, since it can be argued that in both cases the released CO₂ makes part of the short-rotation cycle; it is absorbed by the trees/crop again in a next growth cycle. The only CO₂ emissions that are attributed to biomass, are those caused by fossil fuel burning for biomass collection and transport.

CH₄ and N₂O emissions

Methane and N₂O emission factors are less well known than CO₂ emission factors. From methane emissions within the coal fuel cycle, the emissions associated with the mining of coal are by far the largest; estimates of methane emissions from conventional coal combustion are much smaller and therefore not accounted for in this study. It should be kept in mind that methane emissions for mining are highly site specific. In particular, methane emissions from opencast mining are at least an order of magnitude smaller than underground mining (CIEMAT 1999). Essent Energie purchases its coal mainly from opencast mines (de Vos 2002). The methane emission during anaerobic decomposition of biomass when the biomass is not applied as fuel (or to produce a fuel) can be significant as well. When biomass is used for co-firing, these emissions are avoided.

N₂O emissions during transport and power production are generally very low. N₂O emissions might play a role in the production of biomass; they occur during fertilizer production and can occur during denitrification of nitrogen in the soil.

NO_x emissions

In general, the majority of NO_x emissions (NO and NO₂) occur during power production. Unfortunately, NO_x emissions caused by power production are very hard to predict, since they depend not only on the nitrogen content and volatility of the fuel. Measurements of NO_x emissions during co-firing tests at the Naantali power plant in Finland showed that the boiler and operating conditions (load and stoichiometric ratio) have a strong influence on emissions as well.

If the temperatures in the boiler stay sufficiently low (limiting the formation of thermal NO_x) the NO_x emissions can be reduced by co-firing, since the nitrogen content of the biomass is generally lower than for coal. A high-volatile matter content of the fuel (biomass has a significantly higher volatile matter content than coal) combined with low NO_x combustion techniques can reduce the NO_x emissions formed. The principle of low NO_x burners in reducing NO_x emissions is based on the effect that by staging the addition of air, fuel is devolatilised under conditions of low stoichiometry, promoting the conversion of fuel nitrogen to molecular nitrogen. The higher the volatile content of the fuel, the better, because nitrogen, bound to volatiles, is released already in the burner zone, so that NO_x formation can be controlled and it can be controlled (Kostamo 2002). Moreover, low NO_x burners will also probably reduce the formation of thermal NO_x formation.

Since no data of measurements of NO_x emissions when co-firing are available for the plant considered in this study, NO_x emissions were estimated by means of a simple model. Aspen plus is used to estimate the difference between NO_x emissions with 100% coal and co-firing. The distribution of N between (NO, NO₂ and N₂O) is calculated, assuming a chemical equilibrium in the boiler. It is assumed that NO_x emissions are solely due to the amount of fuel-bound nitrogen in the biomass (nitrogen in the air is modelled inert), just like Mann (2001) assumed in her study on biomass co-firing in coal plants. This is a highly simplified approach leading only to order of magnitude estimates; it is however a manageable approach given the absence of data. Full combustion modelling for the considered plant is out of the scope of this study though.

SO₂ emissions

Nearly all sulphur in the fuel is oxidised to SO₂ during combustion. Between 85-90% of the formed SO₂ is converted into gypsum (CaCO₃ reacts with SO₂ into CaSO₄ and

CO₂) in the flue gas desulphurisation unit (FGD) and the remaining SO₂ is emitted into the atmosphere. A small fraction of the SO₂ is converted into SO₃, which is to a large extent reabsorbed to form sulphates with the alkali metals in the fly ash. Part of the SO₂ also migrates to the fly ash, to what extent depends on the alkali earth metal content of the fly ash (Hamelinck and Faaij 2001).

SO₂ emissions are a function of the sulphur content in the fuel and the efficiency of the flue gas desulphurisation unit. When co-firing biomass, it can be expected that the change in SO₂ emission at the power plant will mainly depend on the sulphur content of the biomass. In this study, it is assumed that the change in SO₂ emission in comparison to the basic situation (100% coal) is linearly dependant from the fuel sulphur content.

Particulate emissions

Particulates emissions occur in various stages: during mining and transport of coal and limestone, collection and transport of biomass, during pelletisation and during combustion of coal/biomass. It must be noted that the emission of particulates is not clearly defined; each database/literature source uses other definitions. In GEMIS, the emissions of particulates are presented, whereas SIMAPRO gives the emission of dust, which is further classified in coarse and PM 10 (mobile/stationary). In this study, particulates are not further classified in the size of the particles; all particles, both coarse and fine, are accounted for.

The change in particulate emissions occurring during power generation when co-firing biomass in comparison to the reference situation of 100% coal was calculated by the BIJSTER model developed by the KEMA. By means of this model, several emissions occurring in a coal-fired power plant can be predicted on the basis of coal and biomass composition and quantities. A co-firing share of 10% biomass (on energy basis) and a mixture of different biomass sources, among which wood and citrus pellets, palm kernel shells, and rest products of cacao, is assumed for these calculations. This calculation is used to estimate the particulate emission occurring during co-firing of wood pellets and palm kernel shells (no distinction is made). It is assumed that the change in particulate emission is 100% attributed to biomass.

Cd, Hg and other heavy metal emissions

Heavy metals are emitted throughout the entire chain, to the air, water and in the form of solid waste (ash). As mentioned earlier, emphasis in this study is put on the conversion part. The electrostatic precipitators (ESP's), where fly ash is partly removed from the flue gas and the FGD are the main sinks for trace elements, among which heavy metals. Trace elements can be classified into 3 groups. Category 1 heavy metals (e.g. Al, Ca, Fe and Mg) do not vaporise during combustion (Meij 1994).

Heavy metals from category II (among which As, Cd, Cu, Pb, Se and Zn) volatise during combustion, but condense on the fly ash particulates and are removed in the electrostatic precipitators. The content of several heavy metals is further reduced in the FGD by the removal of particulate matter, to which several heavy metals are adsorbed. Mercury, a category 3 element (those elements are mainly present in the gas phase), vaporises during combustion and condenses within the installation (in the ESP and FGD), but a great part is emitted to the atmosphere.

The distribution of the heavy metals between bottom ash, fly ash and air will not change when co-firing biomass, so the emission of heavy metals with co-firing biomass is completely depending on the heavy metal content of the biomass in

comparison to coal. So heavy metal emissions are assumed to be linearly dependent on the heavy metal content of the fuel.

2.5 Nutrients

When biomass is applied as (co-firing) fuel, nutrients (N, P, K, Ca, Mg) are removed from the system in the country of origin. These elements are needed for the growth of the plants that form the feedstock of biomass utilization (Narodoslawsky and Obernberger 1996).

Nitrogen is emitted to the air during combustion of the biomass. P, K, Ca and Mg are mainly encountered in the fly and bottom ash in the form of P_2O_5 , K_2O , CaO and MgO . It is possible to close the nutrient cycle by returning the ash to the fields, where it can be applied as fertilizer. The problem is however, that besides nutrients, the ash also contains heavy metals. The highly volatile heavy metals (like Cd, Hg, Pb and Zn) are mainly encountered in the cyclone fly ash and the filter fly ash. Especially cadmium poses a risk to the use of wood ash in agriculture. The least volatile heavy metals (like Co, Ni, Cr and V) are concentrated in the bottom ash and the cyclone fly ash. The main problem is the cyclone fly ash, which contains relatively high amounts of heavy metals (especially Cd), but also contains relatively large amounts of nutrients. Disposal of contaminated cyclone fly ash causes a significant loss of nutrients and moreover, is a considerable economic burden to biomass utilization (Narodoslawsky and Obernberger 1996).

The ash from coal-fired power plants is generally applied as resource in construction material. However, too much biomass ash can disturb this market. For ash utilization, it is relevant whether biomass is applied as fuel in dedicated plants or as co-firing fuel in coal-fired plants. When biomass is co-fired in coal fired plants, the ash will also be contaminated with heavy metals originating from the coal. In that case, return of the ash to the fields seems undesirable. Since clean biomass like wood pellets and palm kernel shells generally contain small quantities of heavy metals, the recycling of ash from biomass combustion plants seems more feasible.

3 System components

In this chapter, the different fuel chains and chain components considered are described in detail, including the relevant data required to perform the LCI. As mentioned in the previous chapter, 3 categories of data distinguished. Case specific data delivered by companies involved in the biomass supply are the composition of the fuels, the technical data of the pellet production process and the technical data and emissions of the conversion systems, which are given in the so-called MER report set up for biomass co-firing (Boudewijn and Koopmans 2002). Data from publications or quotes from experts are mainly used for technical data on biomass production and logistics. The LCA databases considered in this study are GEMIS and SIMAPRO 5.0. These databases contain many industrial and agricultural processes, transport systems and products (fuels, agricultural and industrial products). For each process, the resource use and emissions are reported. Emissions and resource use include 3rd order energy inputs and emissions caused by production of capital goods and fuels. Data from LCA databases are mainly used for the emissions of biomass and coal production and transport and also for the emissions of electricity and heat production in the Netherlands and Canada. International energy statistics from the IEA are used for the average efficiency of electricity and heat production in the considered countries.

3.1 Pellets production in Canada

In several regions in Canada, large amounts of residues become available at chip mills and sawmills, among which bark, sawdust and shavings. These residues can be used to produce pellets by a densification process. Pellets are a high quality fuel, since the energy density is very high and they can immediately be substituted for coal (Suurs 2002). Due to the high energy density, pellet transport is more efficient and cheaper than transport of bulky biomass like chips. Moreover, transport and storage of pellets is safer and the energy content does not change during storage, because decomposition does not occur. Pellets are used as fuel for large electricity and heat utilities (for co-firing purposes) and also for small heating systems in households. One of the suppliers of wood pellets is Fulghum Fiber Fuels Ltd Georgia USA. In 2001, the first load of 7132 metric tonnes wood pellets was delivered. The total logistic chain is given in figure 3-1:

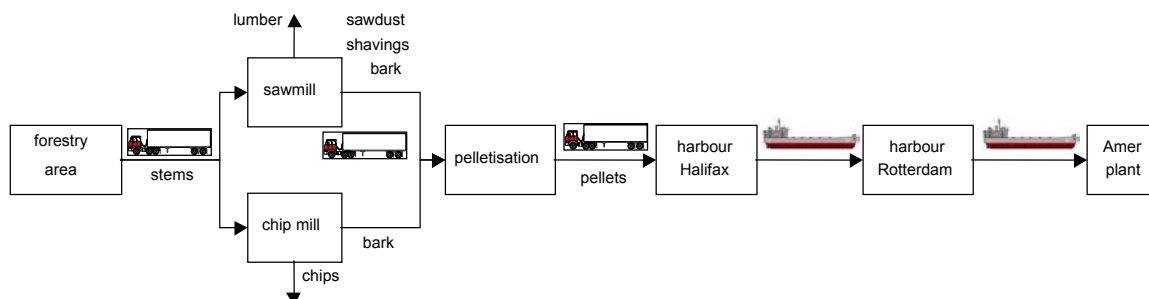


Figure 3-1: Pellet production and transport

In summary, wood cultivated for timber or chip production is transported to saw/chip mills, where bark, sawdust and shavings become available. These residues are transported to a plant and converted into pellets, which are transported to the Netherlands by truck, ship and barge and used as co-firing fuel in a coal plant. Below, each component is discussed extensively.

3.1.1 Production and logistics of wood and forestry residues

Wood (spruce, fir, pine and birch) is extracted from a large forestry area near Truro, Nova Scotia. The harvest area is cut clear completely, after which the area is checked on natural growth. Only if necessary, additional trees are planted (Essent Duurzaam 2001). It is assumed no energy is required for tree cultivation.

Harvesting is performed mechanically by harvesters (de Vos 2002), which fell, delim and buck the trees right in the stump area. A forwarder carries the logs to the road and loads it to a truck, ready for transport. The best trees are delivered to sawmills and the less qualitative stems are transported to chip mills by truck with a load of approximately 35 t (Stadig 2002). The average distance between production sites and the Mactara sawmill, the largest supplier of residues, is estimated at 75 km. The Keyword chip mill, a large supplier of sawdust to the pellet production plant, is located 50 km from the production sites (Essent Duurzaam 2001). At the saw/chip mill, the trees are debarked by a drum debarker, after which the bark is crushed by a hammer mill. The 300 kW_e drum debarker has a capacity of 180 m stem/minute (t/min) (Stadig 2002). The diameter of the stems varies between 9 and 25 cm, an average of 15 cm is assumed. The density of the stems is estimated at 0.8 tfw/m³, assuming a bulk density of 0.5 tdm/m³ for spruce and pine (Patterson 1988) and an average moisture content of 60% of the dry mass (Forest Products Laboratory 1999). The residues from the sawmills (sawdust, bark and shavings) and the chip mills (bark) are transported to the pellet plant by trucks with a load of 30 t. The average transport distance between the chip mill and the pellet plant is estimated at 75 km (Stadig 2002). The sawmill is located very close to the pellet plant, so additional transport of residues from the sawmill is not accounted for.

It is unknown how much wood is exactly harvested to produce the resource quantities given in table 3-2, since the mass balance of the sawmill (Mactara) is not available. The amount of wood to be harvested is estimated using the total amount of bark required to produce 1 tdm of pellets (see table 3-2) and the bark content of the stems (0.14 tfw bark/tfw stems) bark reported by Keyword in (Essent Duurzaam 2001). It is assumed that the stems delivered to Mactara according this calculation will produce the quantities of sawdust and shavings required for pellet production. Biomass losses occurring during loading and transport of the wood to the mills are assumed to be 0.

Energy use and emissions

Data for energy use of wood harvesting of stems and residues are given in table 3-1. No data for diesel use of Canadian trucks were available, so road transport of wood, residues and pellets is assumed to be performed with trucks with a capacity of 35-40 t and a diesel consumption of 0.45 l/km, which is based on Swedish trucks reported in (Suurs 2002). For the emissions occurring during harvesting and forwarding the logs, data given in GEMIS for a process describing the cutting of pine logs are used (see appendix I). Emissions occurring during truck transport are calculated by means of

emission data given per tkm in GEMIS for a truck plus trailer with capacity of 32-40 t and a pay load of 27 t (see appendix I).

Table 3-1: Energy use and capacity of biomass harvest^a

Single-grip harvester^b	
Capacity (m ³ /productive machine hour)	15- 20
Diesel use (l/m ³)	1.5
Hydraulic oil consumption (l/m ³)	0.03-0.04
Chainsaw oil consumption (l/m ³)	0.025-0.04
Forwarder^b	
Capacity (m ³ /productive machine hour)	20
Diesel use (l/m ³)	0.7-0.8
Hydraulic oil consumption (l/m ³)	0.01-0.02

^a Allocation of energy use and emissions occurring during harvest and transport of the stems is done by multiplying the total energy use and emissions with the bark content of the stems, which is 0.136 tfw bark/tfw stems (Essent Duurzaam 2001).

^b These values represent capacity and consumption of diesel and lubricants for single-grip harvesters and forwarders for Swedish conditions (Athanasiadis 2002). No data for Canadian harvesters/forwarders were available, but in the harvest area considered in this study, the same machinery is used.

3.1.2 Pellet production

Pellets are produced at Fulghum Fibre fuels. The annual pellet production is about 100 kt/yr, which requires 169 kt_{48%}/yr of residue-mix and 39 kt_{50%}/yr of sawdust for heat production. The pellets produced consist of circa 65% bark and 35% sawdust/shavings. The moisture content of the pellets is about 6-8% and the pellet diameter and length are 7 mm and 20-40 mm, respectively. In the table below, the resources to produce 100 kt pellets are given:

Table 3-2: Resources to produce 100 kt pellets

Resource	Moisture content	Supplier
72 kt bark	57%	Mactara sawmill
41 kt sawdust	50%	Mactara sawmill
27 kt shavings	17%	Mactara sawmill
22 kt bark	50%	Keyword chip mill
46 kt bark	50%	Other mills

The pelletisation process involves several steps. First, the residues are crushed by a coarse hammer mill, after which they are dried by dry air with a temperature of 650°C to a moisture content of 6%. Stones are removed and the dried residues are crushed again by two fine hammer mills, which make them ready for compression under high pressure and temperature. The final step is cooling and sieving, after which the pellets can be transported. It was estimated that dry matter losses during pelletisation are roughly 1%. The thermal (steam and hot dry air) requirements in the process are fulfilled by a boiler, which is fired with sawdust. In addition, 2000 kW electricity is required in the pelletisation process (Essent Duurzaam 2001).

Energy use and emissions

The primary energy use for the electricity requirement is calculated by means of the average Canadian electric efficiency. The diesel and lubrication oil for internal transport and loaders given in (Kjellström 2002) are used (respectively 11 and 2.2 kWh for 1 tonne of pellets). The emissions caused by burning the sawdust are estimated by means of emission data for a furnace fuelled with wood presented in SIMAPRO (see appendix II). Dust emissions occurring during pellet production are unknown, but are strongly dependent on the installation and filters used. Indirect emissions related to the generation of the required electricity are calculated by means of the emission data for the average Canadian electricity production presented in GEMIS (see appendix II).

3.1.3 Pellet transport to conversion plant

Pellets are transported to the harbour of Halifax over a distance of 60 km by trucks with a capacity of 35 t. In the scenario of pellet use as fuel in a central CHP plant, it is assumed pellets are transported by truck over a distance of 100 km. When the pellets are supplied to households for local heat systems (pellet boilers), the transport distance is expected to be even larger: a value of 200 km is assumed.

At the harbour, the pellets are stored in large silos with a total capacity of 144,000 m³ and then loaded to a sea ship, which takes the load to Rotterdam. The capacity of the ocean vessel is 9000 tonne. The distance between Halifax and Rotterdam is 2705 sea miles (5000 km). In Rotterdam, the cargo is unloaded and subsequently, the pellets are transferred to barges, which deliver the biomass to the Amer power plant, located 52 km from the Rotterdam harbour. At this moment, there is a temporal biomass deposit in Waspik, from where the biomass is transported to the Amer plant by truck. However, biomass storage capacity is constructed beside the power plant, so in the nearby future, the biomass can directly be transported to the power plant. In this study, it is assumed biomass is directly transported to the Amer plant.

Energy use and emissions

The diesel consumption of a truck for pellet transport with a maximum capacity of 35 t (80 m³) is 0.45 l/km (Suurs 2002). Emissions for truck transport are calculated by means of emission data given per tkm in GEMIS for a truck plus trailer with capacity of 32-40 t and a pay load of 27 t (see appendix I). During loading of the pellets to the ship, dust emissions were observed (Essent Duurzaam 2001), but these are not quantified and will also depend on the measures taken.

The average of the fuel consumption of two ocean vessels transporting conventional bulk with a capacity of 21300 and 7000 m³ (corresponding to 12780 and 4200 t pellets) is used for the vessel transporting pellets. Fuel consumption for the return trip is not accounted for, since this ship will transport another bulk good on the way back (Essent Duurzaam 2001). For the barges transporting the biomass from Rotterdam to the Amer plant, diesel consumption is assumed to be 0.10 g/tkm according to data for barges presented in (Kaltschmitt and Reinhardt 1997). It is assumed that the barge returns empty to Rotterdam, so the fuel consumed on the way back should be accounted to biomass transport. Fuel consumption during freights of non-dedicated transports is assumed to be 65% of the full load consumption (Suurs 2002).

Emissions caused by ship transport (both ocean and inland) presented in SIMAPRO are used (see appendix I), although these data are not really up-to-date (they refer to the time period 1990-1994).

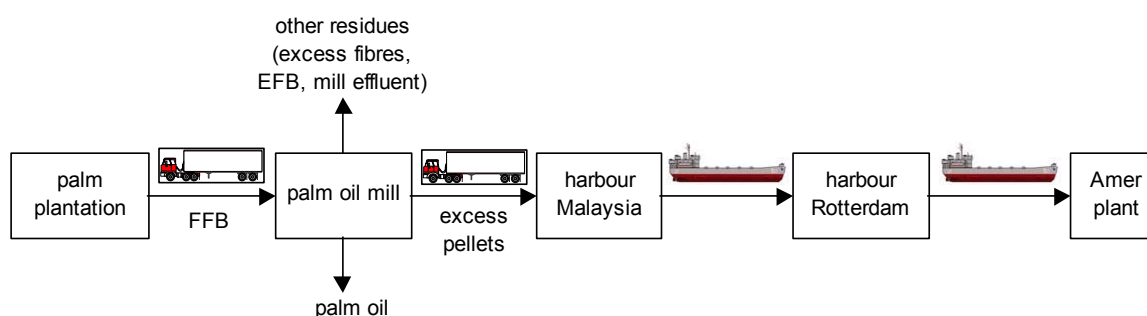
Table 3-3: Energy use and capacity ocean vessel and barge transporting pellets

Ocean vessel A^a	
Capacity (m ³)	21300
Fuel use (t HFO/km)	0.03
Ocean vessel B^a	
Capacity (m ³)	7000
Fuel use (t HFO/km)	0.015
Average fuel consumption pellet vessel (kg HFO/tkm)	0.003
Barge (inland transport)	
Capacity (t) ^b	2000-2200
Fuel use (kg diesel/tkm) ^c	0.01

^a (Suurs 2002)^b (de Vos 2002)^c (Kaltschmitt and Reinhardt 1997)

3.2 Palm kernel shells from Malaysia

Malaysia is the major producer of palm oil in the world (Husain et al. 2002). During the production of palm oil, several residues become available, among which fibre, (palm kernel) shells, the empty fruit bunches and palm oil mill effluent. In general, the fresh fruit bunch (FFB) contains (by weight) about 21% palm oil, 6-7% palm kernel, 14-15% fibre, 6-7% shell and 23% empty fruit bunches (Husain et al. 2002). The major part of the fibres and shell is applied as fuel in boilers to produce steam and electricity for the palm oil production process. The total electrical power generation capacity in the palm oil industry in Malaysia for own milling process consumption is 250 MW_e, representing only 20% of the potential energy of the solid wastes (Shamsuddin 2002). Much of the residues are wasted by pile burning in the open air with attendant air pollution, dumped in areas adjacent to the mill, or utilized as manure in the palm oil plantation (Husain et al. 2002). An alternative for these resources, which does not require additional investment, is export for energy purposes or fodder production. Essent Energie recently started to import palm kernel shells. The total logistic chain is given in figure 3-2:

**Figure 3-2: Logistics palm kernel shells**

An oil palm starts to produce three years after field planting (Mahlia et al. 2001). Energy inputs during cultivation are given in the table below.

Table 3-4: Energy input palm oil cultivation (Wambeck 2002).

Energy input (GJ/ha/yr)	19.2
Fertilizers ^a	11.2
Pesticides, herbicides, rat baits	0.8
Machinery	5.14
Others	2.06

^a 3 rounds a year or equivalent to twice rate of 650 kg N/ha/yr. Extra fertilizer application might be necessary when the palm kernel shells would have been applied as fertilizer if not exported. However, it is unknown whether the excess of palm kernel shells is indeed returned to the fields and if so, how much would be applied as fertilizer. So in this study, no additional energy is accounted for.

The FFB are harvested manually and transported to the mill located within a range of 1-10 km from the plantations by trucks with a load of 1-4 ton (Shamsuddin 2002).

The average FFB yield is approximately 25 t/ha/yr (Mahlia et al. 2001).

At the mill, the fruit bunches are stored for several days. Palm oil is extracted from the mesocarp and kernel of the matured fruits on the fresh fruit bunches (FFB). First, the fresh fruit is cooked before digested and pressed by using steam (sterilisation), after which the sterilised fruits are separated from the sterilised bunch stalks. Then the fruit is reheated (digestion) and the oil is extracted by pressing. Finally, the crude oil is extracted and the nut and fibre is separated. The electrical and steam requirements of the palm oil production are 20-25 kWh and 0.73 t steam per tonne of fresh fruit bunches, respectively. The boilers are fuelled with shells and fibre. According to Shamsuddin (2002), between 50 and 70% of the available shells are required for this energy requirement. In this study, it is assumed that 60% of the available shells are being used as boiler fuel and the remaining 40% can be either exported or burned/dumped/ applied as fertilizer. This number is required to calculate the amount of FFB to be harvested to produce 1 tonne excess palm kernel shells.

The palm kernel shells, which become available at mills in the entire country and are exported, are transported to the harbour (Port Klang and Kuantan port) by small trucks with a capacity of 3-10 tons. An average distance of 100 km is assumed. The same logistics are assumed when the palm kernel shells are applied as fuel in a central electricity plant in Malaysia.

At the harbour, the shells are loaded to an ocean vessel transporting bulk material of the type Panamax (de Vos 2002). The maximal capacity of this vessel is 60 kt and shells are loaded in quantities of minimal 10 kt. The harbours are located in proximity of Singapore. The distance between Singapore and Rotterdam is 8350 sea miles (around 15500 km). In Rotterdam, the cargo is unloaded and transferred to inland ships, which deliver the biomass to the Amer power plant.

It is assumed that dry matter losses are negligible along the chain. In a study of Suurs (2002) considering different biomass logistic chains, it is assumed that dry matter losses only occur as a result of decomposition when biomass is chipped and has a moisture content above 20%. Considering the moisture content of palm kernel shells (approximately 7%), this seems justified.

Energy use and emissions

The emissions caused by production and application of fertilizers are reported in (Kaltschmitt and Reinhardt 1997) and are given in appendix I. No specific data on energy use and emissions for truck transport in Malaysia are available. Data for a 6 wheel diesel truck with a maximum load of 5.3 t used to transport agricultural residues in Thailand were used (Dick 2000). Average diesel use is between 0.25 l/km

(unloaded) and 0.29 l/km (loaded). Emissions for light trucks driving in rural areas give in GEMIS are used (see appendix I).

For the ocean vessels used to transport palm kernel shells, the HFO consumption of 40 kt vessels transporting wood chips between the US and Japan is used, which amounts 0.0022 kg/tkm (Schonewille 2002). Emissions from ocean vessels presented in SIMAPRO are used (see appendix I). The energy use and emissions of barges have already been discussed in the previous paragraph.

3.3 Composition of fuels

The composition of wood pellets, palm kernel shells and coal is given in table 3-5.

Table 3-5: Composition fuels considered in this study (ar = as received, db = dry basis)

Resource	Wood pellets	Palm kernel shells	Coal mix
LHV (MJ/kg, ar)	18.03 ^a	17.13 ^d	23 ^e
Proximate analysis (wt%, ar)			
Moisture content	5.16 ^a	7 ^d	12 ^e
Ash	2.01 ^a	5.8 ^d	13.2 ^e
Volatiles	72.14 ^a	63 ^c	
Ultimate analysis (wt%, ar)			
C	50.1 ^b	42 ^d	60 ^e
H	5.5 ^b	6.4 ^d	2.9 ^e
O	43.6 ^b	35.7 ^d	8.0 ^e
N	0.27 ^b	2.7 ^d	1.2 ^e
S	0.02 ^a (0.03 ^b)	0.24 ^d	0.7 ^e
Elemental analysis (ppm, db)			
As	<0.5 ^a (8.9 ^c)	4.2 ^d	0.1 ^e (inc. TI)
Cd	<0.2 ^a (0.9 ^c)	0.4 ^d	
Co	4.4 ^a (1.5 ^c)	2 ^d	0.34 ^e
Cr	51 ^a (35 ^c)	14 ^d	
Cu	4.2 ^a (53 ^c)	25 ^d	
Hg	<0.03 ^a (0 ^c)	0.1 ^d	
Mn	720 ^a (70 ^c)	265 ^d	
Ni	38 ^a (2.8 ^c)	3.5 ^d	
Pb	<5 ^a (410 ^c)	9 ^d	
Sb	<3 ^a (1.8 ^c)	3.5 ^d	
V	<1 ^a (0.9 ^c)	8.5 ^d	118 ^e
Sum heavy metals ^f	Max. 827	331	
Nutrients in ash (wt%)			
P ₂ O ₅	2.75 ^a	37.9 ^d	
CaO	32.79	12.35 ^d	
MgO	4.08	0.35 ^d	
K ₂ O	7.39	16.85 ^d	

^a Analysis wood pellets imported by Essent in may 2002 (TLR 2002)

^b Analysis of wood pellets produced from 100% sawdust (90% spruce, other 10% fir and pine) by Shaw Resources in Nova Scotia (Essent Duurzaam 2001)

^c Pellets produced from demolition wood given in Phyllis database for biomass (www.ecn.nl/phyllis)

^d Average of 2 analyses of palm kernel shells imported by Essent

^e Expected average coal mix ESSENT, as received (Boudewijn and Koopmans 2002). The calorific value of coal of 23 MJ/kg is very low. The average LHV of coal now bought by ESSENT lies between 24-25 MJ/kg. In this study however, calculations were made with the coal mix given in the table.

^f As + Co + Cr + Cu + Mn + Ni + Pb + Sb + V

What strikes is the relatively high content of several heavy metals (especially Mn) in the pellets in comparison to pellets produced from demolition wood and also in comparison to the values for coal. A typical Mn content of biomass lies in the range of 50-100 mg/kg (van der Drift 2002). According to de Vos (2002), the high content of manganese can be attributed to the typical Canadian soil quality.

3.4 The coal fuel cycle and biomass co-firing

The coal fuel cycle consists of several stages (CIEMAT 1999):

1. coal mining
2. coal transport
3. limestone extraction/milling
4. limestone transport
5. power generation
6. power plant construction
7. power plant dismantling
8. waste transport

Air emissions of a coal fuel cycle for a Dutch electricity plant, which is very similar to the plant considered in this study (see section 3.4.2), are given in the table below:

Table 3-6: air emissions of the coal fuel cycle in g/MWh (CIEMAT 1999)

Fuel cycle stage	CO ₂	NO _x	SO ₂	Particles
coal mining	a	nq	nq	nd
coal transport	79,300	nq	nq	nd
limestone extraction	nq	nq	nq	nd
limestone transport	72.9	1.1	0.13	0.0071
power generation	900,000	714	411	17
power plant construction	23.3	0.49	0.026	0.033
power plant c	23.3	0.49	0.026	0.033
waste transport	232	3.4	0.42	0.023

a = included in transport emission estimate

nq = not quantified but expected to be low relative to power generation emissions

nd = not determined but could be significant

Emphasis in this study will be put on stages 1-5 and especially on power production, because this stage has the largest impact on energy consumption and emissions of CO₂, SO₂, NO_x and particulates (CIEMAT 1999). The stages 6 and 7 are not accounted for. Co-firing can result in a reduction of waste (boiler ash, (pulverised) fly ash, flue gas cleanup waste (sludge) and gypsum). In this study, only the reduction in total ash production when co-firing is considered.

Biomass co-firing will have its impact on the coal fuel cycle. Less coal will be burned, so less coal has to be mined and transported. When SO₂ emissions are reduced when co-firing biomass, less limestone is required for the flue gas cleanup. The impact of SO₂ emissions on limestone extraction and transport is accounted for in the mass balance. Indirect effects due to limestone extraction and transport on emissions are not accounted for, since no data are available and the effects are expected to be negligible.

3.4.1 Coal mining and transport

The Dutch coal mix is imported from mines (the majority are opencast mines) all over the world (among which Poland, South-Africa, Colombia, Australia and Indonesia) (Hooijmaijers 2002). Ocean transport takes place by large ocean vessels with a capacity of circa 120 kt to Rotterdam, where the coal is transferred in barges (with capacity of 2000-2500 t), which deliver the load to the storage area of the power plant.

The energy use and emissions of coal mining and transport for the average Dutch coal mix given in SIMAPRO are used (emissions are given in appendix III). SIMAPRO distinguishes coal produced in Australia, North and South America, Eastern Europe and South Africa, including opencast mining and underground mining.

3.4.2 Amer coal-fired power plant

The Amer plant is a coal-fired power plant located in Geertuidenberg in the province of Noord-Brabant, the Netherlands. At the moment, 2 units are operating: unit 8 and 9. Both units are fired with coal, but can also operate on natural gas and unit 8 can also be fired with oil. Besides these units, there are several gas-fired units, which are required to start unit 8 and 9 after those units have been shut down for maintenance¹. In this study, the Amer-9 unit is considered, which is the most efficient unit. The Amer-9 unit is a state-of-the-art pulverised coal-fired CHP plant constructed in 1993. It has a net electric and thermal capacity of respectively 600 MW_e and 350 MW_{th} of low-calorific heat, which is supplied to the municipal heating system and a horticulture complex. The heat demand is time dependent. In the summer, there is less heat demand, since houses are generally not heated in this period. But even in a smaller time period, the demand for heat will fluctuate. As a consequence, the efficiency will also fluctuate. In this study, base case calculations are performed assuming no heat is produced, so the plant is operating at full electric capacity. The net electric efficiency when no heat is produced is 42.46% (Boudewijn and Koopmans 2002). Since the overall energetic efficiency will be higher when producing heat as well, net avoided primary energy will be higher and emissions per kWh will be lower. Therefore, net avoided primary energy is also calculated for average heat and power production in 2001.

Since a few years, Essent Energie is co-firing different types of biomass in the Amer plant. Biomass is mixed with coal (with eventually a drying step depending on the type of biomass), stored and directly fed to the boiler without thermal pre-treatment. The co-firing share for wood pellets lies between 6 and 8 wt% of the original coal input (as it used to before co-firing) (Wagener 2002). In July 2002, one of the coal supply lines was replaced for a biomass supply with separate biomass storage, to increase the biomass co-firing share to approximately 20 wt% of the original coal input (Boudewijn and Koopmans 2002). Also the mill capacity is being enlarged so that the mills can process higher shares of biomass and coal when the demand for electricity is at its maximum. In this study, both situations are considered and hence co-firing shares of 7 and 20 wt% are used in the calculations.

Apart from direct co-firing, a gasifier has been installed to gasify biomass, after which the syngas can be fed to the boiler of unit 9, but it is not operating constantly yet and is not considered in this study.

¹ The gas required to start unit 8 and 9 is not accounted for in the LCI.

Mass balance Amer 9 unit

The coal is transported to the boiler house, crushed by a mill and the pulverised coal is burnt in the boiler. The temperature in the boiler is around 1200°C and the pressure is slightly lower than 1 atmosphere. The unit is equipped with low NO_x burners and a special designed furnace to minimise the emission of NO_x. In the boiler, high-pressure steam of 540°C and 270 bar is produced, which is expanded in steam turbines to generate electricity. The ash remaining after the coal has been burned can be divided into bottom ash and fly ash. Bottom ash is produced by the melting and sintering of particulates of ash in the boiler. It falls through an opening into collecting tanks. The hot flue gas is fed through electrostatic precipitators (ESP's), where fly ash is partly removed from the flue gas. In the flue gas desulphurisation unit (FGD), 85-90% of the SO₂ in the flue gas is removed (Boudewijn and Koopmans 2002). The polluted water flow from the FGD is treated in the wastewater treatment unit (WWT). The different mass flows are visualised in the figure below.

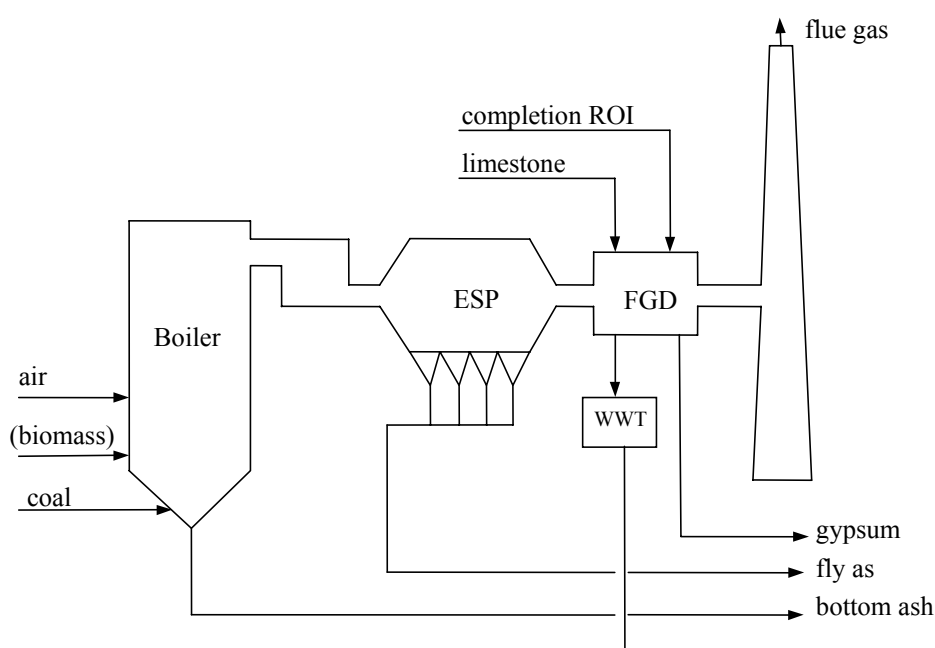


Figure 3-3: Mass flows Amer 9

In table 3-7, the mass balance is given for the Amer 9 unit when it is operating on 100% coal (Boudewijn and Koopmans 2002). Table 3-8 and 3-9 present the mass balance of the Amer plant when co-firing wood pellets and palm kernel shells. The limestone input is adjusted to the SO₂ emission when co-firing, assuming that the SO₂ emission has to remain constant (when biomass has higher S-content than coal, SO₂ emission will increase and more limestone is required).

Table 3-7: Mass balance Amer 9 unit 100% coal (load =7606 hr/yr (in year 2001))

Input (kt/yr)		Output (kt/yr)	
Air for combustion	21,350	Flue gasses (wet)	23,684
Coal	1680	Fly ash	183
Limestone	45	Bottom ash	18
Completion FGD	888	Gypsum	77
Total	23,963	Total	23,963

Table 3-8: Mass balance Amer 9 unit co-firing wood pellets

Input (kt/yr)	7%	20%	Output (kt/yr)	7%	20%
Air for combustion	?	?	Flue gasses (wet)	?	?
Coal	1590	1419	Fly ash coal	173	155
Pellets	118	336	Bottom ash coal	17	16
Limestone	42	38	Ash pellets	2	7
Completion FGD	?	?	Gypsum	73	66

Table 3-9: Mass balance Amer 9 unit co-firing palm kernel shells

Input (kt/yr)	7%	20%	Output (kt/yr)	7%	20%
Air for combustion	?	?	Flue gasses (wet)	?	?
Coal	1595	1432	Fly ash coal	174	156
Palm kernel shells	118	336	Bottom ash coal	18	16
Limestone	44	41	Ash shells	7	20
Completion FGD	?	?	Gypsum	75	71

The impact of biomass co-firing on the efficiency

As mentioned in paragraph 2.3, the overall efficiency of the plant might decrease as a consequence of co-firing. In a simplified model used by ESSENT to determine the impact of co-firing on the overall efficiency, the so-called BOO model, several factors were accounted for, among which:

- Increase of internal energy use (FGD, flue gas ventilators, mills, ventilators which cycle air through the mills)
- Increase heat loss via bottom and fly ash
- Increase heat loss flue gas

According to this model, the efficiency will not be affected when the biomass has a LHV higher than 17.5 MJ/kg (the model assumes coal has a LHV of 24 MJ/kg). Since pellets and palm kernel shells have a higher LHV than 17.5 MJ/kg, the overall efficiency in this specific case will not change when co-firing.

However, this model does not account for de-rating. In order to make an estimation of the reduction in electric efficiency when co-firing biomass in the Amer plant caused by de-rating, a study of the impact of biomass co-firing in a Spanish power plant (Hamelinck and Faaij 2001) will be used. This plant has a net electric efficiency of 33.4% (HHV). Co-firing 5% sawdust by heating value gives a modest decrease in net electric efficiency to 33.2%, whereas co-firing 50% wood residues leads to an efficiency drop to 26.7%. These efficiency calculations include higher internal energy use for drying and milling and decrease of carbon burnout. It must be mentioned that the biomass considered in this study does not require drying and the sizing of pellets will be a different story than sawdust/wood residues with a higher moisture content. In addition, the boiler is de-rated (gas volume is kept constant by decreasing total mass input with increasing co-firing share). The thermal input decreased from 186.3 MW_{th} for 100% coal to 181.3 for 50% co-firing residues. This can be considered as an efficiency loss of approximately 1% point. To illustrate the effect on the results, we assume an efficiency drop of about 0.4% point when co-firing 20% biomass by linear extrapolation (from 42.46% to 42%).

Emissions and ash composition

The emission of CO₂, NO_x (including NO and NO₂), N₂O, SO₂, particulates, Cd, Hg and the sum of other heavy metals caused by the generation of electricity and heat in the Amer 9 unit fuelled with 100% coal reported in (Boudewijn and Koopmans 2002) are given in table 3-10. For the emission of CH₄ a value reported in (CIEMAT 1999) is used. Wastewater emissions are not considered, since co-firing doesn't affect these emissions significantly (Boudewijn and Koopmans 2002). Moreover, wastewater emissions are low compared with other emissions (Mann and Spath 2001).

Table 3-10: Direct emissions unit 9 Amer plant (100% coal).

Compound	Emission 100% coal (g/kWh _e)
CO ₂ ^a	891
CH ₄ ^b	0.0085
N ₂ O ^a	0.01
NO _x ^a	1.04
SO _x ^a	0.56
Dust ^a	0.016
Trace elements	(µg/kWh_e)
Cd + Tl ^c	0.083
Hg ^c	34.1
Heavy metals ^c	71.2

^aAnnual emissions of several compounds from unit 9 are given in (Boudewijn and Koopmans 2002): CO₂: 4237 kt/yr, NO_x: 4923 t/yr, SO₂: 2645 kt/yr and dust: 78 t/yr. N₂O emissions were 47 t/yr in 2001 (de Vos 2002). Net annual power and heat production in 2001 was 16.21 and 4.53 PJ respectively. All emissions are allocated to electricity.

^b Estimate from conventional coal combustion is 1g/GJ (Etsu and IER 1995).

^c Annual emissions of several trace elements from unit 9 are given in (Boudewijn and Koopmans 2002): Cd + Tl: 0.025 µg/m³, Hg: 10.3 µg/m³ and Heavy metals (As + Co + Cr + Cu + Mn + Ni + Sb + Pb + V): 21.5 µg/m³. The flue gas production is 547 m³/s. These concentrations are valid for the plant operating at full capacity (8000 hr/yr, net electricity production of 16.2 PJ_e).

3.4.3 CHP fired with 100% biomass

The biomass-fired CHP plant in Cuijk, the Netherlands, will be used for the central CHP plant in Canada. For the biomass fired power plant in Malaysia, the performance of the Cuijk plant operating without heat production is used. The plant is fuelled with non-contaminated wood chips and is operating approximately 7000 hr/yr at full capacity (Remmers 2002). Pellets or palm kernel shells do not require pre-treatment; the fuels can directly be burned. The energy balance and emissions are given in table 3-11 and 3-12, respectively. The emissions are assumed to be representative for burning pellets or palm kernel shells.

Table 3-11: Energy balance Cuijk plant, a SOTA CHP plant fuelled with biomass, equipped with gas cleaning (Remmers 2002). The data in the right column are representative for the case in which the plant operates in CHP mode, which is used for the imaginary CHP plant in Canada.

	Without heat supply (MW)	With heat supply (MW)
Fuel input	82	82
Gross electric capacity	29.5	24.5
Net electric capacity	26.3	21.3
Thermal capacity (steam)	0	40
Heat loss chimney	7	7

Heat loss condensor	45	10
Net electric efficiency	32.1%	26.0%
Total net efficiency	32.1%	74.8%

Table 3-12: Direct measured emissions Cuijk plant (13-02-'01). Input: clean wood (Remmers 2002)

Compound	Maximum measured concentration (mg/m ³ , 6 vol% O ₂) ^a
CO ₂	0
C _x H _y (inc. CH ₄)	< 2
NO _x	99
SO _x	< 2
Dust	6
Cd	0.0001
Hg	0.0008
Sum heavy metals ^b	0.06

^a exhaust gas (dry): 28 Nm³/sec

^b Sb + Pb + Cr + Cu + Mn + V + Sn + As + Co + Ni + Se + Te

3.4.4 Heat production in households

Capacity and efficiency of a pellet boiler to produce heat in households in a Swedish context are reported in (Gustavsson and Karlsson 2002) and will be used in this study. The capacity of a typical boiler is 11 kW_{heat} and the net efficiency of such a system is 78%. According to Gustavsson (2002), the annual utilisation time for small-scale heaters is approximately 2500 hr/yr. Emissions for pellet boilers reported in GEMIS are used (see table 3-13).

Table 3-13: Emissions pellet boiler (GEMIS “wood-pellet-heating D”)

Compound	Emission (g/MJ _{th})
CO ₂	0
CH ₄	0.051
N ₂ O	0.0046
NO _x	0.28
SO ₂	0.036
Dust	0.086
Trace elements	(µg/MJ_{th})
Cd + Tl	0.071
Hg	0.23

3.5 Reference systems

In this paragraph, the data related to the reference systems of power and heat production based on the national average fuel mix are given, followed by the required data to calculate energy production/consumption and emissions associated with the fate of biomass when it is not exported as co-firing fuel.

The energy use involved with the production and transport of secondary energy carriers (2nd order energy use) is determined by means of efficiency factors presented in table 3-14. The efficiencies of electricity production are specified in the next sections.

Table 3-14: Conversion efficiencies for the production of primary and secondary energy carriers

Energy carrier	Efficiency (%)
Crude oil ^a	95
Heavy fuel oil ^a	93
Diesel ^a	89
Natural gas ^a	92
Coal ^b	89
Electricity Netherlands	41
Electricity Canada	60
Electricity Malaysia	45
Heat ^c	90

^a These values represent average values from different literature sources given in (Hendriks 2000)

^b Dutch coal mix given in Simapro

^c Represents efficiency of gas-fired boiler (Dornburg 1999)

3.5.1 Reference system 1b: Average Dutch electricity and heat production

The Dutch electricity generation mix is reported in the GEMIS database and in the international energy statistics (IEA 2000) and presented in table 3-15. The electricity generation mix presented in GEMIS is estimated for the year 2000 by means of linear interpolation from data 1997-2005. The average efficiency of 46% reported in GEMIS is high in comparison to the value of 43.5% reported in (Novem 1999). Moreover, the energy input for production and transport of fossil energy carriers should be accounted for as well. Considering the share of coal, oil and gas in table 3-15 and the efficiencies of production and transport given in table 3-14, we estimated the overall electric efficiency at 41%, in which we also accounted for the fact that much of the gas used in the Netherlands for power production is produced in the country itself. Emissions (direct emissions and emissions caused by production, transport fuels and construction capital goods) related to electricity generation are reported in GEMIS and given in appendix II.

For the Netherlands, an average heat efficiency of 90% is assumed (Dornburg 1999). Heat is commonly produced in gas-fired boilers, so it is assumed heat is produced 100% from natural gas. Emission data for a 10 MW gas furnace with an efficiency of 85% reported in GEMIS are used, so it must be kept in mind that these emissions are slightly overestimated.

Table 3-15: Dutch electricity production 2000 (GEMIS “el-generation-mix-NL”). Values between brackets refer to the values presented in (IEA 2000).

Energy carrier	Electricity generation mix (%)	Efficiency (%)
Coal	25.46 (29.9)	38 ^a
Oil	5.47 (3.9)	42 ^b
Gas	61.46 (57)	53 ^c
Nuclear	2.27 (4.2)	33
Hydropower	0.15 (0.1)	100
Other	0.99 (wind) 4.2 (waste) (4.9)	100 (wind) 11 (waste)
Total	100	46

^a Technology: typical Dutch coal-fired steam turbine power plant

^b Technology: typical Dutch oil-fired steam turbine power plant

^c Technology: typical Dutch gas-fired combined cycle power plant

3.5.2 Reference system 2a: Average electricity and heat production in biomass exporting country

Canada

The predicted Canadian electricity production mix for the year 2000 reported in the GEMIS database and of the year 1998 reported in (IEA 2000) are given in the table below. Canada has a high overall electrical efficiency of 55-60%, which is caused by the relative high share of hydropower. In this study, the value 60% reported in (IEA 2000) is used. The energy use for fossil fuel production and transport in Canada is expected to be minimal, since the share of fossil fuels in the energy mix is generally low and fossil fuels are generally produced in the country itself. Emissions for the average Canadian fuel mix (direct emissions and emissions caused by production, transport fuels and construction capital goods) for electricity production reported in GEMIS are used (see appendix II). For heat production in Canada, the same gas boilers as considered for the Netherlands were used.

Table 3-16: Average electricity production in Canada 2000 (GEMIS “el-generation-mix-CAN”). Values between brackets refer to the values presented in (IEA 2000).

Energy carrier	Electricity generation mix (%)	Efficiency (%)
Coal	16.03 (19.1)	36 ^a
Oil	2.1 (3.3)	41 ^b
Gas	4.7 (4.6)	53 ^c
Nuclear	15.59 (12.7)	33
Hydropower	60.25 (59.1)	100
Other	1.3 (waste) (1.1) 0.03 (geothermal)	11 100
Total	100	55 (60)

^a Technology: typical Canadian coal-fired steam turbine power plant

^b Technology: typical Canadian oil-fired steam turbine power plant

^c Technology: typical Canadian gas-fired combined cycle power plant

Malaysia

The average electricity production in Malaysia in 1998 is reported in (IEA 2001). The overall efficiency calculated from the energy inputs and electricity in 1999 is 45%. When considering the energy system of Malaysia (www.eid.doe.gov), it appears that the country has large natural gas reserves. The country exports oil, but imports some coal for power generation. However, the share of coal in the fuel mix is quite small, so the energy for transport of fossil fuels from production site to plant is expected to be relatively small, in contrast to coal transport to the Netherlands.

Table 3-17: Average electricity production in Malaysia (1999) (IEA 2001)

Energy carrier	Electricity generation mix (%)
Coal	2.5
Oil	8.34
Gas	77.62
Nuclear	0
Hydropower	11.54
Total	100

Unfortunately, there are no specific figures for the emissions related to electricity production in Malaysia. Therefore, direct and indirect emissions for a generic coal fired, oil fired and gas fired power plant (with steam turbines) reported in GEMIS are used (see appendix II).

3.5.3 Reference system 2b: Alternative biomass utilization

Wood residues in Canada

In 1998, 70% of produced wood residue in Canada was used for biomass (Hatton 1999). The remainder was stock piled, but is now required to be dumped in landfills (in Ontario and Quebec). Wood waste landfills are privately owned and operated by forest industries, such as sawmills and pulp and paper mills. These industries use the landfills to dispose of surplus wood residue such as sawdust, wood shavings, bark and sludges (Jaques 2001). In this study, it is assumed that all bark, sawdust and shavings coming available at chip/sawmills that is not used for pellet production, is disposed at landfills. During biomass decomposition at landfills, the carbon compounds are degraded into CO_2 and CH_4 . The emission of these gasses depends on the conditions under which biomass is degraded and the composition of the resource. Emissions of CO_2 and CH_4 that would have occurred during the normal routes of biomass disposal in the US are quantified in a study performed by Mann (2001). The assumptions made in this study are used to calculate the emissions of wood residue decomposition at landfills in Canada (see figure 3-4).

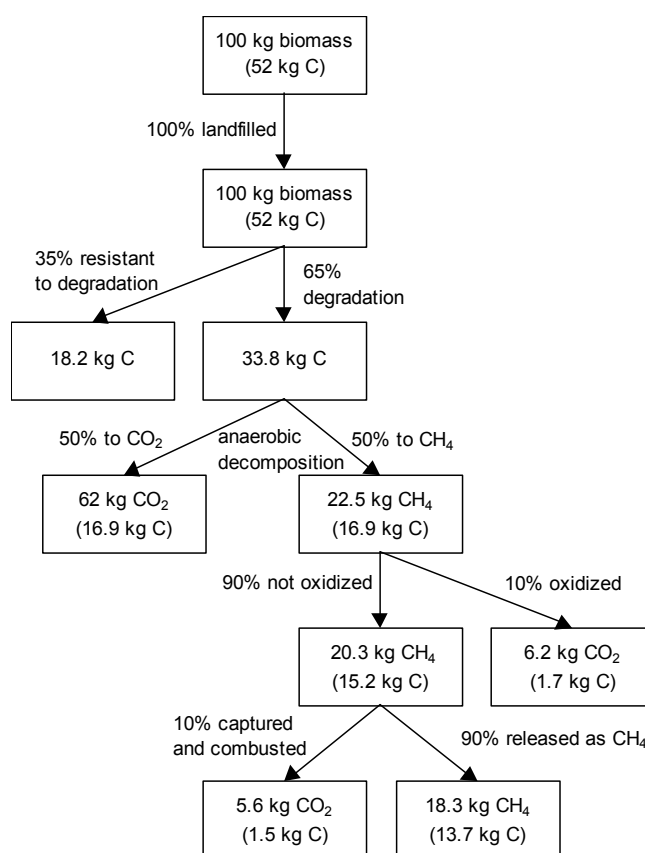


Figure 3-4: Carbon balance of forestry residues decomposition adapted from (Mann and Spath 2001).

The carbon-content of bark (pine) and sawdust (pine) is 52 and 53 wt% on dry basis, respectively (www.ecn.nl/phyllis). For the mix of sawdust, bark and shavings used for pellet production, a carbon content of 52% is assumed. According to several studies on waste decomposition mentioned in (Mann and Spath 2001), decomposition at landfills occurs under mostly anaerobic conditions, resulting in a gas that can be approximated as a mixture of 50% CO₂ and 50% CH₄. Although its composition can vary, landfill gas is typically half methane and half carbon dioxide, with trace levels of sulphur compounds and volatile organic compounds (Environment Canada 2002). From the formed methane, approximately 10% is oxidised into CO₂ by soil microbes (Mann and Spath 2001). To comply with air regulations, a fraction of the gas produced at the landfills is captured and either flared off or piped to nearby facilities for use as fuel in heating buildings or generating electricity. Landfill regulations are a provincial jurisdiction and only Ontario has such a regulation, which requires landfill gas capture from all large landfills. Approximately 25% of Canada's landfills have methane collection systems (Bird 2002). These occur in the major cities only. Landfill gas capture is generally not practiced at wood waste landfills (Jaques 2001). In this study, it is assumed that 10% of the landfills receiving wood residues has methane collection systems and the other 90% of the methane emissions is vented to the atmosphere. The methane that is captured is assumed to be combusted in a gas engine with a net electric efficiency of 30%. The primary energy requirements to produce an equivalent amount of electricity is calculated by means of the average electrical efficiency in Canada and this is accounted for in the net avoided primary energy.

Palm kernel shells in Malaysia

When the palm kernel shells are not applied as (co-firing) fuel, palm kernel shells are either burned, dumped, applied as fertilizer or sold as resource for fodder production. In this study, two alternative scenarios are considered: either the shells are burned in open air or applied as resource for fodder production. These two scenarios represent a wide range in avoided emissions. Burning of palm kernel shells in the open air can be considered as a best case, whereas the case of fodder production from palm kernel shells can be considered as a worst case.

Pile burning in open air

Burning of crop residues in the open air is a significant source of CH₄, CO, NO_x and N₂O. The emissions of CH₄, NO_x and N₂O during pile burning are calculated by means of data for field burning of agricultural residues presented in (IPCC 1995). The emissions are calculated according to the following formula:

$$\text{CH}_4 = \text{carbon released} \times \text{emission ratio} \times 16/12$$

$$\text{NO}_x = \text{carbon released} \times (\text{N/C ratio}) \times \text{emission ratio} \times 44/28$$

$$\text{N}_2\text{O} = \text{carbon released} \times (\text{N/C ratio}) \times \text{emission ratio} \times 46/14$$

Carbon released is the amount of carbon present in the biomass multiplied with the fraction oxidised to account for the carbon that remains on the ground as a result of charcoal formation and other aspects of incomplete combustion. The fraction oxidised is typically 90%. The average emission factor for CH₄, NO_x and N₂O are respectively 0.005, 0.007 and 0.121 (IPCC 1995).

It is assumed that all sulphur in the biomass is converted into SO₂. Data for particulate emissions of biomass burning in the open air were not available, so these could not be included in the calculations. Heavy metal emissions during pile burning are assumed

to be zero, since vaporization is expected to be negligible, because the flame temperature is relatively low.

Alternative resource fodder production

When palm kernel shells are used for fodder production, an equivalent amount of alternative resource must be produced and imported. Fodder is produced from several resources among which soybeans, wheat and barley. In this study, soybeans are chosen as alternative for palm kernel shells. The US is the largest soybean producer in the world. About 80% of the US soybeans are produced in the north-central States (Scherer and Yang 1999). In a study comparing soybean production in the US and Brazil (Baumer et al. 2000), soybean production in Iowa and transport to New Orleans (from where soybeans are exported to e.g. Europe) is considered. Soybeans are transported by rail from Jefferson to East Clinton, Illinois, a distance of about 200 miles (320 km). There, the soybeans are transferred into barges for movement to New Orleans, a distance of about 1300 miles (2100 km). This is the typical route for most soybeans from Iowa to New Orleans regardless of export destination (Baumer 2002). From New Orleans, soybeans are transported to Rotterdam over sea, a distance of 4880 sea miles (9040 km).

Energy use of train transport is 0.7 MJ/tkm for a train with a loading capacity of 800 t (30 carriages) (Börjesson 1996). Emissions for a diesel train for freight transport in the US are reported in GEMIS. Energy use and emissions for barge and ocean transport have already been discussed in section 3.1.3.

4 Results

In the first paragraph, the mass balance of both biomass import chains will be presented. Paragraph 2 considers the energy balance of biomass logistics and the net avoided primary energy of biomass co-firing in the Netherlands and its application as fuel in the country of origin in several conversion systems. The third paragraph will deal with the emissions of biomass import and (co-)firing and the final paragraph summarizes the nutrient flows.

4.1 Mass balance

In the tables below, the mass balance of the entire logistic chain of wood pellet/palm kernel shell production and import is given. The mass balance for the conversion part has already been given in section 3.4.2. It should be mentioned that the mass balance of wood pellet import was originally set up for one specific load in 2001 as can be seen in table 4-1. No data on loads of palm kernel shells were available, so the mass balance for palm kernel shell import (table 4-2) was set up assuming the power plant should be fuelled for a year.

Table 4-1: Mass balance wood pellet import (load of pellets in May 2002)

Process	Moisture content	Dry matter left	Flow (ktdm)	Flow (ktfw)
Wood harvested for chip/sawmills ^a	±60%		±29.95	±74.87
Sawdust for heat production	50%		1.43	2.87
Biomass mix for pellet production	48%		6.83	13.14
Pelletisation	±48%	100% ^b	8.26	16.00
Transport to export terminal	7%	82%	6.76	7.27
Storage/transfer at export terminal	7%	82%	6.76	7.27
Sea transport ^c	7%	82%	6.76	7.27
Transfer/storage at import terminal	5%	82%	6.76	7.13
Transport to conversion unit	5%	82%	6.76	7.13
Storage at conversion unit	5%	82%	6.76	7.13
Conversion	5%	82%	6.76	7.13

^a Since the exact amount of wood to be harvested is in fact unknown, it was decided to define the biomass input in the pelletisation process as 100%.

^b Dry matter losses during pelletisation are assumed to be 1%.

^c The moisture content of the pellets measured in Rotterdam is 5.16%, whereas the moisture content reported in (Essent Duurzaam 2001) is between 6-8%. An explanation might be that the moisture content decreases during sea transport.

Table 4-2: Mass balance PKS import (biomass input for 1 year of 7% co-firing)

Process	Moisture content	Dry matter left	Flow (ktdm)	Flow (ktfw)
Harvesting and transport FFB	20%	100%	3952	4940
Total availability palm shells	8%	7%	298.8	324.7
Shells available for export	8%	3%	119.5	129.9
Truck transport shells	8%	3%	119.5	129.9
Sea transport to conversion unit	8%	3%	119.5	129.9
Conversion	8%	3%	119.5	129.9

4.2 Energy balance

4.2.1 Energy use biomass supply

In table 4-3, the energy use for the production and transport of pellets and palm kernel shells is given. In figure 4-1 and 4-2, these numbers are shown graphically.

Table 4-3: Energy inputs biomass production and transport. The values between brackets refer to the energy consumption when the harvesting and transport of wood/FFB are not accounted for.

Energy use (MJ _{prim} /tdm)	Co-firing pellets Amer	Pellets in boiler Canada	Pellets in CHP Canada	Co-firing PKS Amer	PKS in power plant Malaysia
Harvesting and transport trees/FFB	269 (0)	269 (0)	269 (0)	101 (0)	101 (0)
Debarking	91	91	91	-	-
Truck transport residues	49	49	49	-	-
Pelletisation	858	858	858	-	-
Truck transport pellets/PKS	67	222	111	439	439
Sea transport pellets/PKS	686	0	0	1591	0
Barge transport pellets/PKS	4.3	4	0	4.5	0
Total energy use	2023 (1754)	1493 (1224)	1378 (1109)	2134 (2034)	539 (439)
% of LHV biomass	11% (10%)	8% (7%)	8% (6%)	12% (12%)	3% (3%)

The energy use of biomass transfer is not accounted for, but is expected to be negligible. Several transfer operations occur in the chain; loading of biomass to a truck, transfer truck to ocean vessel, transfer ocean vessel to barge and unloading of barge at the Amer plant. For each transfer operation, approximately 0.47 MJ/t biomass is required (Feenstra et al. 1994).

The primary energy required for coal mining and transport is approximately 12% for the Dutch coal mix (see table 3-14). So it can be concluded that energy use for production and transport of pellet and palm kernel shells is in the same order of magnitude. When the biomass sources are used in the country of origin, energy use is significantly lower, because ocean transport is relatively energy-intensive.

From figure 4-1, it can be concluded that pelletisation and the ocean transport represent the biggest share in the total energy consumption of biomass supply, whereas the contribution of barge transport is negligible. Although pelletisation is an energy intensive process, it is more favourable to perform this step instead of transporting chips, since the energy density is very high, making pellet transport more efficient. Although the palm kernel shells do not undergo densification, the total energy consumption of biomass supply to the Netherlands is higher in comparison to pellets (see figure 4-2), which is caused by the fact that the distance Singapore-Rotterdam is about three times larger as Halifax-Rotterdam.

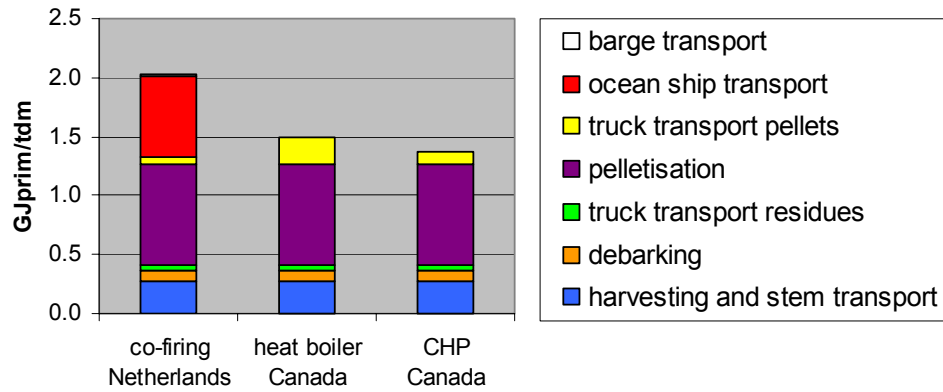


Figure 4-1: Breakdown energy use pellet production and transport (GJ_{prim}/tdm). In this picture, energy consumption of wood harvesting/transport is included.

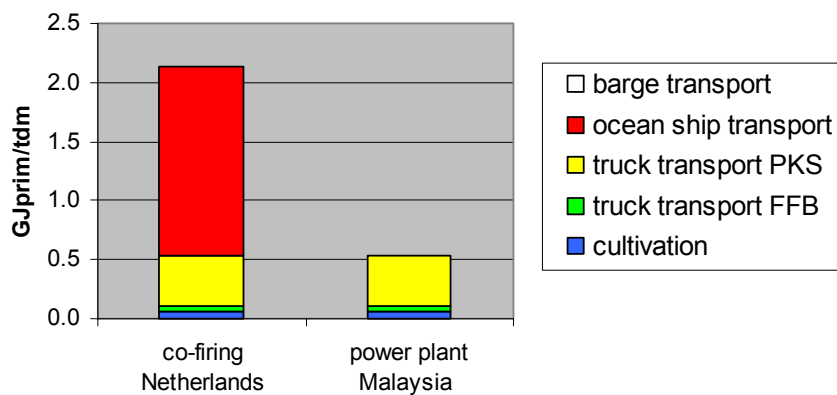


Figure 4-2: Breakdown energy use palm kernel shell transport (GJ_{prim}/tdm)

4.2.2 Net avoided primary energy

Biomass import and co-firing in the Netherlands

Table 4-4 presents the net avoided primary energy per unit biomass energy for pellets and palm kernel shells co-firing in the Amer plant with respect to different reference systems.

Table 4-4: Net avoided primary energy per unit biomass energy of pellet and PKS import and co-firing in the Amer plant. It is assumed that only power is produced (600 MW_e, net electric efficiency of 42.46%), except the value in italics, in which both power and heat are produced.

Co-firing system	7% pellet co-firing	20% pellet co-firing	7% PKS co-firing	20% PKS co-firing
Biomass input (Mtfw/yr) (PJ _{bio} /yr)	0.12 (2.12)	0.34 (6.07)	0.12 (2.02)	0.34 (5.76)
Coal input (Mtfw/yr) (PJ _{coal} /yr)	1.59 (36.6)	1.42 (32.6)	1.59 (36.7)	1.43 (32.9)
Electricity production (PJ _e /yr)	16.4	16.3	16.4	16.3
“Green electricity” production (PJ _e /yr)	0.9	2.55	0.86	2.42
Energy input biomass production and transport (PJ _{prim} /yr)	0.23	0.65	0.23	0.66

Reference system 1a (100% coal)				
Coal input (Mt/yr) ($PJ_{\text{coal}}/\text{yr}$)	1.68 (38.7)	1.68 (38.7)	1.68 (38.7)	1.68 (38.7)
Electricity production (PJ_e/yr)	16.4	16.4	16.4	16.4
Reference system 1b (Dutch power production)				
Electricity production (PJ_e/yr) ^a	0.09	2.55	0.86	2.42
Primary energy input ($PJ_{\text{prim}}/\text{yr}$)	2.2	6.22	2.09	5.91
Energy input electricity production from methane recovered at landfill ($PJ_{\text{prim}}/\text{yr}$)	0.32	0.90	-	-
Energy input soybean production ($PJ_{\text{prim}}/\text{yr}$)	-	-	0.24	0.68
Net avoided primary energy per unit biomass energy ($GJ_{\text{prim}}/GJ_{\text{bio}}$)				
in comparison to 100% coal ^b	0.86	0.80	1.01	0.95
in comparison to Dutch power production ^c	0.78	0.77	0.92	0.91
<i>in comparison to Dutch power production^d</i>	0.81	-	0.96	-
in comparison to 100% coal and soybean production ^e	-	-	0.89	0.83
in comparison to Dutch power production and soybean production ^f	-	-	0.80	0.79

^a Equal to “green electricity” production in co-firing system, which replaces “grey electricity” (produced from fossil fuels).

^b [Replaced coal ($PJ_{\text{prim}}/\text{yr}$) - energy input biomass production and transport ($PJ_{\text{prim}}/\text{yr}$) - energy input electricity production from methane recovered at landfill ($PJ_{\text{prim}}/\text{yr}$)]/biomass input ($PJ_{\text{bio}}/\text{yr}$)

^c [Energy input green electricity production ($PJ_{\text{prim}}/\text{yr}$) - energy input biomass production and transport ($PJ_{\text{prim}}/\text{yr}$) - energy input electricity production from methane recovered at landfill ($PJ_{\text{prim}}/\text{yr}$)]/biomass input ($PJ_{\text{bio}}/\text{yr}$).

^d This value is calculated assuming both power and heat are produced. Net electric efficiency of the Amer 9 unit operating in CHP mode on 100% coal is 40.2% and overall efficiency is 49.4%. These values are used for a co-firing share of 7%.

^e [Replaced coal ($PJ_{\text{prim}}/\text{yr}$) - energy input biomass production and transport ($PJ_{\text{prim}}/\text{yr}$) - energy input soybean production ($PJ_{\text{prim}}/\text{yr}$)]/biomass input ($PJ_{\text{bio}}/\text{yr}$)

^f [Energy input green electricity production ($PJ_{\text{prim}}/\text{yr}$) - energy input biomass production and transport ($PJ_{\text{prim}}/\text{yr}$) - energy input soybean production ($PJ_{\text{prim}}/\text{yr}$)]/biomass input ($PJ_{\text{bio}}/\text{yr}$)

The difference in net avoided primary energy of wood pellets and palm kernel shells is explained by the additional electricity generation from methane when the resources for wood pellet production would have been dumped at a landfill. When the landfills receiving wood waste do not have a methane recovery system, the net avoided primary energy is $1.02 GJ_{\text{prim}}/GJ_{\text{bio}}$ for 7% co-firing. The fact that more primary energy can be avoided than the energy content of the biomass is caused by the fact that the energy consumption of biomass supply is slightly lower than for coal mining and transport. When co-firing 20% biomass, this effect is compensated by the expected efficiency drop caused by de-rating.

An important conclusion that can be drawn from table 4-4 is that especially the choice of the reference system has a significant impact on the net avoided primary energy. The net avoided primary energy is higher when the reference system consists of the power plant operating at 100% coal. The efficiency of the average Dutch power production is higher than the efficiency of the coal-fired power plant², so when this reference system is chosen, co-firing seems less attractive. The results also confirm

² The net electric efficiency of the Amer plant is 42.46%, but this does not include the additional energy required to mine and transport the coal (efficiency of 0.89%). When this is accounted for, the overall efficiency of the complete system is around 38%. For the Dutch power production, we assumed an overall efficiency of 41% (including energy use for production and transport fossil fuels).

that the net avoided primary energy when both power and heat are produced is higher in comparison to the case in which 100% electricity is produced.

The choice of the biomass fate is relevant as well. When palm kernel shells are indeed used as resource for fodder production, more primary energy is required for the production and transport of an alternative resource, in this case soybeans. As can be observed, this has a significant impact on the net avoided primary energy.

Biomass as fuel in country of origin

Table 4-5 presents the avoided primary energy for pellets and palm kernel shells use in biomass combustion systems in Canada and Malaysia.

Table 4-5: Net avoided primary energy per unit biomass energy of pellet and PKS utilization in stand-alone combustion systems in country of origin.

100% biomass system	Pellets in boiler Canada	Pellets in CHP Canada	PKS in power plant Malaysia
Biomass input (Mtfw/yr) (PJ_{bio}/yr)	7E-6 (1.27E-4)	0.12 (2.07)	0.12 (2.07)
Electricity production (PJ_e/yr)	-	0.54	0.66
Heat production (PJ_{th}/yr)	9.9E-5	1.01	-
Energy input biomass production and transport (PJ_{prim}/yr)	9.77E-6	0.15	0.06
Reference system (Canadian power/heat production)			
Energy input electricity production (PJ_{prim}/yr)	-	0.90	1.47
Energy input heat production (PJ_{prim}/yr)	1.20E-4	1.22	-
Energy input electricity production from methane recovered at landfill (PJ_{prim}/yr)	1.89E-5	0.31	-
Net avoided primary energy per unit biomass energy (GJ_{prim}/GJ_{bio})^a	0.71	0.80	0.68

^a [Energy input electricity/heat electricity production (PJ_{prim}/yr) - energy input biomass production and transport (PJ_{prim}/yr) - energy input electricity production from methane recovered at landfill (PJ_{prim}/yr)]/biomass input (PJ_{bio}/yr)

It is not surprising that the net avoided primary energy of a central CHP plant is higher in comparison to local boilers, since a CHP has a higher overall efficiency in comparison to separate power and heat generation. Moreover, the transport distance is lower for a central CHP, but this will not contribute strongly to the energy input.

Biomass import and co-firing versus internal use of biomass in country of origin

In the figure below, the net avoided primary energy per unit biomass energy of all different options for biomass import and co-firing and utilization in conversion systems in the country of origin are summarized. The figure illustrates the energy efficiency of the different options; it shows us how much primary energy can be avoided when applying a GJ of biomass as (co-firing) fuel. The higher the column, the more efficient the considered chain and the more primary energy can be saved.

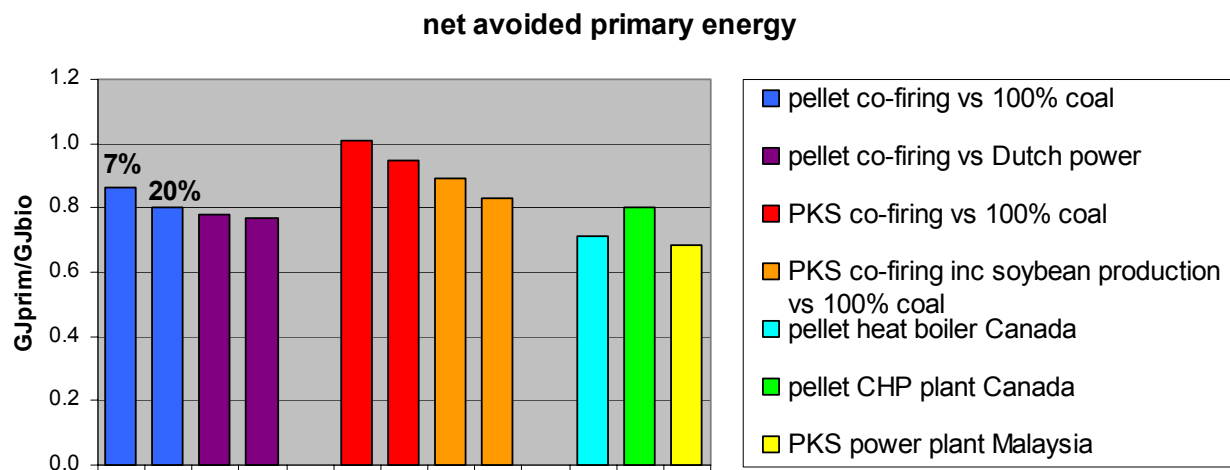


Figure 4-3: Net avoided primary energy per unit biomass energy of pellet and PKS import and co-firing and use in stand-alone combustion systems in the country where the biomass is produced. The left column of each series refers to 7% co-firing share (on mass basis) and the right column to 20%.

When comparing the different possibilities of pellet utilization, it can be concluded that the use as fuel in Canada is less efficient than exporting it to the Netherlands and co-fire the pellets there with co-firing shares around 7% (in comparison to the 100% coal reference). This can be explained by the fact that the efficiency of the Amer plant is higher than the efficiency of the considered conversion systems in Canada. Another reason is that coal mining and import to the Netherlands is quite energy extensive, whereas in Canada, bio-electricity replaces electricity, which is to a large extent produced from renewables (hydropower) with a high efficiency. It must be remarked that a large share of the generated hydropower in Canada is exported to California, so the capacity for internal use is less efficient and more carbon intensive. When this is accounted for, the perspectives for biomass utilization in Canada are better than the values in figure 4-3 show us.

The net avoided primary energy is expected to decrease when increasing the biomass co-firing share to 20%, due to an expected drop in the electric efficiency. When assuming an efficiency drop from 42,5% to 42% at a share of 20 wt%, it becomes more attractive to use the biomass in a central CHP in Canada instead of exporting it for co-firing purposes.

The prospects for palm kernel shell export and co-firing in the Amer plant are good from energetic point of view. Even at co-firing shares of 20% or when the biomass is used as fodder resource, it is still more efficient to export the shells than using them in biomass combustion power plants in Malaysia. But it should be mentioned again that the choice of the reference system of electricity generation and biomass utilization is very relevant for the prospects of biomass import for co-firing purposes.

4.3 Emissions

Emissions are presented per theme in 3 sections: greenhouse gas emissions, NO_x, SO₂ and particulate emissions and heavy metal emissions. For each theme, both a breakdown of emissions and net emissions are presented. It must be noted that all emissions were calculated assuming the Amer plant does not produce heat. When it operates in CHP mode, the overall efficiency will be higher, resulting in slightly lower emissions per kWh.

4.3.1 Greenhouse gasses

The emission of greenhouse gasses is expressed as CO₂-equivalents/kWh. Hereto, the emission of CH₄ and N₂O are normalized to CO₂-equivalents, which occurs on the basis of the global warming potential of these gasses. The GWP of CH₄ and N₂O is respectively 21 and 310 times that of CO₂ (Houghton et al. 1996).

Biomass import and co-firing in the Netherlands

In order to get insight in the contribution of the different processes of biomass import and co-firing to GHG emissions, a breakdown of the GHG emissions is presented in figure 4-4 and 4-5 for respectively pellets and palm kernel shells.

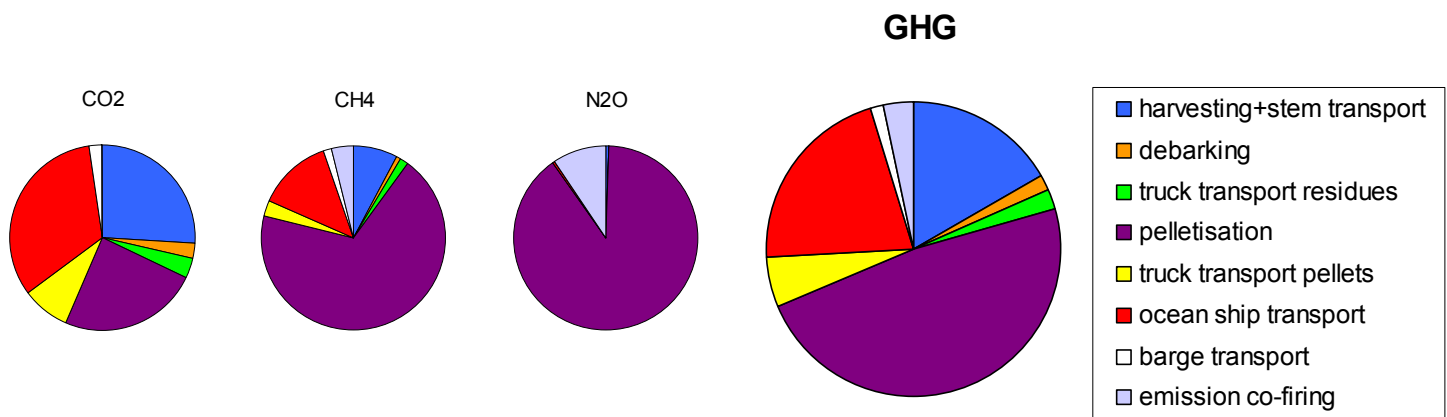


Figure 4-4: Breakdown of GHG emissions for pellet import and co-firing in Amer plant

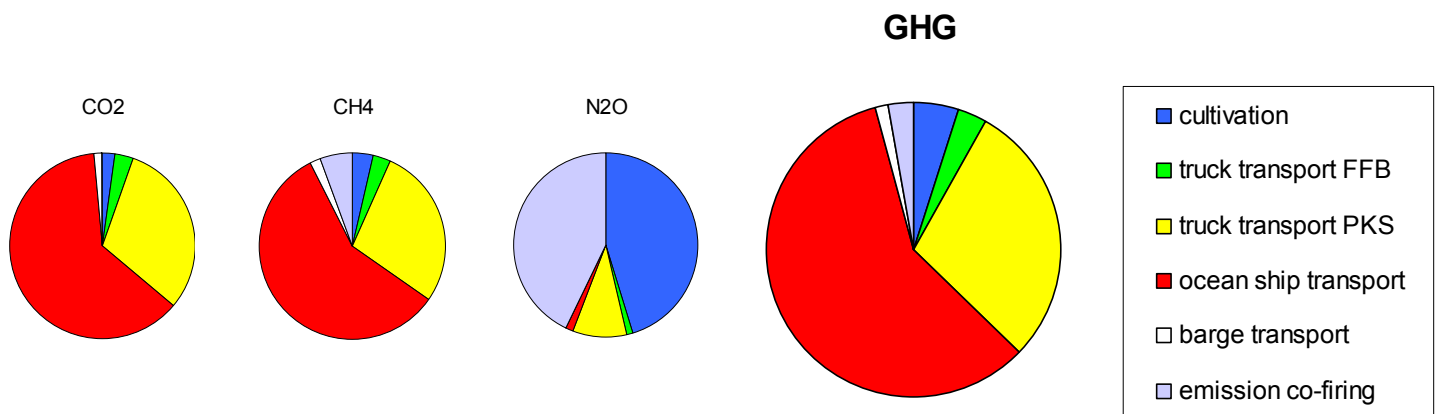


Figure 4-5: Breakdown of GHG emissions for PKS import and co-firing in Amer plant

Figure 4-4 shows that nearly half of the GHG emissions of pellet production, transport and co-firing are caused by the pelletisation process. Other strong contributors are ocean transport and wood harvesting and transport. GHG emissions caused by co-firing are relatively low, mainly because CO₂ emissions are assumed to be zero for biomass co-firing. The breakdown of GHG emissions for palm kernel shell import and co-firing shows us that CO₂ and CH₄ emissions caused by ocean and truck transport and N₂O emissions caused by fertilizer production/application dominate the picture.

In the table below, the emission of CO₂, CH₄ and N₂O when importing and co-firing biomass and avoided GHG emissions are given to get a feeling of the impact of each process on the net GHG emissions. Figure 4-6 gives an overview of the net GHG emissions of the biomass import and co-firing scenarios in comparison to several reference situations. The results indicate that the difference in GHG emission between 7% and 20% co-firing share is negligible, from which it can be concluded that the impact of the assumed de-rating on net GHG emissions is modest. All figures presented in this paragraph refer to the case in which 7% biomass is co-fired.

Table 4-6: GHG emissions of pellet and PKS import and co-firing (g/kWh bio) and reference systems (g/kWh fossil). Values between brackets refer to co-firing share of 20%, other values to 7%.

Pellet import	CO₂	CH₄	N₂O	CO₂-eq
Biomass supply	62.5	0.21	0.098	97.2 (98.1)
co-firing	0 ^a	0.0085 ^b	0.01 ^c	3.37 (3.37)
avoided biomass decomposition	0 ^a	-53.7	-	-1129 (-1128)
avoided coal mining + transport	-75.2	-1.23	-0.0014	-102 (-103)
net emissions	-12.7	-54.8	0.11	-1130 (-1129)
PKS import				
Biomass supply	105	0.15	0.014	110 (111)
co-firing	0 ^a	0.0085 ^b	0.01 ^c	3.37 (3.37)
soybean production	107	0.34	0.48	263 (266)
avoided PKS burning	0 ^a	-1.23	-0.13	-66 (-67)
avoided coal mining + transport	-75.2	-1.23	-0.0014	-102 (-103)
net emissions + PKS burning	29.8	-2.32	-0.11	-52 (-53)
net emissions + soybean production	137	-0.74	0.50	278 (280)
Reference emissions				
1a: 100% coal	966	1.24	0.052	1009
1b: Dutch power production	584	1.11	0.028	615

^a CO₂ emissions caused by biomass co-firing, decomposition and pile burning are assumed to be absorbed again by the trees/crop again in a next growth cycle.

^b The impact of biomass co-firing on CH₄ emissions is unknown. It is assumed that it does not change when co-firing.

^c The impact of biomass co-firing on N₂O emissions is unknown. It is assumed that it does not change when co-firing. Aspen calculations were performed to get an idea of the order of magnitude of N₂O emissions when co-firing biomass. When co-firing 7% wood pellets, N₂O emissions will decrease with approximately 10%. When assuming that the change in N₂O emissions when co-firing are attributed to biomass only, the N₂O emissions kWh bio are about 140% higher as emissions of 100% coal only. It must be noted that emissions caused by additional coal input when co-firing (to maintain the thermal input) are attributed to biomass as well.

The net GHG emission of pellet import and co-firing is strongly negative, because avoided methane emissions during decomposition at landfills and coal mining are very high in comparison to GHG emissions caused by biomass supply and co-firing. In this study, it is assumed that landfills receiving forestry and saw/chip mill residues recover only 10% of the released methane. But even if all methane would be recovered and burned, the net GHG emission would still be negative. As can be observed in figure 4-6, the fate of palm kernel shells has a strong impact on the net GHG emissions, although in both cases, the net GHG emissions are significantly lower with regard the reference systems. When the shells are burned in the open air, net GHG emissions are slightly negative due to avoided CH₄ and N₂O emissions. If the shells used as co-firing fuel would normally be sold to a fodder production company, the net GHG emission is positive since soybean cultivation and transport

causes relatively high GHG emissions. Especially the contribution of N₂O emissions is relatively high, which is caused by production and application of fertilizer in soybean cultivation.

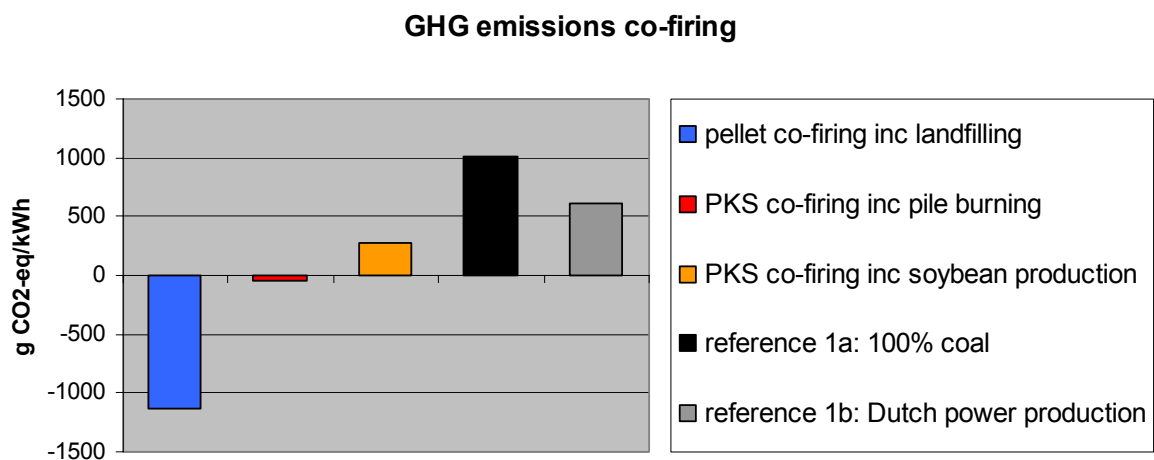


Figure 4-6: GHG emissions of pellet and PKS import and co-firing in the Amer plant (g/kWh bio) in comparison to reference power production (g/kWh fossil).

The overall conclusion is that the net GHG emission of biomass import and co-firing is significantly lower than the GHG emission of fossil fuel cycles and in most cases even negative, from which it can be concluded that biomass import and co-firing is an effective greenhouse mitigation option in those specific cases.

Biomass as fuel in country of origin

The GHG emissions of pellet and palm kernel shell burning in several biomass combustion systems are presented in the figure below. As can be concluded from this figure, GHG emissions of biomass use for power/heat production in the country of origin are negative as well, due to avoided emissions of biomass decomposition/ burning in the open air.

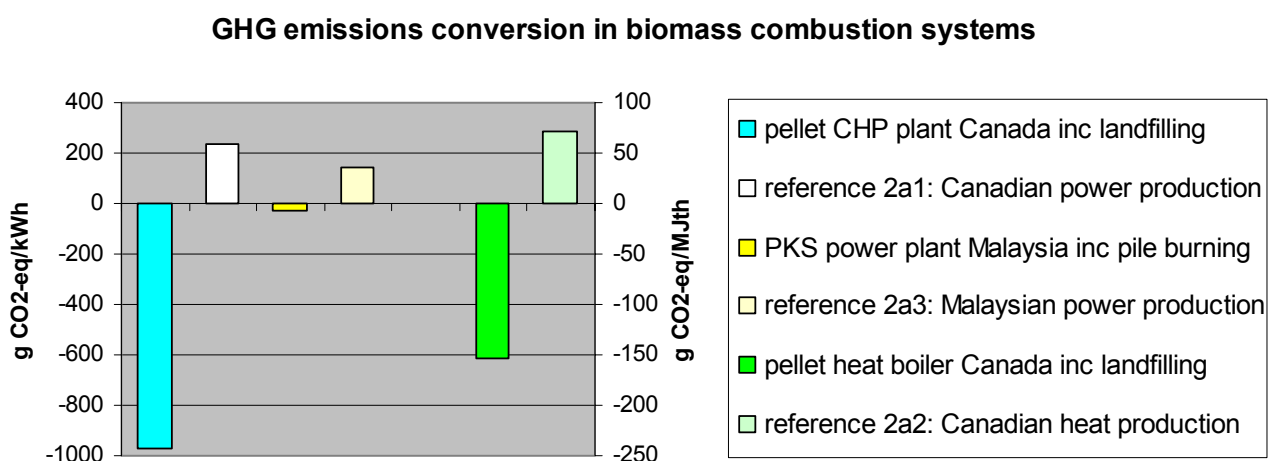


Figure 4-7: GHG emissions of pellets and PKS burning in stand-alone combustion systems in country of origin in comparison to reference power/heat production. Left axis for 4 columns left: emission allocated to electricity (g/kWh). Right axis for 2 columns right: emission allocated to heat (g/MJth).

Biomass import and co-firing versus internal use of biomass in country of origin

From figure 4-8 and 4-9, it can be concluded that biomass trade and co-firing is a more effective way to reduce GHG emissions than using the biomass in conversion systems in the country of origin for the studied cases. This is coherent with what we found for the net avoided primary energy of the different options. The difference is a bit underestimated, since the emissions involved with the production and transport of the fossil fuels, which are replaced when biomass is used in Canada/Malaysia, should be accounted for. For Canada, this value is expected to be low, since 60% of the electricity in Canada is produced at hydroelectric plants (which does not involve any direct emissions) and the fossil fuels that are used are produced in the country itself. Again, it must be reminded that a large share of the generated hydropower in Canada is exported to the USA (especially California), so the generation capacity for internal use is less efficient and more carbon intensive. Consequently, the GHG emissions of the reference cases are higher than the value given in figure 4-7, which makes the prospects for biomass utilization in Canada slightly better.

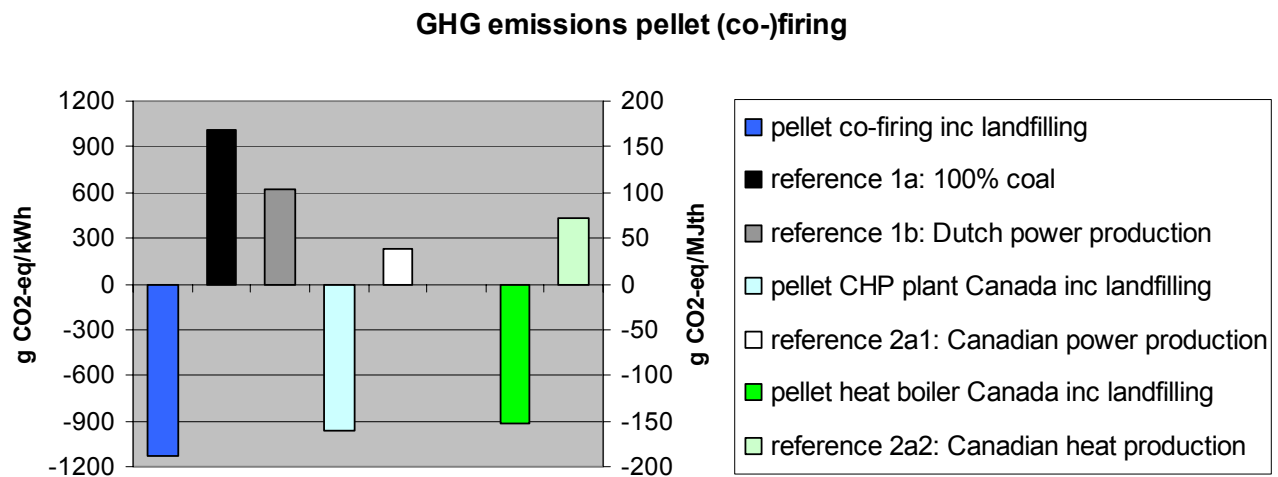


Figure 4-8: GHG emissions for utilization of pellets as (co-firing) fuel in different conversion systems in comparison to reference power/heat production. Left axis for 5 columns left: emission allocated to electricity (g/kWh). Right axis for 2 columns right: emission allocated to heat (g/MJth).

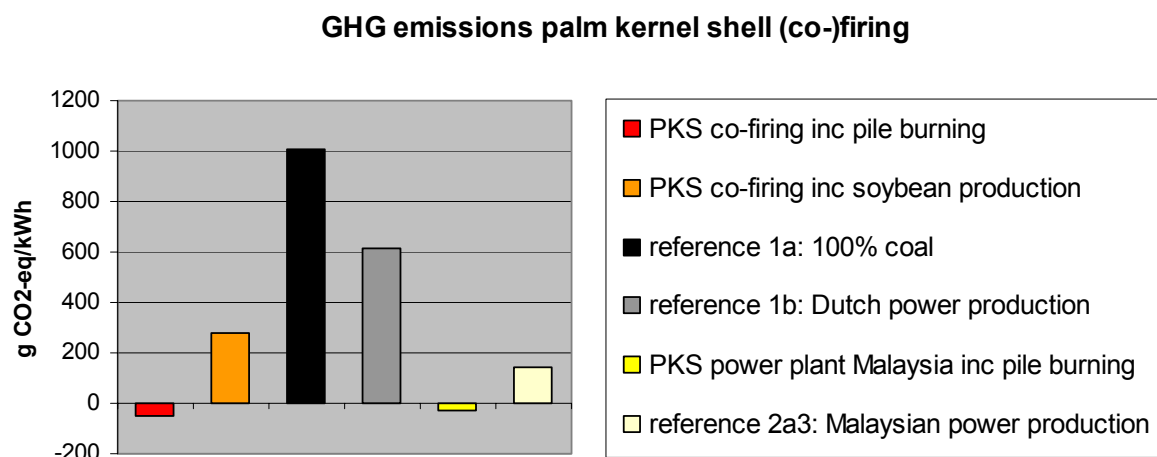


Figure 4-9: GHG emissions for utilization of PKS as (co-firing) fuel in different conversion systems in comparison to reference power production.

In Malaysia, mainly gas is used for electricity production, which is produced in the country itself and is probably transported by pipeline, so the emissions caused by transport of gas are expected to be limited.

4.3.2 NO_x, SO₂ and particulate emissions

Figure 4-10 and 4-11 show the breakdown of NO_x (as a sum of NO and NO₂), SO₂ and particulate emissions caused by biomass production, transport and co-firing for wood pellets and palm kernel shells, respectively.

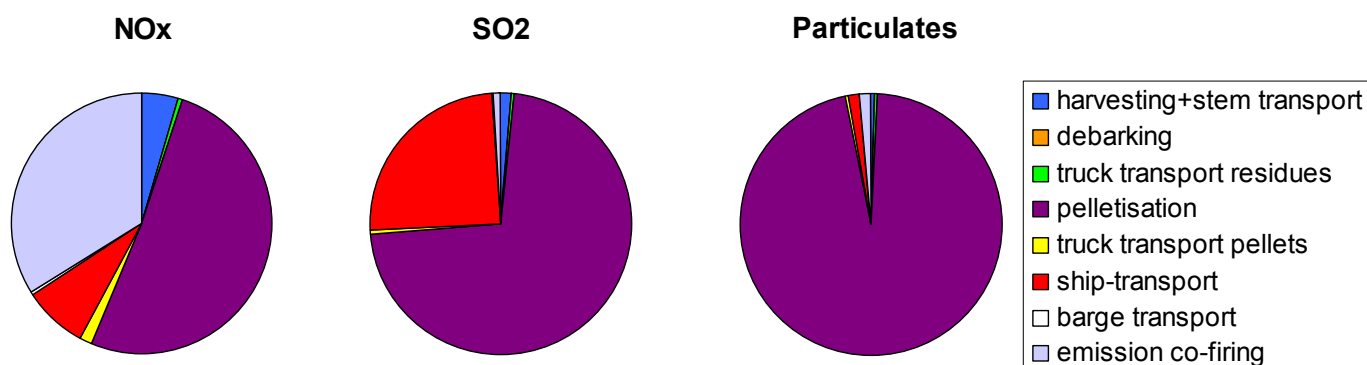


Figure 4-10: Breakdown of NO_x, SO₂ and particulates emissions for pellet import and co-firing in Amer plant

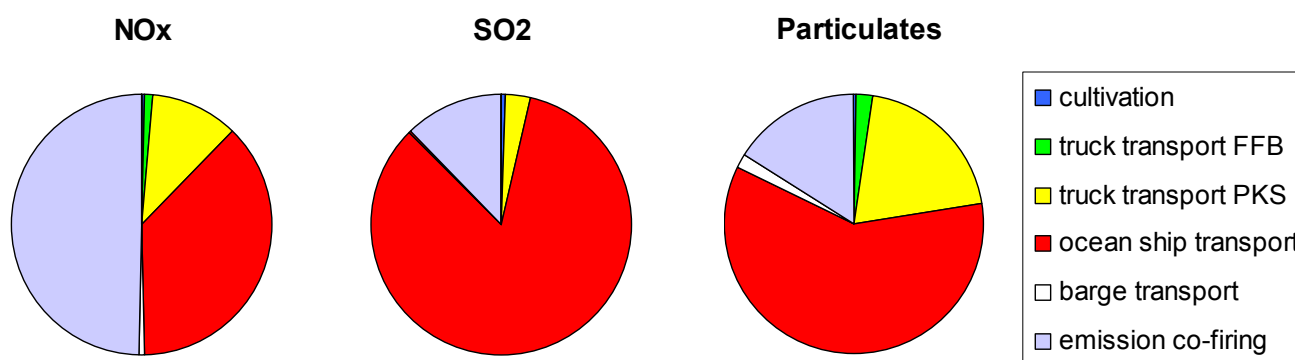


Figure 4-11: Breakdown of NO_x, SO₂ and particulates emissions for PKS import and co-firing in Amer plant.

As figure 4-10 shows, the contribution of pelletisation to NO_x, SO₂ and particulate emissions is large. These emissions are mainly caused by the boiler fuelled with sawdust to provide steam for the pelletisation process. The high emissions are probably due to the fact that it does not contain a flue gas cleaning system and the efficiency is relatively low. It is the question whether the data used for the boiler are representative for the boiler used in the pellet company in Canada; the emissions of these compounds might be overestimated. If the NO_x, SO₂ and particulate emissions of the boiler appear to be lower than the values used in the calculations, the contribution of the pelletisation process to total the NO_x, SO₂ and particulate

emissions will be much smaller. Consequently, the contribution of other processes (ocean transport) will become more important. This is a relevant issue in order to determine where the largest emission reductions can be achieved. For palm kernel shell import and co-firing, NO_x, SO₂ and particulate emissions are mainly caused by ocean transport and co-firing.

Table 4-7 gives the emissions of NO_x, SO₂ and particulates caused by biomass supply and co-firing, including avoided emissions of coal mining and transport and biomass decomposition/pile burning. The net emissions of NO_x, SO₂ and particulates for biomass co-firing and for the use of biomass in combustion systems in the country of origin are presented graphically in figure 4-12 and 4-13.

Table 4-7: NO_x, SO₂ and particulates emissions of pellet and PKS import and co-firing (g/kWh bio) and reference systems (g/kWh fossil).

Pellet import	NO_x	SO₂	particulates
biomass supply	2.03	1.66	1.26
co-firing	1.04	0.015	0.016
avoided coal transport	-0.73	-1.07	-1.29
net emissions	2.33	0.61	-0.007
PKS import			
biomass supply	1.05	1.38	0.084
co-firing	1.04	0.19	0.016
soybean production	1.10	0.96	0.12
avoided PKS burning	-4.73	-2.37	?
avoided coal transport	-0.73	-1.07	-1.29
net emissions vs PKS	-3.4	-1.86	?
burning			
net emissions vs soybean production	2.44	1.46	-1.06
Reference emissions			
1a: 100% coal	1.77	1.62	1.30
1b: Dutch power production	1.43	0.50	0.96

NO_x, SO₂ and particulate emissions co-firing

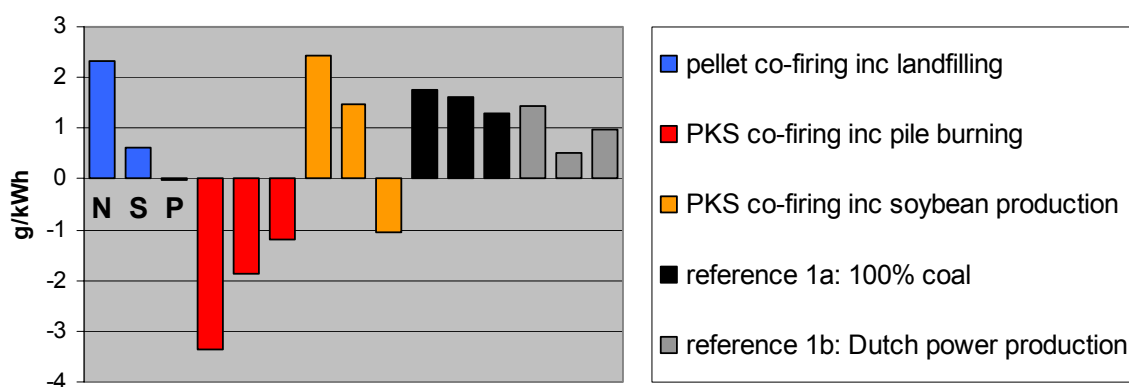


Figure 4-12: NO_x (N), SO₂ (S) and particulate (P) emissions of pellet and PKS import and co-firing in the Amer plant (g/kWh bio) in comparison to reference power production (g/kWh fossil).

NO_x, SO₂ and particulate emissions biomass combustion systems

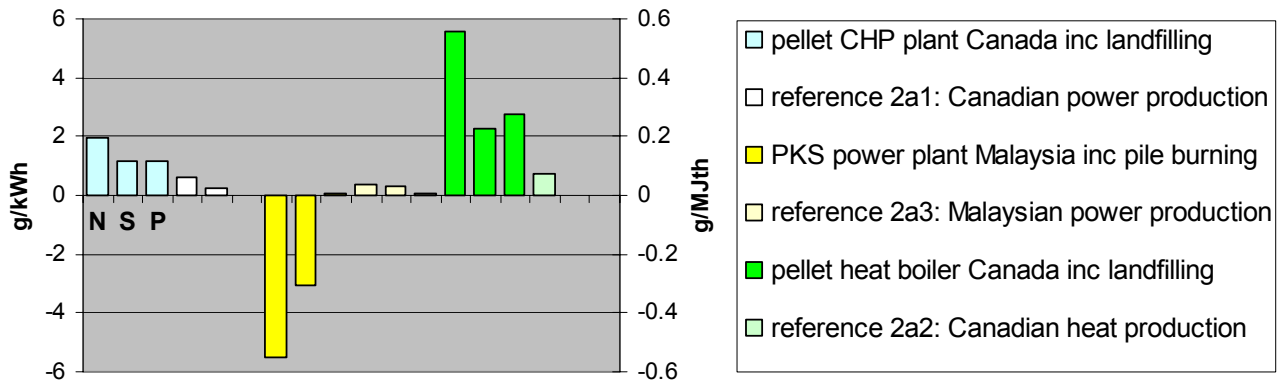


Figure 4-13: NO_x (N), SO₂ (S) and particulate (P) emissions of pellet and PKS use as fuel in stand-alone combustion systems in Canada and Malaysia in comparison to reference power/heat production. Left axis for 4 series left: emissions allocated to electricity (g/kWh). Right axis for 2 series right: emissions allocated to heat (g/MJth). The particulate emission of Canadian power/heat production is not visible, because they are low in comparison to other emissions.

Before the emission of each compound is discussed separately, some generic conclusions can be drawn. From figure 4-12, it can be observed that the prospects of biomass co-firing vary per compound and also depend on the reference system. Figure 4-13 shows that the emissions of NO_x, SO₂ and particulates caused by wood pellet burning in a CHP plant/boiler in Canada are significantly higher than the reference system, which is not very surprising considering the relatively “clean” Canadian energy system. Net emissions for palm kernel use in a central power plant are negative due to the avoided emissions of pile burning in the open air.

NO_x emissions

NO_x emissions of biomass (co-)firing are generally higher than the reference systems, except the case in which palm kernel shells are burned in the open air when not applied as (co-firing) fuel, because avoided NO_x emissions are very high. Total NO_x emissions are expected to increase when co-firing wood pellets in comparison to 100% coal, since NO_x emissions of biomass supply are higher than emissions caused by avoided coal mining and transport. As mentioned earlier, this can be explained by the high emissions of the boiler in the pellet production process; it is the question whether these emissions are indeed so high. Because the pelletisation process accounts for approximately 50% of total NO_x emissions, total NO_x emissions might decrease to a level of the fossil fuel references when the emissions of the boiler appear to be lower.

Another uncertainty is the impact of co-firing on NO_x emissions during power production itself. In the calculations, NO_x emissions per kWh biomass are assumed to be equal to those of coal. The Aspen calculations indicate that the sum of NO and NO₂ when 7% co-firing wood pellets will decrease with about 4%. When this reduction is completely attributed to biomass, the NO_x emissions per kWh biomass are about 57% lower than the emission of 100% coal. When co-firing palm kernel shells, an increase in NO_x emissions is predicted by the model due to the higher N-content in comparison to coal. When the co-firing share is 7%, the total NO_x emission increases with 10%. When this is completely attributed to biomass, the NO_x emission

is expected to increase with 150%! It must again be stressed that the N present in the additional coal is allocated to biomass as well. The results are given in more detail in appendix IV. The value of those results and the model will be discussed in the next chapter.

SO₂ emissions

The total emission of SO₂ when co-firing biomass are lower in comparison to the 100% coal reference, but slightly higher in comparison to the average Dutch power production. The SO₂ emission caused by the generation of an average Dutch kWh is lower than biomass co-firing and 100% coal combustion, which can be explained by the high share of power produced from natural gas. Natural gas has a low sulphur content in comparison to coal and moreover, power generation from natural gas is more efficient than from coal.

SO₂ emissions of palm kernel shells burning in the open air are relatively high, because all sulphur present in the fuel is emitted to the air. As a result, net SO₂ emissions of palm kernel shell utilisation as (co-firing) fuel are negative, offering good opportunities to reduce SO₂ emissions in this way.

Particulate emissions

Net particulate emissions when co-firing wood pellets and palm kernel shells appeared to be lower than the reference systems. For wood pellets import and co-firing, the net emissions are slightly negative, because the particulate emissions of avoided coal mining and transport compensate emissions caused by biomass supply and co-firing. The prospects are even better when the boiler in the pelletisation process has a (better) gas cleaning system to remove particulates.

Particulate emissions of palm kernel shell co-firing and use as fuel in biomass combustion plants in Malaysia are lower than the reference power production. However, particulate emissions of palm kernel shell burning in the open air are not accounted for, but are expected to be very high. So the net particulate emission of palm kernel shell use as (co-firing) fuel is even lower (more negative).

4.3.3 Heavy metal emissions

The emissions of heavy metals are given in the figure below. They include emission of Cd, Hg, Σ heavy metals (As, Co, Cr, Cu, Mn, Ni, Pb, Sb and V) to air and water occurring during coal mining and transport, biomass transport by ocean vessel and barge and air emissions occurring during co-firing. Since heavy metal emissions to surface water from the wastewater treatment unit of the power plant are not expected to change during co-firing, these are not accounted for. So the net emissions in figure 4-14 will be higher, but the difference with the reference situation (100% coal) will not change. Heavy metal emissions (apart from Cd and Hg) occurring during biomass production and transport on the road is not accounted for either, because no complete data were available for all these processes. However, the contribution to total heavy metal emission is expected to be limited.

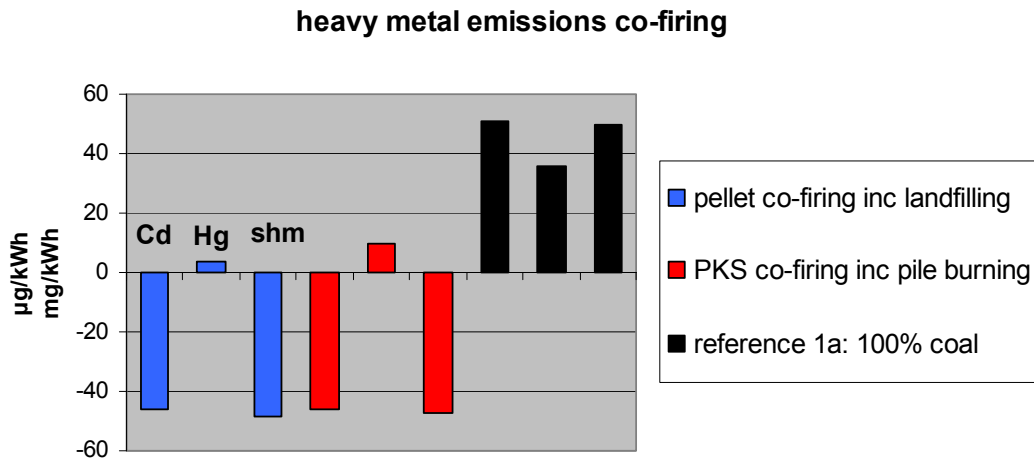


Figure 4-14: Heavy metal emission of pellet and PKS import and co-firing in the Amer plant in comparison to reference power production (µg/kWh fossil). The emissions of Cd and Hg are given in µg/kWh bio and the sum of other heavy metals (shm) is given in mg/kWh bio.

For all elements, importing biomass for co-firing shows lower emissions than for power production from 100% coal. With the exception of Hg, net heavy metal emissions are negative, which can be explained by the fact that avoided heavy metal emissions to air and water of coal mining and transport when co-firing are larger than the emissions occurring during biomass supply and co-firing. Especially emissions to water appeared to be large. Net Hg emissions are positive for all biomass import and co-firing cases, because Hg emissions of biomass co-firing are relatively large. Emissions of Cd and other heavy metals caused by biomass co-firing are lower, since the majority of these elements are encountered in fly and bottom ash. The emission of Cd at the power plant chimney when co-firing pellets and palm kernel shells increases in comparison to 100% coal, whereas the emission of Hg will decrease, since both biomass sources have a higher Cd content³ and a lower Hg content than coal. The emission of heavy metals will also increase when co-firing those biomass sources, mainly because the high manganese content, especially for wood pellets.

4.4 Ash and nutrients

The total ash production will be reduced when co-firing biomass, since the biomass sources considered in this study have a lower ash content than coal. The distribution of ash originating from biomass into fly ash and bottom ash is unknown. According to the mass balance for the Amer 9 unit for 100% coal given in (Boudewijn and Koopmans 2002), the sum of fly and bottom ash is 120 kg/t coal, corresponding to 3.41 g/kWh. As a consequence of co-firing, the total ash production will be reduced to 3.27 and 3.0 g/kWh for respectively 7% and 20% pellet co-firing. When co-firing palm kernel shells, ash production will be reduced to 3.35 and 3.27 g/kWh for co-firing shares of 7 and 20%.

The tables below give the nutrients removed from the biomass production system and present in the ash originating from the biomass after it has been burned.

³ Assuming the Cd content of pellets is 0.2 ppm (the Cd content of the coal mix is circa 0.1 ppm).

Table 4-8: Nutrient balance pellet import (kg/tdm pellets)

	Nutrients removed	Nutrients ash	Lack
N	-2.8	-	-2.8
P	± -0.20 ^a	0.20	±0
K	± -1.30 ^a	1.30	±0
Ca	± -4.97 ^a	4.97	±0
Mg	± -0.52 ^a	0.52	±0

^a Except for nitrogen, the nutrient content of biomass is not expected to change during biomass transport and burning; nutrients present in the biomass are encountered in the ash after combustion. Check: P-content for bark and sawdust (pine) is estimated at 300 and 43 ppm on dry basis, respectively (www.ecn.nl/phyllis). When using these numbers to calculate the P-content of pellets, a number of 0.23 kg/tdm is obtained, which is close to the ash concentration.

Table 4-9: Nutrient balance PKS import (kg/tdm shells)

	Nutrients removed ^a	Nutrients ash	Lack
N	-29	-	-29
P	± -8.29	8.29	±0
K	± -8.74 ^a	8.74	±0
Ca	± -0.01 ^a	0.01	±0
Mg	± -0.13 ^a	0.13	±0

^a Except for nitrogen, the nutrient content of biomass is not expected to change during biomass transport and burning; nutrients present in the biomass are encountered in the ash after combustion. It must be reminded that fertilizers are added to the system to retain nutrients in the soil.

5 Discussion

In this chapter, the most important limitations in methodology and uncertainties in data and assumptions are discussed. The same structure as the previous chapter will be maintained.

5.1 Mass balance

The mass balance of pellet production is quite complex, because the pellets are produced from different resources, which are delivered by different suppliers. In order to get a more accurate image of energy use and emissions, the origin of resources should be specified. Another aspect that is not accounted for is dry matter losses in both biomass supply systems. Although these losses are expected to be low (decomposition rates will be negligible due to low moisture content of both pellets and palm kernel shells), this should be confirmed.

5.2 Energy balance

Biomass supply

For most processes in the biomass supply chain, quite generic information on energy use and emissions were used, because more detailed information was not available. Moreover, it was not the purpose of this study to perform an extensive study of diesel use and emissions of forestry operations, truck and ship transport. However, some sources did not clearly define the features of the process/technology reported or the data were not really updated. This could be improved by using more updated and high quality information. Especially the energy use of ocean vessels should be checked, since the contribution of ocean transport on total energy use is significant.

Biomass co-firing

One of the major uncertainties, which can affect net avoided primary energy and emissions, is the efficiency drop caused by de-rating of the boiler and higher internal energy use caused by higher mass throughput when co-firing. As mentioned before, the necessity of de-rating depends on the boiler design. Unfortunately, the issue of de-rating is unknown for biomass co-firing shares of 20%, since there is hardly any experience with such high shares. The adaptation to 20% biomass co-firing was initialised recently and is still in an experimental phase. The mill capacity is enlarged at this moment, so soon it will be possible to calculate the additional power requirements of the mills when increasing the biomass co-firing share to 20%. Measurements during co-firing tests at the Naantali power plant in Finland showed that co-firing at blending ratios of 4-10% by mass, the power consumption of the mill crushing biomass/coal were higher than the mills crushing coal only. This effect was probably due to the high wearing of the grinding table of this mill (Kostamo 2002). Both boiler de-rating and the internal energy requirements are issues that should be considered in more detail to quantify the reduction in power production, since they might have significant impact on the total performance.

5.3 Emissions

Before the emission of each compound will be discussed in more detail, some general shortcomings and results will be discussed.

Since the data used for emissions of transport processes and heat/power production are generally quite generic and the quality is not always good, the results should be considered as guidelines. Especially the relatively high emission of CH₄, SO₂, particulates and heavy metals of (avoided) coal mining in comparison to power generation and biomass supply cause the net emission of those compounds when co-firing biomass to be lower than the reference systems. It should be confirmed that these emissions are indeed so high. Methane emissions associated with coal mining are indeed by far the largest within the coal fuel cycle (Fasella 1995). From table 3-6, it can be concluded that particulate emissions caused by coal mining might be significant, but SO₂ emissions are expected to be relatively small in comparison to power generation. When comparing the emissions of SO₂, particulates and heavy metals for mining and transport of the Dutch coal mix reported in SIMAPRO with the data given in GEMIS, it strikes that the emissions given in SIMAPRO are generally higher. So it can be concluded that the emissions of SO₂, particulates and heavy metals caused by coal mining and transport might be overestimated, which makes net emissions of biomass import and co-firing higher.

It is also striking that the emissions of all compounds (except CO₂) of biomass production and transport are high in comparison to emissions occurring during power production. This is partly explained by the high emissions caused by heat production in the pelletisation process. It must be noted that particulate emissions can easily be reduced with gas cleaning equipment (filters). The emissions caused by ocean transport are significant as well, which can be reduced by using more efficient technologies in ships.

Another uncertainty relevant for this study is the biomass fate/application when it is not used as (co-firing) fuel. It is not really clear what is actually done with the resources (especially for palm kernel shells), and the emissions of these processes could not be quantified accurately. In spite of those uncertainties, the method of different reference systems proved to be successful to show the range of emissions that can be expected.

A final issue worth mentioning is that the calorific value of the coal mix used in the calculations represents a minimum value; the coal mix actually burned has a higher calorific value than the value given in (Boudewijn and Koopmans 2002) used for the calculations. Co-firing biomass is more favourable when replacing coal with a lower calorific value, because more coal is replaced when co-firing biomass on energy basis. However, the impact on the net avoided primary energy is negligible when varying the LHV of the coal between 23 and 24.5 MJ/kg, the range of the coal mix provided by Essent.

CO₂

In this study, CO₂ emitted during biomass combustion/decomposition is assumed to make part of the short CO₂ rotation cycle and hence is not accounted for. However, there are alternative methods to account for CO₂ emissions originating from biomass. In a study of Mann (2001), a very similar study has been performed, in which an LCA is performed of biomass co-firing in a coal-fired plant in the US. The biomass used in that study is assumed to be wood residue. Because the biomass used at the power plant is not grown for the purpose of co-firing, a credit is not taken for the absorption

of CO₂ during the growth cycle. So in contrast to this study, the CO₂ emitted during power generation originating from biomass is accounted for, which makes the prospects for biomass residue co-firing as CO₂ mitigation option less promising.

CH₄

Since CH₄ has a higher GWP than CO₂ and moreover, CH₄ emissions are not negligible, it would be desirable to quantify this emissions more carefully. For both biomass import and co-firing chains considered, net CH₄ emissions are negative, which is mainly caused by the high emission occurring during biomass decomposition/burning and during (avoided) coal mining and transport. CH₄ emissions caused by biomass decomposition are expected to be strongly dependent from local conditions (temperature, moisture, O₂ availability), but it goes beyond the scope of this study to investigate this in more detail. However, it is of importance to confirm whether landfills receiving wood residues have methane recovery systems. In this study, a rather general number for emissions during coal mining of coal imported by the Netherlands has been used, representing coal from both underground and opencast mines from different countries. Since a large share of the coal purchased by Essent is produced at opencast mines, avoided CH₄ emissions might be lower than the generic value used in this study. Consequently, net GHG emissions when co-firing biomass are higher.

NO_x

The NO_x emissions for 100% coal calculated in the Aspen model are nearly a factor 10 higher than the value reported in (Boudewijn and Koopmans 2002). This confirms the fact that the Amer plant is equipped with low NO_x burners and a specially designed boiler, which reduces NO_x formation in the fireplace. The results from these model calculations must be considered as an indication what the effect of co-firing on NO_x emissions might be. The exact impact of co-firing during power generation on NO_x emissions cannot be modelled, since it is depending on many specific factors, which are related to boiler design and conditions. The impact of biomass co-firing on NO_x emissions requires more work. One of the activities to be undertaken is measuring NO_x emissions at the Amer 9 unit for different biomass sources and co-firing shares.

SO₂

It is not unreasonable to assume that SO₂ emissions occurring during co-firing are linearly dependent on the sulphur content of the fuel, since the capture efficiency of the flue gas desulphurisation unit is not expected to change when co-firing biomass. However, reality is somewhat more complicated. A small fraction of the SO₂ is converted into SO₃, which is to a large extent reabsorbed to form sulphates with the alkali metals in the fly ash. Part of the SO₂ also migrates to the fly ash, to what extent depends on the alkali earth metal content of the fly ash (Hamelinck and Faaij 2001). When co-firing biomass, the equilibrium between SO₂ and SO₃ might change, as well the distribution of sulphates between flue gas and fly ash particles. This needs to be verified by testing.

Particulates

Particulate emissions mainly occur during coal mining and limestone extraction. In this study, the impact of limestone extraction on particulate emissions has not been accounted for. Since the SO₂ emission during power generation is lower when co-

firing wood pellets, less limestone is necessary for the FGD. Table 3-6 shows that the impact of limestone mining/transport on the emission of CO₂, SO₂ and NO_x is low or expected to be low. An exception is particulate emissions caused by limestone extraction, which might be significant. This is confirmed in a study by Mann (2001), who concludes that the majority of the system particulates emission is due to the production of limestone. This issue deserves further attention.

Another weak spot is the particulate emission occurring during pelletisation process (from the boiler and in other parts of the process) and the transfer of wood pellets to ocean vessel. These might be significant and should be accounted for. Finally, a better distinction between coarse and fine particles is desirable. Especially fine particles (PM10) deserve special attention, since they are responsible for acute health impacts (Fasella 1995).

Heavy metals

According to the calculations performed in this study, the direct air emission of Hg at the power plant during co-firing will decrease, whereas the emission of Cd and the sum of other heavy metals will increase. This is confirmed for co-firing several biomass sources in (Boudewijn and Koopmans 2002). According to a calculation in the BIJSTER model (de Vos 2002), the emission of the sum of heavy metals increases with 16% when co-firing 10% biomass (a mixture of different biomass sources, among which wood and citrus pellets, palm kernel shells, and rest products of cacao) on energy basis. However, the increase observed in this study is relatively high due to the high content of Mn, especially in wood pellets.

In this study, the impact of biomass co-firing on heavy metal emissions to water are not included, because there were no data available and because heavy metal emissions to water do not significantly change when co-firing (Boudewijn and Koopmans 2002). It is concluded that 10% co-firing biomass does not affect the quality of the effluent of the FGD. For higher co-firing shares, this might become an issue.

The emissions of heavy metals (apart from Cd and Hg) during biomass production and transport should be considered as well, although it is expected that the emissions will be small in comparison to coal mining and power production.

Wastewater

The wastewater flow might increase as a result of biomass co-firing, because this flow mainly depends on the quantities of soluble salts in the effluent from the FGD. When the concentration of these salts increases, the wastewater flow is increased to maintain the water quality (Boudewijn and Koopmans 2002).

5.4 Ash recycling: nutrients and heavy metals

Generally, only the return of bottom ash originating from (clean) biomass is considered. Ash from a coal plant in which biomass is co-fired is generally more contaminated with heavy metals from coal and is therefore not suitable as fertilizer. However, a few critical notes are required with regard the use of ash as fertilizer:

- The release of nutrients and minerals from ash into the soil is a rather slow process, which makes its application as fertilizer less feasible.
- The ash from the Cuijk power plant, a stand-alone fluidised bed combustion system fuelled with non-contaminated biomass chips, does not fall within the standards of the regulation for organic fertilizers in the Netherlands. This is due to the fact that nearly all heavy metals (and nutrients) present in the biomass

precipitate on the fly ash in fluidised bed combustion systems (Remmers 2002). So for fluidised bed combustion system, ash recycling is less feasible.

- The biomass sources considered in this study have a relatively high heavy metal content (in comparison to other clean biomass sources and even to coal), which is mainly caused by the high Mn content. It is striking that the Mn content of both biomass sources is very high. Also the Cd content of palm kernel shells is high in comparison to coal, which is an important issue, due to the toxicity of Cd. So in this specific case, it is the question whether it is useful to make a distinction between ash from biomass combustion plants and ash from co-firing plants.

Although the heavy metal content of the considered biomass sources is relatively high, it should be realised that using biomass as fuel in stand-alone combustion plants can be seen as a way to concentrate and dispose a part of the heavy metals. In (Narodoslawsky and Obernberger 1996), a cadmium balance is set up for the sustainable recycling of wood ash from a conventional biomass combustion system. In this case study, the amount of wood ash recycled is equal to the amount of minerals withdrawn by wood harvesting. The figure shows that the cadmium flow caused by biomass harvesting and biomass utilization is relatively small compared with the deposition and wash out fluxes. It also shows clearly that recycling of wood ash does not result in an accumulation of Cd in the forest ecosystem, provided that the filter fly ash, containing the bulk of Cd, is separated and not recycled to the forest eco-system. Since other highly volatile heavy metals (Zn, Hg and Pb) show a similar distribution over the different ash fractions, it can be expected that these heavy metals can be removed from the forest eco-system as well. The bottom ash, which contains the majority of nutrients, may be recycled. Mn, which is mainly encountered in the bottom ash, deserves special attention for the biomass sources considered in this study, although its toxic effects are much less severe than Cd. The cyclone fly ash from biomass combustion systems still contains a relatively large amount of nutrients, approximately 40%, but also contain relatively large amounts of heavy metals. So this fraction is less suited as fertilizer. A medium term solution to the recycling of solid residues from biomass combustion is blending cyclone fly ash and bottom ash and using the mixture as fertilizer (Narodoslawsky and Obernberger 1996). A large part of nutrients might be recycled in this manner. However, the Cd content of cyclone fly ash may be too high in some cases, making it inappropriate as fertilizer even when it is blended with bottom ash.

6 Conclusion

In this study, a Life Cycle Inventory (LCI) was set up for 2 biomass import chains to provide a basis for judging the overall environmental impact of biomass import and its application as co-firing fuel in coal plants to generate electricity. This study is contracted by Essent Energie, a Dutch utility company, which is actively involved in biomass import and co-firing to increase its market share of green electricity. Since green electricity has a high market value, strict requirements are set on the environmental and socio-economic impact of the product. An LCI is the first step in the procedure to determine whether biomass import and co-firing is a sustainable process.

The biomass import chains considered were pellets produced from wood residues, which become available at saw/chip mills in Canada, and palm kernel shells, a residue of palm oil production in Malaysia. The main objective was to investigate the net avoided primary energy and emissions of the major greenhouse gasses and several other harmful compounds associated with biomass import and co-firing in the Amer 9 unit, a state-of-the-art 600 MW_e coal fired power plant in the Netherlands. The reference systems consisted of power production from 100% coal and the average Dutch power production and also included the fate of biomass when it was not applied as co-firing fuel. For wood pellets, decomposition at landfills was considered and for palm kernel shells, pile burning in the open air and resource for fodder production were considered. Biomass co-firing was also compared to the use of biomass in combustion systems to produce power/heat in the country where it is produced, in this case Canada and Malaysia.

As can be concluded from figure 6-1 and 6-2, biomass import and co-firing in coal fired plants in the Netherlands is an efficient way to reduce fossil fuel use and greenhouse gasses in comparison to power production from 100% coal or the average Dutch fuel mix.

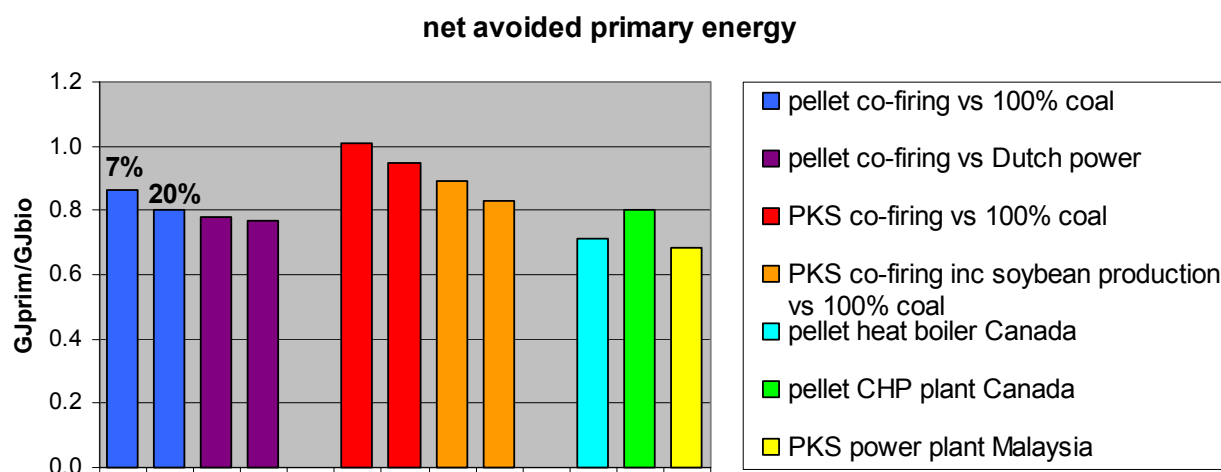


Figure 6-1: Net avoided primary energy per unit biomass energy of pellet and PKS import and co-firing and use in stand-alone combustion systems in the country where the biomass is produced. The left column of each series refers to 7% co-firing share (on mass basis) and the right column to 20%.

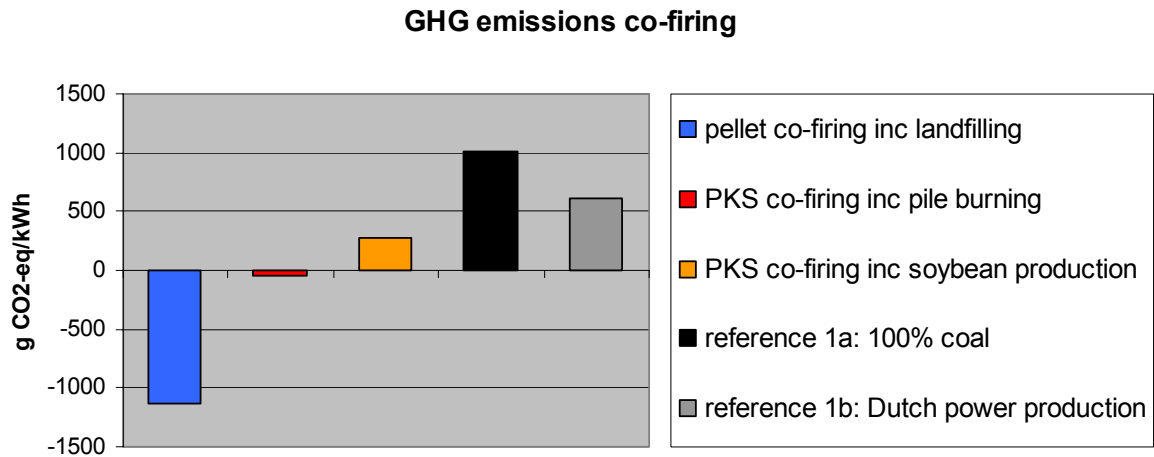


Figure 6-2: GHG emissions of wood pellet and PKS import and co-firing in the Amer plant (g/kWh bio) in comparison to reference power production (g/kWh fossil).

The emission of SO₂, particulates and heavy metals of biomass co-firing are also lower in comparison to emissions caused by power production from fossil fuels. This is mainly explained by the fact that coal mining and transport to the Netherlands is an energy consuming process causing high emissions of especially CH₄, SO₂, particulates and heavy metals. Also the avoided emissions of CH₄ caused by decomposition of wood residues at landfills in Canada and CH₄, N₂O, SO₂ and particulate emissions caused by palm kernel shells burning in the open air in Malaysia contribute to the positive impact of biomass import and co-firing.

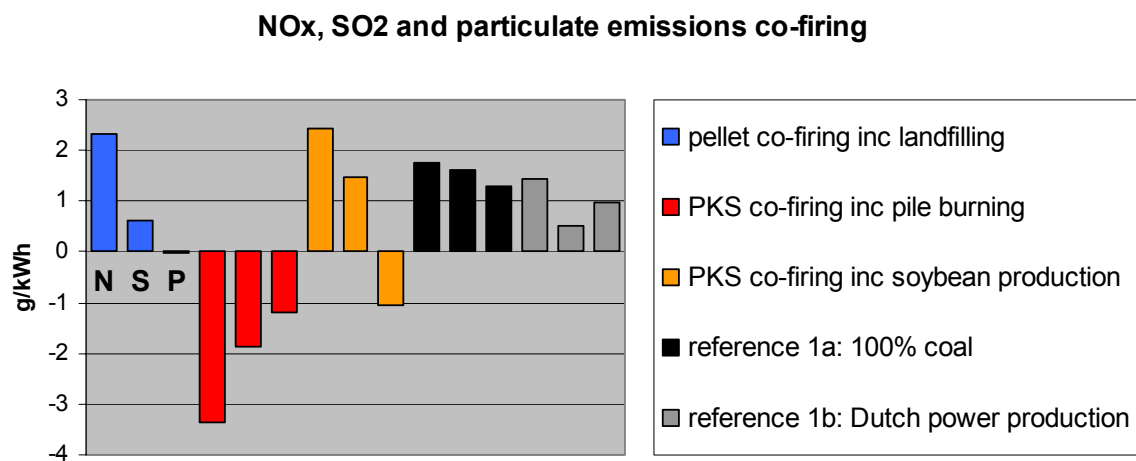


Figure 6-3: NO_x (N), SO₂ (S) and particulates (P) emissions of pellet and PKS import and co-firing in the Amer plant (g/kWh bio) in comparison to reference power production (g/kWh fossil).

According to the results of this study, biomass import and co-firing has some less desired impacts as well. NO_x emissions might increase when importing and co-firing of wood pellet. Co-firing the biomass sources considered in this study will also lead to an increase in heavy metal content of the ash, due to the high quantities of mainly Mn in both wood pellets and palm kernel shells. This could hamper the return of the ash to the country where the biomass was produced. Ash contains significant quantities of

nutrients required for biomass growth, so it would be desirable to recycle the ash to the forest in Canada or to the palm oil plantations in Malaysia.

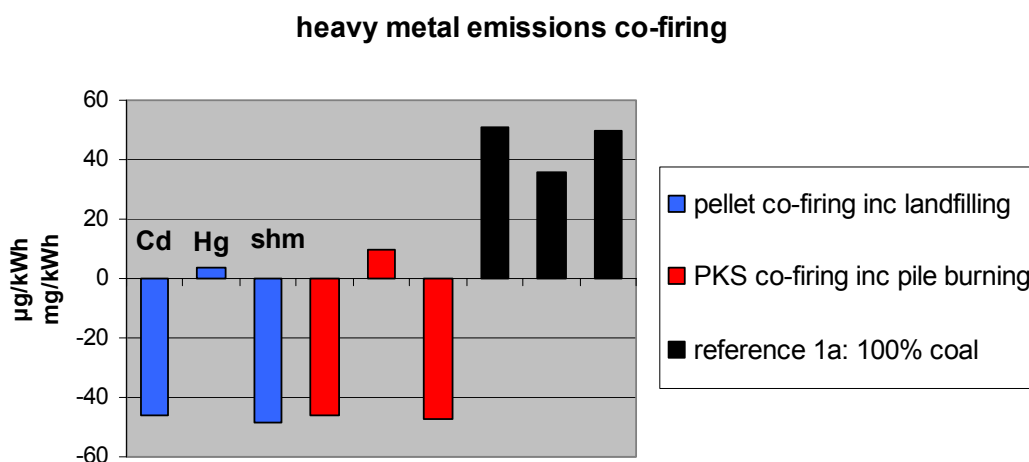


Figure 6-4: Heavy metal emission of pellet and PKS import and co-firing in the Amer plant in comparison to reference power production (µg/kWh fossil). The emissions of Cd and Hg are given in µg/kWh bio and the sum of other heavy metals (shm) is given in mg/kWh bio.

The prospects of pellet and palm kernel utilization as fuel in stand-alone combustion systems in the country where the biomass is produced is less promising than transporting the biomass to the Netherlands for co-firing purposes, in spite of energy use and emissions caused by sea transport over a large distance. This is explained by the lower efficiency of those relatively small-scale systems in comparison to the Amer plant considered for co-firing. Secondly, the relatively high energy use and emissions of coal mining and transport to the Netherlands is avoided when co-firing. A third reason that makes export preferable above intern use, is the larger share of renewables in the electricity mix of especially Canada, in which 60% of the electricity is produced in hydro-electric plants. It should be noted however, that when the efficiency drop caused by de-rating for co-firing shares higher than 7% appear to be significant, the use of pellets in a CHP in Canada might become more favourable.

The usefulness of an LCI is that it does not only make clear what the overall environmental performance of a considered chain is, but also which component contributes strongly to energy use and emissions. In this way it is possible to put the finger on components/processes, which require technological improvement or measures to improve energy efficiency and to reduce emissions. An example is the relatively high emission of NO_x, SO₂ and particulates caused by pelletisation and by ocean transport. These emissions can be reduced by introducing more advanced gas cleaning systems, filters and more efficient engines. It is expected that by introducing those technologies, the prospects (from energetic and environmental point of view) for biomass import can be improved significantly.

Finally, this study has shown that the choice of the biomass resource, origin and reference system is very important for the environmental performance of biomass import and co-firing. The country/region of interest where a biomass potential exists, local conditions and market effects of biomass trade should be considered with care. Crucial aspects are the type of biomass source, the fate of the biomass when it is not

exported, the internal demand (e.g. as energy carrier in the local industry), competition with other applications (e.g. resource for fodder production) and the energy system of a country. To take the example of biomass import to the Netherlands from Canada and Malaysia; the Netherlands import large amounts of coal to produce electricity. Canada and Malaysia both have a relatively efficient energy system and have large reserves of fossil fuels. So in this specific case, biomass export for co-firing purposes in countries like the Netherlands can be an effective way to save energy and reduce (GHG) emissions. In countries with a large biomass potential, which are strongly dependent on oil and coal, it would generally be wiser to use the biomass internally to reduce the dependence of energy intensive, polluting fossil fuels like oil and coal.

In summary, it can be concluded that not only the composition, availability and price of biomass should be decisive in biomass import, but also the context in which biomass production and trade occurs.

References

- Athanassiadis D, 2002, Personal communication on fuel and oil consumption forestry machines.
- Baumer P, 2002, Personal communication on soybean transport.
- Baumer P, Wisner B, Duffy M and Hofstrand D, 2000, Brazilian soybeans- Can Iowa farmers compete?, AgDM newsletter article.
www.extension.iastate.edu/agdm/articles/baumel/BaumelDec00.htm.
- Bird N, 2002, Personal communication on wood residues, Woodrising Consulting Inc.
- Bradley D, 2002, Personal communication on landfill regulations in Canada, Climate Change Solutions.
- Blok K, 2001, Energy analysis, Department of Science, Technology and Society, Utrecht University.
- Börjesson P, 1996, Energy analysis of biomass production and transportation, Biomass and Bioenergy, 11 (4): 305-318.
- Boudewijn R and Koopmans WF, 2002, Milieu-effectrapport (MER). Mee- en/of bijstoken van secundaire brandstoffen op het Amercentralecomplex te Geertruidenberg, Essent Energie Productie B.V.
- CIEMAT, 1999, ExternE Externalities of Energy, National Implementation, European Commission.
- CML, 2001, Life Cycle Assessment. An operational guide to the ISO standards.
- de Vos R, 2002, Personal communication on biomass resources, logistics and biomass co-firing in the Amer plant, Essent Duurzaam.
- Dick P, 2000, Personal communication on truck transport Thailand, The Freight Co. Bangkok.
- Dornburg V, 1999, A system analysis of biomass energy systems in relation to scale, Utrecht, Department of Science, Technology and Society, Utrecht University.
- Essent Duurzaam, 2001, Verslag dienstreis Halifax.
- Environment Canada, 2002, Harnessing the Power of Landfill Gas. Science and Environment Bulletin.
www.ec.gc.ca/science/sandemay99/article1_e.html
- Fasella P, 1995, ExternE Externalities of energy. Volume 3: Coal & Lignite, European Commission, Directorate-General for Science, Research and Development, Luxembourg.

- Feenstra F, Gigler J, de Mol R and Bosma R, 1994, Logistics concerning the collection of biomass (in Dutch), IMAG-DLO, Wageningen.
- Forest Products Laboratory, 1999, Wood handbook--Wood as an engineering material.
- Gustavsson L and Karlsson A, 2002, A system perspective on the heating of detached houses, *Energy policy*, 30: 552-574.
- Hamelinck CN and Faaij APC, 2001, Joule III COBIOCOWA: Modelling of the Narcea power plant for evaluating the impacts of various co-combustion schemes on plant performance and emissions, Department of Science, Technology and Society, Utrecht University.
- Hatton T, 1999, Canada's wood residues, National Climate Change Process.
- Hendriks F, 2000, Natural gas as a feedstock for automotive fuels. An alternative to crude oil, Utrecht, Science and Policy.
- Hooijmaijers F, 2002, Personal communication on coal logistics, Essent Energieproductie BV.
- Houghton JT, Meira Filho LG, Callander BA, Harris N, Kattenberg A and Maskell K, 1996, *Climate change 1995 - The science of climate change.*, Cambridge University Press, New York.
- Husain Z, Zainac Z and Abdullah Z, 2002, Briquetting of palm fibre and shell from the processing of palm nuts to palm oil, *Biomass and Bioenergy*, 22(6): 505-509.
- IEA, 2000, Energy balances of OECD countries 1997-1998.
- IEA, 2001, Energy balances of Non-OECD countries 1998-1999.
- IPCC, 1995, Greenhouse gas inventory. Reference manual. IPCC guidelines for national greenhouse gas inventories, volume 3.
- Jaques A, 2001, Canada's Greenhouse Gas Inventory 1990 -1999. Emission and Removal Estimation Practices and Methods.
http://www.ec.gc.ca/pdb/ghg/1990_99_report.
- Kaltschmitt M and Reinhardt GA, 1997, *Nachwachsende Energieträger. Grundlagen, Verfahren, ökologische Bilanzierung*, Vieweg.
- Kjellström B, 2002, Energy inputs for biofuel pellet production and long distance transport.
- Kostamo JA, 2002, Co-firing of sawdust in a coal fired utility boiler, *IFRF combustion Journal*.

- Mahlia TMI, Abdulmuin MZ, Alamsyah TMI and Mukhlishien D, 2001, An alternative energy source from palm waste industry for Malaysia and Indonesia, *Energy conversion and management*, 42: 2109-2118.
- Mann MK and Spath PL, 2001, A life cycle assessment of biomass cofiring in a coal-fired power plant, *Clean production processes*, 3: 81-91.
- Meij R, 1994, Trace element behaviour in coal-fired power plants, *Fuel process Technology*, 39.
- Narodoslawsky M and Obernberger I, 1996, From waste to raw material - the route from biomass to wood ash for cadmium and other heavy metals, *Journal of Hazardous materials*, 50: 157-168.
- Novem, 1999, Protocol Monitoring Duurzame Energie.
- Patterson D, 1988, *Commercial Timbers of the World*, Gower Technical Press, Aldershot, UK.
- Remmers R, 2002, Personal communication on Cuijk plant, Essent Duurzaam.
- Scherh H and Yang XB, 1999, Risk assessment for sudden death syndrome of soybean in the north-central United States, *Agricultural systems*, 59(3): 301-310.
- Schonewille W, 2002, Personal communication on ocean vessels, Port of Rotterdam.
- Shamsuddin AH, 2002, Personal communication on palm oil production.
- Smit R and Nieuwlaar E, 1994, Life Cycle Assessment of integrated coal gasification combined cycle, Department of Science, Technology and Society, Utrecht University.
- Stadig M, 2002, Personal communication on co-firing and wood pellets from Canada. Essent Duurzaam.
- Suurs R, 2002, Long distance bioenergy logistics, Utrecht, Department of Science, Technology and Society, Utrecht University.
- TLR, 2002, Certificate of Analysis, Technical Laboratory Rotterdam BV.
- van der Drift A, 2002, Personal communication on biomass composition, ECN.
- Wagener M, 2002, Personal communication on co-firing, Essent Duurzaam.
- Wambeck N, 2002, Oil palm tree matrix, www.biomass-energy.com/files/oilpalmtreeatrix.htm.

Appendix I: Emissions cultivation, harvesting, road and water transport

Table I-1: Emissions fertilizer production/application (Kaltschmitt and Reinhardt 1997)

Compound	Emission (g/Kg N)
CO ₂	2764
CH ₄	6.69
N ₂ O	13.24
NO _x	11.68
SO ₂	3.76
Particulates	0.78

Table I-2: Emissions wood harvesting (GEMIS “Forestry cutting logs pine”)

Compound	Emission (g/tdm wood)
CO ₂	1.81E+04
CH ₄	1.39E+01
N ₂ O	5.04E-01
NO _x	1.42E+02
SO ₂	1.90E+01
Particulates	1.16E+01
Cd	3.30E-06
Hg	1.37E-05

Table I-3: Emissions truck, pay load 27 t (GEMIS “Truck-trailer-rural euro 1 32-40 tons”)

Compound	Emission (g/tkm)
CO ₂	9.05E+01
CH ₄	1.07E-01
N ₂ O	2.67E-03
NO _x	7.44E-01
SO ₂	1.43E-01
Particulates	3.89E-02
Cd	1.13E-07
Hg	2.60E-07

Table I-4: Emissions truck, pay load 3 t (GEMIS “Truck-D-rural<7.5 t”)

Compound	Emission (g/tkm)
CO ₂	3.25E+02
CH ₄	4.35E-01
N ₂ O	2.30E-02
NO _x	2.28E+00
SO ₂	5.17E-01
Particulates	2.03E-01
Cd	6.45E-07
Hg	1.41E-06

Table I-5: Emissions ocean vessel (SIMAPRO “Freighter oceanic ETH”)

Compound	Emission (g/tkm)
CO ₂	8.58E+00
CH ₄	1.16E-02
N ₂ O	4.70E-05
NO _x	1.02E-01
SO ₂	1.72E-01
Dust	7.77E-03
Cd	2.88E-07
Hg	1.00E-08

Table I-6: Emissions barge (SIMAPRO “Freighter inland ETH”)

Compound	Emission (g/tkm)
CO ₂	5.87E+01
CH ₄	1.14E-01
N ₂ O	6.84E-04
NO _x	4.40E-01
SO ₂	1.57E-01
Dust	7.16E-02
Cd	3.00E-06
Hg	3.52E-07

Appendix II: Emissions electricity and heat production

Table II-1: Emissions electricity production Netherlands (GEMIS “el-generation-mix-NL”)

Compound	Emission (g/MJe)
CO ₂	1.62E+02
CH ₄	3.08E-01
N ₂ O	7.67E-03
NO _x	3.97E-01
SO ₂	1.40E-01
Particulates	2.67E-01
Cd	1.84E-08
Hg	3.91E-08

Table II-2: Emissions electricity production Canada (GEMIS “el-generation-mix-Can”)

Compound	Emission (g/MJe)
CO ₂	6.19E+01
CH ₄	8.61E-02
N ₂ O	2.90E-03
NO _x	1.67E-01
SO ₂	7.38E-02
Particulates	5.98E-03
Cd	9.07E-09
Hg	2.07E-08

Table II-3: Emissions electricity production Malaysia (composed from fuel mix Malaysia (see table 3-17 in section 3.5.2 and emissions of coal, oil and gas fired power plant with steam cycles (GEMIS “coal/gas/oil-ST-big-generic”))

Compound	Emission (g/MJe)
CO ₂	1.35E+02
CH ₄	4.75E-01
N ₂ O	3.31E-03
NO _x	3.73E-01
SO ₂	3.03E-01
Particulates	3.19E-02
Cd	1.44E-08
Hg	3.04E-08

Table II-4: Emissions heat production Netherlands (GEMIS “gas boiler NL”)

Compound	Emission (g/MJth)
CO ₂	6.79E+01
CH ₄	6.08E-02
N ₂ O	1.41E-03
NO _x	7.36E-02
SO ₂	1.26E-03
Particulates	1.18E-03
Cd	5.36E-09
Hg	1.12E-08

Table II-5: Emissions heat production Canada (GEMIS “gas boiler CAN”)

Compound	Emission (g/MJth)
CO ₂	6.93E+01
CH ₄	6.33E-02
N ₂ O	1.38E-03
NO _x	7.38E-02
SO ₂	9.31E-04
Particulates	5.59E-04
Cd	5.91E-09
Hg	1.23E-08

Table II-6: Emissions heat production pellet production (SIMAPRO “furnace wood B”)

Compound	Emission (g/MJth)
CO ₂	1.29E+02 ^a
CH ₄	2.33E-02
N ₂ O	1.75E-02
NO _x	2.79E-01
SO ₂	2.16E-01
Dust	2.23E-01
Cd	2E-07
Hg	2.75E-07

^a CO₂ emissions is assumed to be 0 when using sawdust as fuel

Appendix III: Emissions coal mining

Table III-1: Emissions mining and transport Dutch coal mix (SIMAPRO “Imported coal Netherlands”)

Compound	Emission (g/kg)
CO ₂	2.04E+02
CH ₄	3.35E+00
N ₂ O	3.88E-03
NO _x	1.99E+00
SO ₂	2.89E+00
Dust	3.49E+00
Cd	1.37E-04
Hg	4.65E-06

Appendix IV: NO_x calculations Aspen plus

100% coal

	COAL	BIOMASS	AIR	FLUE
Temperature C	15	15	15	1200
Pressure bar	1		1	1
Vapor Frac	0.367		1	1
Mole Flow kmol/hr	7890.658	0	27737.12	29912.25
Mass Flow kg/hr	100000	0	799121.5	899121.5
Volume Flow cum/hr	68919.47	0	664461.4	3.66E+06
Enthalpy MMkcal/hr	39.164		-1.979	-258.356
Mole Flow kmol/hr				
C	4995.421	0	0	0
H2	1440.562	0	0	0.076
O2	250.259	0	5547.424	39.459
H2O	666.101	0	0	2106.587
N2	42.837	0	22189.7	22189.7
NO	0	0	0	85.346
NO2	0	0	0	0.037
N2O	0	0	0	0.145
CO	0	0	0	0.444
CO2	0	0	0	4994.977
S	495.478	0	0	495.478

7% wood pellets

	COAL	BIOMASS	AIR	FLUE
Temperature C	15	15	15	1200
Pressure bar	1	1	1	1
Vapor Frac	0.367	0.497	1	1
Mole Flow kmol/hr	7457.698	580.827	27699.22	29948.02
Mass Flow kg/hr	94513	7000	798029.6	899542.6
Volume Flow cum/hr	65137.86	6928.985	663553.5	3.67E+06
Enthalpy MMkcal/hr	37.015	2.687	-1.976	-265.57
Mole Flow kmol/hr				
C	4721.322	291.982	0	0
H2	1361.518	191.678	0	0.077
O2	236.528	95.4	5539.844	41.013
H2O	629.552	0	0	2182.671
N2	40.486	0.675	22159.38	22159.38
NO	0	0	0	82.023
NO2	0	0	0	0.037
N2O	0	0	0	0.131
CO	0	0	0	0.437
CO2	0	0	0	5012.867
S	468.291	1.091	0	469.383

7% PKS	COAL	BIOMASS	AIR	FLUE
Temperature C	15	15	15	1200
Pressure bar	1	1	1	1
Vapor Frac	0.367	0.587	1	1
Mole Flow kmol/hr	7479.318	593.272	27703.43	30002.05
Mass Flow kg/hr	94787	7000	798150.9	899937.9
Volume Flow cum/hr	65326.7	8343.993	663654.4	3.68E+06
Enthalpy MMkcal/hr	37.122	1.502	-1.977	-264.56
Mole Flow kmol/hr				
C	4735.01	244.985	0	0
H2	1365.465	222.826	0	0.086
O2	237.213	78.123	5540.686	34.892
H2O	631.377	27.199	0	2246.782
N2	40.603	6.739	22162.75	22162.75
NO	0	0	0	94.272
NO2	0	0	0	0.039
N2O	0	0	0	0.187
CO	0	0	0	0.471
CO2	0	0	0	4979.524
S	469.649	13.399	0	483.048