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A GREENHOUSE GAS BALANCE OF TWO EXISTING INTERNATIONAL BIOMASS IMPORT CHAINS

THE CASE OF RESIDUE CO-FIRING IN A PULVERISED COAL-FIRED POWER PLANT IN THE NETHERLANDS

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Abstract. Various utility companies are considering or already initiated the import of biomass from abroad for electricity generation, especially via co-firing in coal-fired power plants. This results in international logistic biomass supply chains, which raise questions on the environmental performance of such chains. In this study, a life cycle inventory has been performed on two existing biomass import chains to evaluate the greenhouse gas balance of biomass import for co-firing. We considered production, transport and co-firing of wood pellets from Canada and palm kernel shells from Malaysia in a 600 MW_e coal-fired power plant in the Netherlands. Those chains are compared with various reference systems for energy production and the alternative use of biomass. Primary energy savings of these import and co-firing chains are between 70% and 100% of the biomass energy content. Net avoided greenhouse gas emissions are in the range of 340–2100 g/kWh. In the most optimistic scenario, pellet co-firing avoids methane emissions that would have occurred if the pellets were decomposed at landfills when not applied for energy production. In the most pessimistic scenario, palm kernel shell co-firing competes with the application as resource for animal feed production, which requires production and transport of an alternative resource. As the energy reference systems of the importing and exporting country and the alternative application of biomass have a significant impact on the net avoided greenhouse gas emissions, these factors should be considered explicitly when studying biomass trade for energy purposes.

Keywords: co-firing, international biomass trade, life cycle inventory, palm kernel shells, wood pellets

1. Introduction

Bio-energy is on the energy policy agenda of various countries as a strategy to mitigate greenhouse gas (GHG) emissions, reduce dependency on fossil fuels from unstable regions and/or stimulate regional economies. Estimations for global biomass potentials for energy purposes are potentially large, the upper range exceeding 1000 EJ/yr in 2050 (Berndes et al. 2003; Hoogwijk et al. 2003). The bulk of this potential lies in the production of energy crops on abandoned agricultural land. It has been estimated that circa 130–270 EJ/yr of energy crops may be produced at costs below 2 $ /GJ (Hoogwijk 2004), corresponding to 30–60% of the present world energy consumption. The potential for agricultural and forest residues estimated from various studies varies between 20 and 48 EJ/yr in 2050 (Hoogwijk et al. 2003). As the biomass supply potentials and demand centres are not evenly distributed across the globe, international biomass trade among various regions is foreseen. Regions that may become net exporters over time are Eastern Europe and Russia, Oceania, Sub-Saharan Africa, East Asia and parts of Latin and North America (Hoogwijk 2004). Potentially large importers of biomass energy are various EU member states (Faaij 2005) and other countries with a large dependency on fossil fuel imports like Japan.

While the long-term opportunities for biomass trade are promising, biomass markets are already developing all over Europe (most notably in Scandinavia), from purely regional to international markets. Growing international trade of biomass and biomass-derived energy carriers can be observed (Faaij 2005). Two example countries where biomass trade is gaining ground are Sweden and the Netherlands. The former imports wood chips, stem wood, pellets and tall oil from The Baltic States, Germany, the Netherlands and North America, mainly for application in district heating (Ericsson and Nilsson 2004). In the Netherlands, biomass import has been increasing significantly current years, principally driven by the objective to reduce GHG emissions by increasing the share of renewable electricity. The Dutch government set a target of 10% renewable energy of the domestic primary energy demand in 2020, mainly in the form of electricity (Minister of Economic Affairs 1995). Biomass is considered to play a key role in the realisation of this target; about 40% of the renewable energy should be produced from biomass. Since the availability of indigenous biomass resources of good quality is limited and prices tend to be high (Agterberg and Faaij 1998), Dutch utility companies are (considering) importing biomass from other countries. Co-firing biomass with coal is the most important conversion route, being relatively cheap (modest investments are required to adapt coal-fired power plants), efficient and resulting in direct replacement of coal (van Loo and Koppejan 2002). Biomass resources from other countries used so far include wood pellets, palm kernel shells (PKS), olive kernel pulp and cacao kernels.

Given the fact that various biomass streams are being traded internationally and these markets are likely to expand, questions arise on the environmental impact of these logistic chains, especially the (avoided) GHG emissions. The primary objective of this study is to set up an energy and GHG balance for two *existing* biomass import chains by means of a life cycle inventory. The considered chains consist of production, transport and co-firing wood pellets from Canada and palm kernel shells from Malaysia in a 600 MW_e coal-fired power plant in the Netherlands. These chains currently represent two major streams for co-firing purposes (M. Wagener 2002, personal communication). The former are produced from residues that become available in the large forestry industry in Canada. Palm kernel shells are process residues produced in the palm oil industry.

The energy use and GHG emissions related to biomass import and co-firing are compared to several reference systems. These include electricity/heat production and the application of biomass when it would not have been used for energy purposes. Since the reference systems can be fairly different, which may affect net avoided energy use and GHG emissions, this aspect is explicitly accounted for in our analysis.

As biomass trade raises the question whether biomass potentials would not better be used more efficiently in the country where it is produced, also local use of biomass in heat boilers and dedicated power plants is considered. By comparing the net avoided primary energy and GHG emissions of local energy systems with co-firing in the Netherlands, it can be evaluated whether international biomass trade is a desirable strategy for some of the currently available biomass resources. In addition, critical factors that affect the outcome can be identified, which might serve as criterion for the assessment of other biomass trade schemes.

In Section 2, the methodology is discussed, followed by the description and input data of the various system components in Section 3. The results of the analysis are given in Section 4 and will be discussed more extensively in Section 5. Finally, conclusions will be drawn in Section 6.

2. Methodology

A life cycle inventory (LCI) covers the first two steps in a life cycle assessment (LCA) (CML 2001). This method enables systematic quantification of inputs (resources) to the system and outputs (emissions) to the environment, from resource extraction to final product use and disposal (Cradle-to-the-Grave approach). The primary parameters to evaluate biomass use as (co-firing) fuel are the net avoided primary energy and GHG emissions. Only 1st and 2nd order energy inputs (based on LHV) and the most important GHG emissions (CO_2, CH_4 and N_2O) are accounted for. In a more extensive report (Damen and Faaij 2003), also the emissions of NO_x, SO_2, particulates and heavy metals are accounted for to give a more complete view on the overall environmental performance.

2.1. DEFINITION OF THE CONSIDERED CHAINS

Figure 1 illustrates the different chains considered in this study: import and co-firing of biomass (system 1) and the use of biomass in the country where it is produced as a fuel in different dedicated combustion systems (system 2). Each chain is compared to one or more reference systems, which include energy production and the application of biomass when it is not used as (co-firing) fuel.

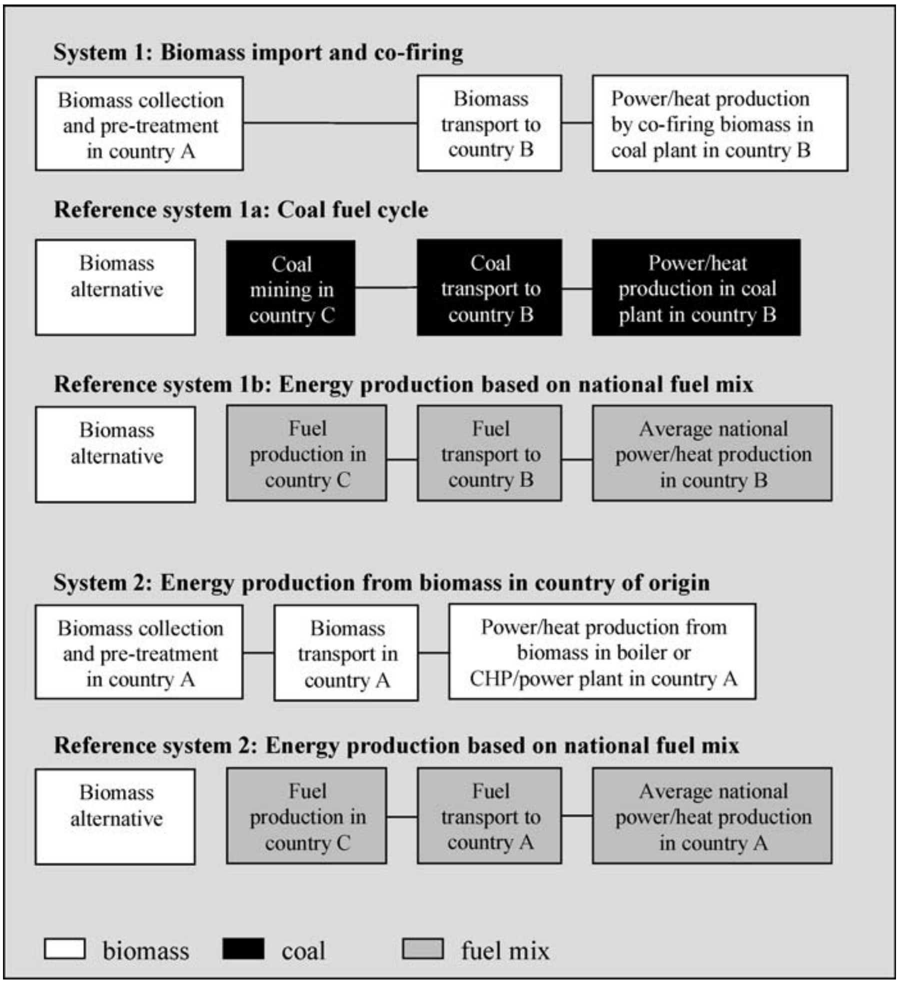


Figure 1. Various biomass chains versus reference systems. Country A: biomass producing country (Canada/Malaysia). Country B: biomass importing country (Netherlands). Country C: coal/gas/oil producing country, can be country A/B.

2.1.1. *System 1*

System 1 includes the production and transport of biomass from Canada and Malaysia to the Netherlands, where it is co-fired in a coal-fired power plant.

2.1.2. *System 2*

System 2 consists of biomass use in the country where it is produced as fuel for a dedicated combustion system (fired with 100% biomass). In Canada, basically

2 options can be distinguished. The pellets can be used as fuel in a combined heat and power (CHP) plant or can be used as a fuel for boilers to produce heat in detached houses. For Malaysia, where no heat market as in Canada exists, we consider production of electricity in a power plant.

2.1.3. *Energy Reference System 1a/b*

We consider both a coal-fired power plant (1a) and the average Dutch fuel mix for electricity generation (1b) as reference for system 1. The former is the most logical reference system, as the co-fired biomass in fact replaces a part of the coal. However, it can also be argued that the electricity produced by co-firing biomass in a coal-fired power plant replaces electricity from the grid.

2.1.4. *Energy Reference System 2*

The reference system consists of the average electricity/heat generation in the country where biomass is produced based on the national fuel mix (Canada and Malaysia).

2.1.5. *Biomass Reference System*

The application of biomass when it is not used as (co-firing) fuel depends on the resource and the context in the exporting country. The excess of wood residues in Canada is dumped at landfills or stock piled (Hatton 1999). In this study, it is assumed that the excess of wood residues not used for pellet production is disposed at a landfill site. This implies that methane emissions caused by decomposition at the landfill site are avoided when using the excess of residues for pellet production.

The major part of the palm kernel shells is used as fuel in the local palm oil industry. The excess is 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). Malaysia is also a large exporter of oil cake and other solid residues of oil from palm nuts and kernel (UNCOMTRADE 2003), which is used as resource for animal feed production. A growing demand of PKS for energy purposes abroad may cause competition with use for animal feed production.

In this study, we consider a best-case scenario (burning the excess of PKS in the open air) and a worst-case scenario (using the excess of PKS as resource for animal feed production in the Netherlands), to get insight in the ranges of net avoided primary energy and GHG emissions. In the best-case scenario, the use of PKS excess as (co-firing) fuel will avoid the emissions caused by pile burning. If PKS are used as resource for animal feed production, the energy use and emissions associated with the production and transport of an alternative resource for animal feed production should be accounted for.

2.2. NET AVOIDED PRIMARY ENERGY

The net avoided primary energy is defined as the substituted primary energy (coal for reference system 1a or fuel mix for reference system 1b and 2) minus:

- primary energy to produce and transport the biomass. In our analysis, the energy use (and emissions) caused by cultivation/harvesting and transport of the main product is partly allocated to the residues. This can be justified, as the residues represent a market value when used for energy purposes. As the price of residues is variable, we allocate on mass basis between main products and residues. One may argue not to allocate production and transport expenses of the main product to the residues and only consider the additional processes required for energetic use and their alternative application. This would result in a more positive result for biomass export. In the discussion, we will briefly come back to the impact of allocation rules.
- primary energy loss as a consequence of co-firing. When co-firing biomass, the electricity output can decrease versus 100% coal[1] for several reasons (Tillman 2000; Hamelinck and Faaij 2001; van Loo and Koppejan 2002):
  - Increase of internal energy use (mills, ventilators which cycle air through the mills, flue gas desulphurisation and flue gas ventilators).
  - Biomass has a different chemical composition, which affects the combustion characteristics and consequently the boiler efficiency.
  - With increasing biomass co-firing share, a decrease of carbon burnout could occur.
  - 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. Relatively more air is required to burn the fuel mix in comparison to coal only, which causes a higher throughput of flue gas through the boiler. This may result in a lower heat transfer for steam production. 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.

In the scenario that PKS would be used for animal feed production in the Netherlands if not used as co-firing fuel, the net avoided primary energy is the substituted primary energy minus:

- primary energy use of PKS transport from the main port (where animal feed production site is located) to the power plant where PKS is co-fired.
- primary energy use to produce and transport an alternative resource to produce an equivalent amount of fodder.

Net avoided primary energy

- For system 1 versus reference system 1a:

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

in which:
η: net avoided primary energy per unit biomass energy (MJ_{prim}/ $\text{MJ}_{\text{biomass}}$)
$\%_{\text{biomass}}$: 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})
$\eta_{\text{coalsupply}}$: efficiency coal production and transport
$\eta_{e,\text{coal}}$: electric efficiency 100% coal
$\eta_{e,\text{cofiring}}$: electric efficiency co-firing
$\eta_{e,\text{average}}$: average electric efficiency Dutch fuel mix
$E_{\text{biosupply}}$: energy required for the production and transport of the biomass (MJ_{prim})
$E_{\text{alternative}}$: energy use/production of alternative biomass application, which is either dumping at landfills or animal feed production (MJ_{prim})
E_{biomass}: biomass input (MJ_{bio})

- For system 1 versus reference system 1b:

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

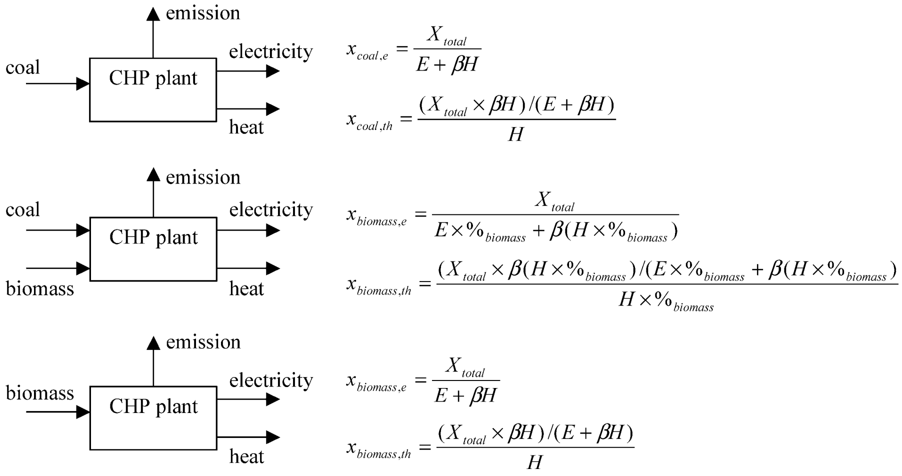
- For system 2:

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

in which:
$\eta_{e,\text{biomass}}$: electric efficiency biomass-fired power plant
$\eta_{\text{th,biomass}}$: thermal efficiency heat boiler
$\eta_{e,\text{average}}$: average electric efficiency Canada/Malaysia
$\eta_{\text{th,average}}$: average thermal efficiency.

2.3. NET AVOIDED GHG EMISSIONS

The net avoided GHG emission of biomass use as (co-firing) fuel is the emission of 1 kWh “reference” electricity/heat minus the emission of 1 kWh



$$x_{coal,e} = \frac{X_{total}}{E + \beta H}$$

$$x_{coal,th} = \frac{(X_{total} \times \beta H)/(E + \beta H)}{H}$$

$$x_{biomass,e} = \frac{X_{total}}{E \times \%_{biomass} + \beta(H \times \%_{biomass})}$$

$$x_{biomass,th} = \frac{(X_{total} \times \beta(H \times \%_{biomass}))/(E \times \%_{biomass} + \beta(H \times \%_{biomass}))}{H \times \%_{biomass}}$$

$$x_{biomass,e} = \frac{X_{total}}{E + \beta H}$$

$$x_{biomass,th} = \frac{(X_{total} \times \beta H)/(E + \beta H)}{H}$$

Figure 2. Formulas to calculate emissions related to different conversion systems; $x_{\text{coal,e:}}$ emission of compound X for 100% coal allocated to electricity (g/MJ$_e$); $x_{\text{coal,th}}$: emission of compound X for 100% coal allocated to heat (g/MJ$_{\text{th}}$); $x_{\text{biomass},e}$: emission of compound X allocated to electricity from biomass (g/MJ$_e$); $x_{\text{biomass,th}}$: emission of compound X allocated to heat from biomass (g/MJ$_{\text{th}}$); X_{total}: total emission of compound X (g); E: net electricity production (MJ$_e$); H: net heat production (MJ$_{\text{th}}$); β: ratio between the exergy and enthalpy of the heat produced, which is depending on the temperature of the steam. Typical values for β are 0.4 for process steam and 0.1 for hot water in district heating systems (Blok 2001); $\%_{\text{biomass}}$: biomass co-firing share on energy basis.

"green" electricity/heat (produced by biomass production, transport and conversion, including avoided/additional emissions of alternative biomass use). In Figure 2, the different conversion systems with the formulas to calculate the emissions occurring during conversion are given. Allocation of emissions to electricity/heat in a CHP plant is done on exergy basis, which also reflects the "energy quality" of electricity and heat and is therefore considered more realistic than allocation on energy basis. The additional emissions caused by de-rating are allocated to the biomass. CO_2 emissions caused by pile burning or decomposition of biomass are assumed to be zero, since the released CO_2 makes part of the short-rotation cycle; it is absorbed by the trees/crop again in a next growth cycle. Emissions of CH_4 and N_2O when co-firing are assumed to be equal to emissions of 100% coal.

3. System Components

In this section, the different chain components considered are described in detail, including the input data required to perform the LCI. Case specific data provided by companies involved in biomass import and co-firing were used for biomass composition, production, transport and co-firing. For energy use and process emissions such as transport and power generation from national fuel mixes, scientific

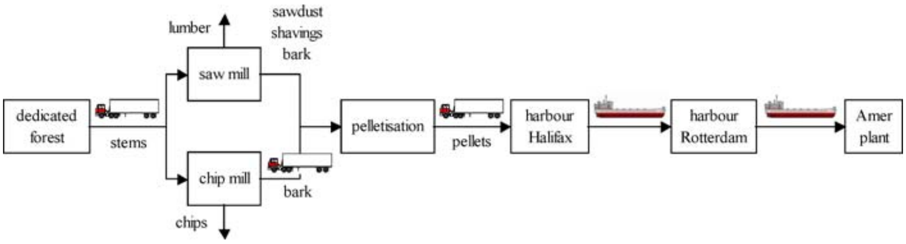


Figure 3. Pellet production in Canada and transport to the Netherlands.

publications and reports, statistics and LCA databases (GEMIS and SIMAPRO 5.0) were used. Direct and indirect GHG emissions of transport (diesel and heavy fuel oil) are derived from (IPCC 1997; Hekkert et al. 2005).

First, the biomass supply chains are discussed in Sections 3.1 and 3.2, followed by the characterisation of the energy conversion systems (including reference electricity and heat production) in Sections 3.3 to 3.7. Sections 3.8 and 3.9 describe the alternative applications of biomass.

3.1. PELLETS PRODUCTION IN CANADA

In several regions in Canada, large amounts of wood residues become available at chip mills and sawmills, among which bark, sawdust and shavings. These residues can be used to produce pellets, a high quality fuel with a high energy density. Pellets can directly substitute coal. Due to the high energy density, pellet transport is more efficient and cheaper than transport of untreated biomass like chips. Also pellets can be stored for long periods without aerobic degradation. The total logistic chain we consider is given in Figure 3.

3.1.1. *Production and Logistics of Wood Residues*

Wood is extracted from a large forestry area in Nova Scotia. Harvesting is performed mechanically, after which a forwarder carries the logs to the road and loads them to a truck.[2] Energy use of single-grip harvesters and forwarders for Swedish conditions are used (see Table I). The best trees are delivered to sawmills (at circa 75 km) and the logs of lower quality are transported to chip mills (at circa 50 km) by trucks with a capacity of 35 tonnes (Mg). Diesel consumption of trucks is set at 0.4 MJ/tkm [3] after (Hamelinck et al. 2003).

At the saw/chip mill, the logs 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. The diameter of the stems varies between 9 and 25 cm with a typical density (fresh weight) of 800 kg/m^3 (Patterson 1988). The residues from the sawmills (sawdust, bark and shavings) and the chip mills (bark) are transported to the pellet plant by similar trucks used for wood transport. The average transport distance between the chip mill and the pellet plant is estimated at 75 km. The

TABLE I

Energy use and capacity of biomass harvest (D. Athanassiadis 2002, personal communication)

Single-grip harvester	
Capacity (m^3/productive machine h)	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	
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

TABLE II

Resources to produce 100,000 Mg pellets (moisture content: 7%)

Resource (Mg)	Moisture content	Supplier
72,000 bark	57%	Sawmill
41,000 sawdust	50%	Sawmill
27,000 shavings	17%	Sawmill
22,000 bark	50%	Chip mill
46,000 bark	50%	Other mills

sawmill is located very close to the pellet plant, so additional transport of residues from the sawmill is not required.

3.1.2. *Pellet Production*

The pellets production plant considered in this study (Fulghum Fibre fuels) produces about 100,000 Mg pellets annually. This requires 169,000 Mg/yr of residue-mix and 39,000 Mg/yr of sawdust for heat production (see Table II).

First, the residues are crushed by a coarse hammer mill, after which they are dried 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 heat required for the process is provided by a boiler, which is fired with sawdust. Electricity requirements are 125 kWh/Mg pellets. Diesel and lubrication oil for internal transport and loaders given in (Kjellström 2002) are used (39.6 and 7.9 MJ/Mg pellets, respectively). We used CH_4 and N_2O emissions of a heat boiler fired with pine wood given in SIMAPRO.

3.1.3. *Pellet Transport to Conversion Plant*

Pellets are transported to the harbour of Halifax over a distance of 60 km by similar trucks used for wood and residue transport.[4] At the harbour, the pellets are stored in large silos and loaded to a sea ship with a capacity of circa 9,000 tonnes. Heavy fuel consumption is estimated at 0.12 MJ/tkm based on fuel consumption of bulk vessels with comparable capacity (Hamelinck et al. 2003). Fuel consumption for the return trip is not accounted for, since this ship transports another bulk good on the way back. The distance between Halifax and Rotterdam is circa 5,000 km. In Rotterdam, the pellets are transferred to barges with a capacity of circa 2,000 tonnes, which deliver the biomass to the Amer power plant, located 52 km from the Rotterdam harbour. Energy use of transfer is not accounted. Diesel use of the barges is assumed to be 0.43 MJ/tkm after (Kaltschmitt and Reinhardt 1997). Fuel consumption of the return trip (empty cargo holds) is 65% of the full load consumption level (Wasser and Brown 1995).

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 (EFB) and palm oil mill effluent. Fresh fruit bunches (FFB) contains (by weight) about 21% palm oil, 6–7% palm kernel, 14–15% fibre, 6–7% shell and 23% EFB (Husain et al. 2002). The total logistic chain for PKS production, transport and co-firing is given in Figure 4.

Diesel input for palm cultivation is 5.1 GJ/ha/yr (Wambeck 2002). Main fertilizer inputs are 100 kg N/ha/yr (we consider ammonium nitrate), 45 kg P_2O_5/ha/yr in the form of phosphate rock, 205 kg K_2O/ha/yr in the form of potassium chloride and 50 kg MgO ha/yr in the form of kieserite (Raof et al. 1999; FAO 2002). Energy use and (non-energy related) emissions of fertilizer (intermediate) production are derived from an extensive LCA study (Brentrup 2002). For N_2O emissions occurring during fertilizer application, we use a factor of 1.25% N_2O-N of total N applied (IPCC 1997).

The average FFB yield is approximately 25 Mg/ha/yr (Mahlia et al. 2001). The fresh fruit bunches are harvested manually and transported to the mill located within

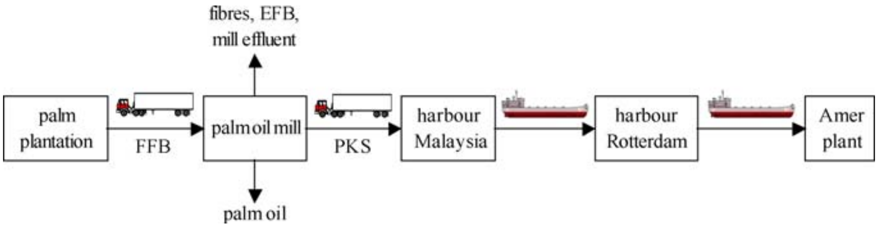


Figure 4. Palm kernel shell (PKS) production in Malaysia and transport to the Netherlands (EFB: empty fruit bunches, FFB: fresh fruit bunches).

a range of 1–10 km from the plantations (Shamsuddin 2002, personal communication). Diesel consumption of the trucks (capacity of 5 t) is assumed to be 1.8 MJ/tkm (Dick 2000, personal communication).

At the mill, palm oil is extracted from the mesocarp and kernel of the matured fruits. Between 50 and 70% of the available shells are required for electricity and steam requirements of the process (Shamsuddin 2002, personal communication). The palm kernel shells, which become available at mills in the entire country, are transported to the harbour (Port Klang and Kuantan port) by trucks similar to those used for FFB transport. An average distance of 100 km is assumed. At the harbour, the shells are loaded to an ocean vessel of the type Panamax with a maximal capacity of circa 60,000 tonnes. HFO consumption of these ships is 0.04 MJ/tkm (Hamelinck et al. 2003). The distance between the Malaysian harbours and Rotterdam is circa 15,500 km. In Rotterdam, the cargo is transferred to barges, which deliver the biomass to the Amer power plant.

3.3. System 1: Biomass co-firing

Since a few years, different types of biomass are co-fired in the Amer-9 unit, a state-of-the-art pulverised coal-fired power plant equipped with low NO_x burners operated by Essent, located in the province of Noord-Brabant, the Netherlands. It has a net electric and thermal capacity of 600 MW_e and 350 MW_{th}, respectively. The low-calorific heat is supplied to a district heating system and a horticulture complex. In this study, base case calculations are performed assuming no heat is produced resulting in a net electric efficiency of 42.5% (Boudewijn and Koopmans 2002). The plant is operating approximately 7600 hr/yr at full capacity.

Biomass is mixed with coal and transported to the boiler house, where the mix is crushed by a mill and fed to the boiler. The plant has run steadily with co-firing shares between 6 and 8 weight % (wt%) of the original coal input. Recently, the plant has been adapted to increase the biomass co-firing share to approximately 20 wt% of the original coal input, but there is still little operative experience with such high co-firing shares. In this study, both co-firing shares of 7 and 20 wt% are considered, corresponding to 6 and 16% on LHV basis for pellets and 5 and 15% for PKS. The composition of wood pellets, PKS and coal, based on specific analyses, is given in Table III.

Modelling the impact of co-firing on the electric efficiency of the Amer plant performed by Essent indicated that the efficiency will hardly be affected when co-firing pellets and PKS at low co-firing shares (6–8 wt%).

In order to estimate the reduction in electric efficiency when co-firing biomass at a co-firing share of 20 wt%, results of Aspen modelling to calculate the impact of biomass co-firing in a Spanish coal-fired power plant are used (Hamelinck and Faaij 2001). Co-firing 4.3% sawdust (LHV basis) gives a modest decrease in net electric efficiency from 33.4% to 33.2%, whereas co-firing 46.5% wood residues leads to an efficiency drop to 29.2%. The efficiency penalty is caused by higher internal energy

TABLE III

Fuel composition (ar: as received, db: dry basis)

Resource	Wood pellets	Palm kernel shells	Coal mix
LHV (MJ/kg, ar)	18.03	17.13	23
Bulk density (kg/m^3, ar)	600	750	
Proximate analysis (wt%, ar)			
Moisture content	5.16	7	12
Ash	2.01	5.8	13.2
Volatiles	72.14	63	
Ultimate analysis (wt%, ar)			
C	50.1	42	60
H	5.5	6.4	2.9
O	43.6	35.7	8.0
N	0.27	2.7	1.2
S	0.02	0.24	0.7
Elemental analysis (ppm, db)			
As	<0.5	4.2	
Cd	<0.2	0.4	0.1 (inc. Tl)
Co	4.4	2	
Cr	51	14	
Cu	4.2	25	
Hg	<0.03	0.1	0.34
Mn	720	265	
Ni	38	3.5	
Pb	<5	9	
Sb	<3	3.5	
V	<1	8.5	
Sum heavy metals	Max. 827	335	118
Sum heavy metals without Mn	107	70	
Nutrients in ash (wt% of ash)			
P_2O_5	2.75	37.9	
CaO	32.79	12.35	
MgO	4.08	0.35	
K_2O	7.39	16.85	

use for drying and milling, decrease of carbon burnout and boiler de-rating.[5] These numbers are corrected for the energy use of drying, which is not required in case of pellets and PKS. This results in an efficiency penalty of 3% (or 1.3% points) when co-firing 20 wt% pellets and PKS, assuming a linear relation between efficiency penalty and co-firing share (on LHV basis). Based on data from various co-firing tests at coal-fired power plants, Mann and Spath (2001) estimated the efficiency penalty for 15% co-firing wood waste (LHV basis) at 3%. However, the moisture content of wood waste is 50%, which is considerably higher than the moisture content of wood pellets and PKS. Tillman (2000) derived a generic equation to relate co-firing share on mass basis with boiler efficiency reduction based on tests with co-firing wood waste at various power plants. When applied to our case, this results in a reduction of the boiler efficiency with 1.9% (this does not include the efficiency loss due to higher internal electricity use for the feeding lines). In this analysis, we assume an efficiency penalty of 3%. The impact of co-firing on the efficiency is further discussed in Section 5.

3.4. SYSTEM 2A: CHP FIRED WITH 100% BIOMASS

A state-of-the-art biomass-fired CHP in Cuijk, the Netherlands, serves as reference for the CHP plant in Canada. The plant has a bubbling fluidised bed boiler and is equipped with a catalytic and non-catalytic DeNOX and electrostatic precipitators. For the dedicated power plant in Malaysia, the performance of the Cuijk plant operating in condensing mode (without heat production) is used. The plant is fuelled with non-contaminated wood chips and is operating approximately 7000 hr/yr at full capacity. The electric and thermal efficiency and emissions are given in Tables IV and V, respectively. Although the electric efficiency might vary slightly with different biomass feedstocks (due to difference in composition, heating value, moisture content etc.), this is not accounted for.

3.5. SYSTEM 2B: HEAT PRODUCTION IN HOUSEHOLDS

We used data of a pellet boiler to produce heat in households reported in (Gustavsson and Karlsson 2002) for the Swedish context. 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. GHG emissions for 15 kW pellet boilers reported in GEMIS are used.

TABLE IV

Energy in and outputs Cuijk plant (MW, on LHV basis), a CHP plant fuelled with wood chips

	Condensing mode	CHP mode
Fuel input	82	82
Net electric capacity	26.3	21.3
Thermal capacity[a]	0	40
Net electric efficiency	32.1%	26.0%
Total net efficiency	32.1%	74.8%

[a] Process steam at circa 20 bar (Remmers 2002, personal communication).

TABLE V

Direct measured emissions Cuijk plant in 2001

Compound	Maximum concentration (mg/m$_o^3$, 6 vol% O_2)[a]
CO_2	0
C_xH_y (inc. CH_4)	<2
NO_x	99
SO_x	<2
Dust	6
Cd	0.0001
Hg	0.0008
Sum heavy metals	0.06

[a] Exhaust gas (dry): 28 Nm^3/s. Input: clean wood (Remmers 2002, personal communication).

TABLE VI

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_2O[a]	0.01
NO_x[a]	1.04
SO_x[a]	0.56
Dust[a]	0.016
Trace elements	(μg/kWh$_e$)
Cd + Tl[a]	0.083
Hg[a]	34.1
Heavy metals[a]	71.2

[a] Annual emissions reported in (Boudewijn and Koopmans 2002).

[b] Estimate from conventional coal-fired power plants is 1g/GJ (CIEMAT 1999).

3.6. ENERGY REFERENCE SYSTEM 1A: PULVERISED COAL-FIRED POWER PLANT

The Amer plant fuelled with 100% coal (as described in Section 3.3) is used as reference system 1a. The emissions caused by power production are given in Table VI. The coal mix is imported from mines (the majority opencast) in Poland, South-Africa, Colombia, Australia and Indonesia. The primary energy required for mining and transport of the Dutch coal mix reported in SIMAPRO is 11% of the calorific value.

3.7. Energy reference system 1b and 2: National electricity and heat production

The average efficiency of Dutch electricity production (reference 1b) as reported in the GEMIS database is circa 41% (including energy input for production and transport of fossil energy carriers). Canada has a high overall electric efficiency of circa 60%, which is caused by the relative high share of hydropower with an efficiency set at 100% (IEA 2000). The overall efficiency of electricity production in Malaysia is 45% (IEA 2001). For heat production, an average efficiency of 90% is assumed based on gas-fired boilers reported in GEMIS and SIMAPRO. Emission factors of national electricity and heat production from GEMIS were used.

3.8. Biomass reference system: Wood residues in Canada

Decomposition at landfills occurs under mostly anaerobic conditions, resulting in a gas composed of approximately 50% CO_2 and 50% CH_4 (Bingemer and Crutzen 1987; Barlaz 1998; Hatton 1999). Only a part of the non-lignin compounds (basically cellulose and hemicelloluse) is degraded. Mann and Spath (2001) assumed 50% of cellulose and hemicelloluse is degraded in the full lifetime[6] in which landfilled wood will contribute to climate change, based on experiments assessing decomposition of non-lignin compounds in branches (Eleazor et al. 1997; Barlaz 1998). This corresponds to 35% of the carbon present in biomass. Recent experiments in which landfills in Australia have been excavated indicate much lower degradation rates (Gardner et al. 2002). The amount of carbon present in wood products that has been decomposed varied between 2.5 and 4.1% for 2 landfills of 19 and 29 years old, respectively. This corresponds well with the range of 0–3% of carbon decomposition in wood products calculated by (Micales and Skog 1997). In this study, we consider a range of 3 to 35% in the amount of carbon that is being decomposed at landfills.

Of the formed methane, approximately 10% is oxidised into CO_2 by soil microbes (Bogner 1992). Landfill gas capture is generally not practiced at wood waste landfills in Canada (Hatton 1999).

3.9. Biomass reference system: Palm kernel shells in malaysia

3.9.1. *Pile Burning in Open Air*

Burning of crop residues in the open air is a significant source of CH_4, CO, NO_x, N_2O and particles. The GHG emissions occurring during pile burning are calculated using a method to estimate emissions of field burning of agricultural residues given in (IPCC 1997):

$$CH_4 = \text{carbon released} \times \text{emission ratio} \times 16/12$$

$$N_2O = \text{carbon released} \times (\text{N/C ratio}) \times \text{emission ratio} \times 44/28$$

Carbon released is the amount of carbon present in the biomass multiplied with the fraction oxidised, which is typically 90%. The average emission ratio for CH_4 and N_2O are 0.005 and 0.007, respectively (IPCC 1997).

3.9.2. *Alternative Resource Animal Feed Production*

The Netherlands is the main importer of Malaysian palm oil residues, accounting for nearly 70% of the Malaysian export in 2003 (UNCOMTRADE 2003). Palm kernel shells are one of the components of mixed feed for mainly cattle, and also pigs (Neessen et al. 2003). If palm kernel shells are used for animal feed production, an equivalent amount of an alternative resource must be produced and transported. Animal feed is a mix of a large variety of resources, the most important being cereals (wheat, barley), oil-containing products and by-products (soya bean (meal), rapeseed (meal), palm kernel shell), seeds, pulses and tuber (potato, sugar beet) (Neessen et al. 2003). The exact composition of animal feed may vary substantially; an optimal resource mix is modelled, accounting for resource prices, energy content, protein content and quality (Hin 2002). We assume PKS can be replaced by soya bean meal in a 1:1 ratio. Soya bean meal, a by-product of soya bean crushing, is an important animal feed resource (especially for pigs), representing circa 15% of resources used in mixed feed (Hin 2002). It is imported from the USA, Brazil and Argentina or produced in the Netherlands from imported soya beans. In 2000, more than 60% was produced in the Netherlands, the rest was imported (Hin 2002). In our analysis, we assume soya bean import from the USA and production of soya bean meal in the Netherlands. We consider soya bean production in Iowa, USA. Soya beans are transported to New Orleans by train (320 km) and barge (2100 km), from where they are transported to Rotterdam over sea, a distance of 9000 km. This is a typical transport route for soya bean export to Europe (Baumer 2002, personal communication). In Rotterdam, the soya beans are finally crushed to produce soya oil and soya bean meal.

Primary energy inputs for soya bean production in the USA are 916 MJ/t (GEMIS). Energy use of train transport is 0.7 MJ/tkm for a train with a loading capacity of 800 tonnes (30 carriages) (Börjesson 1996). Emissions occurring during soya bean production and train transport from GEMIS are used. Crushing 1 Mg of soya beans generates approximately 0.17 Mg soya oil and 0.76 Mg soya bean meal (Sheehan et al. 1998). Electricity, natural gas and steam requirements for the soya bean crushing process (excluding oil extraction, recovery and treatment) are 63.5 kWh/Mg beans, 1114 MJ/Mg beans and 767 MJ/Mg beans, respectively (Sheehan et al. 1998). Steam is produced in a natural gas-fired boiler with an efficiency of 90%. Energy use and corresponding emissions of soya bean cultivation, transport and crushing are allocated to soya bean meal on mass basis.

4. Results

4.1. ENERGY

In Figure 5, the primary energy use for the production and transport of pellets and PKS is given.[7] The primary energy use of these operations corresponds to 7–10% of the biomass heating value when exporting to the Netherlands versus 3–7% when used locally. We did not include the bio-energy required in the pelletisation process (sawdust for heat production), which represents circa 17% of the pellet heating value.

Figure 6 shows the primary energy that can be avoided by (co-) firing 1 MJ of biomass versus various energy and biomass reference systems. The results indicate that the use of pellets as fuel for dedicated CHP plants or heat boilers in Canada is less efficient than export to the Netherlands for co-firing purposes at co-firing shares up to 7 wt.% to replace electricity produced from 100% coal. This can be explained by the high electric efficiency of the Amer plant. Another reason is that coal mining and transport to the Netherlands is energy intensive, whereas in Canada, electricity produced from biomass replaces electricity, of which circa 60% is produced in hydro-electric plants. However, the energetic performance when co-firing 20 instead of 7 wt% pellets (assuming an electric efficiency penalty of 3%) is decreased to a level similar to local application as fuel for CHP plants or heat boilers.

For PKS co-firing, the net primary energy avoided is similar as for pellet co-firing provided that PKS would otherwise be pile burned. In the scenario that soya beans are imported from the USA to produce soya bean meal as replacing animal feed resource, the net avoided energy decreases with circa 16% in comparison to the case considering PKS pile burning.

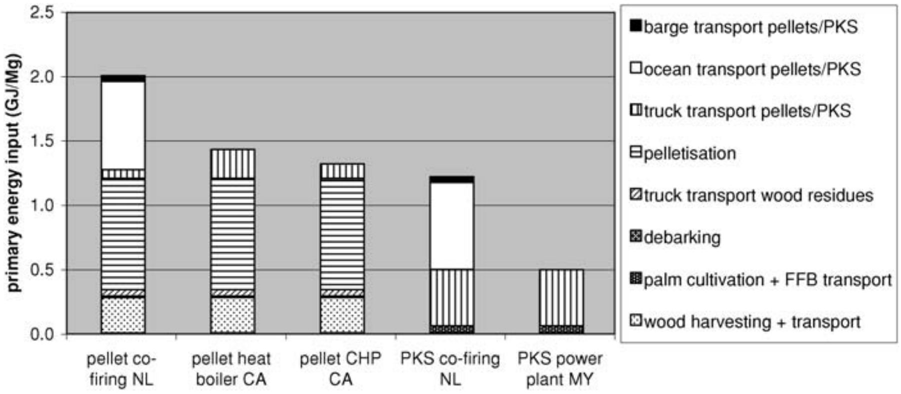


Figure 5. Breakdown energy use pellet and palm kernel shell (PKS) production and transport (on dry basis). NL: Netherlands, CA: Canada, MY: Malaysia.

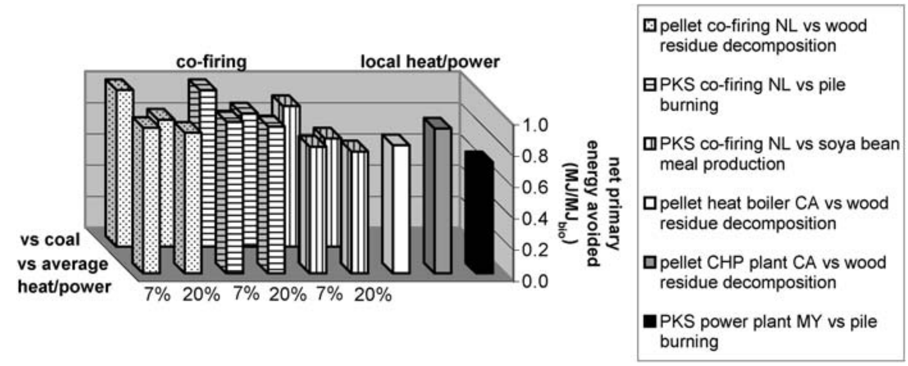


Figure 6. Net avoided primary energy per unit biomass energy of pellet and palm kernel shell (PKS) import and co-firing and use as fuel in dedicated combustion systems in country of origin. The left column of each co-firing series refers to 7 wt.% co-firing share and the right column to 20 wt.%. NL: Netherlands, CA: Canada, MY: Malaysia.

4.2. GREENHOUSE GAS EMISSIONS

Figure 7 shows the GHG emission breakdown of biomass production, transport and (co-) firing for the different conversion systems, which logically corresponds to a large extent with the energy use of biomass supply as presented in Figure 5. The additional emissions caused by de-rating (when co-firing 20 wt% pellets or PKS), which are fully allocated to the biomass, increase the GHG emissions per "green" kWh with a factor 2.4. More than half of the GHG emissions of pellet

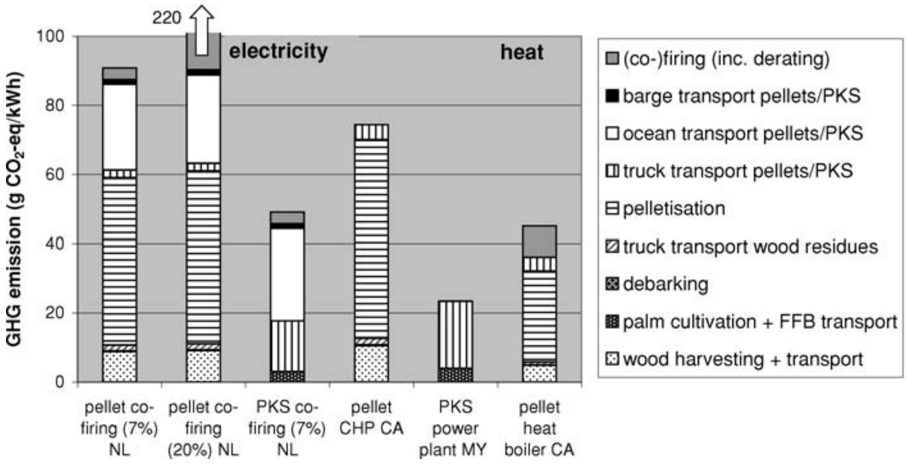


Figure 7. GHG emissions of pellet and palm kernel shell (PKS) import and co-firing and use as fuel in dedicated combustion systems in country of origin. Emissions are expressed in g/kWh "green" electricity or heat. NL: Netherlands, CA: Canada, MY: Malaysia.

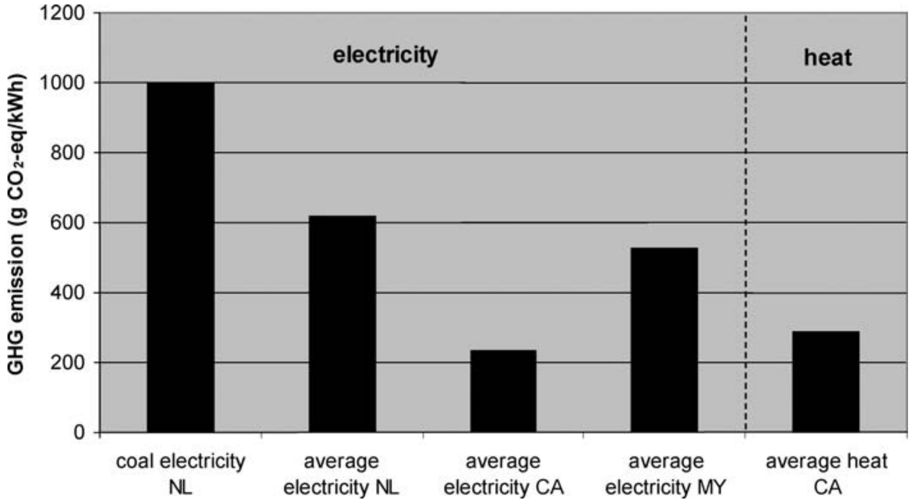


Figure 8. GHG emissions of energy reference systems. NL: Netherlands, CA: Canada, MY: Malaysia.

production, transport and co-firing are caused by the pelletisation process. CO_2 and CH_4 emissions caused by ocean and truck transport dominate the picture for PKS import and co-firing.

GHG emissions of the energy and biomass reference systems are depicted in Figures 8 and 9, respectively. The GHG intensity of power production in the Netherlands is higher in comparison to Canada and Malaysia, due to the relatively large share of coal and natural gas and relatively low share of hydropower and nuclear

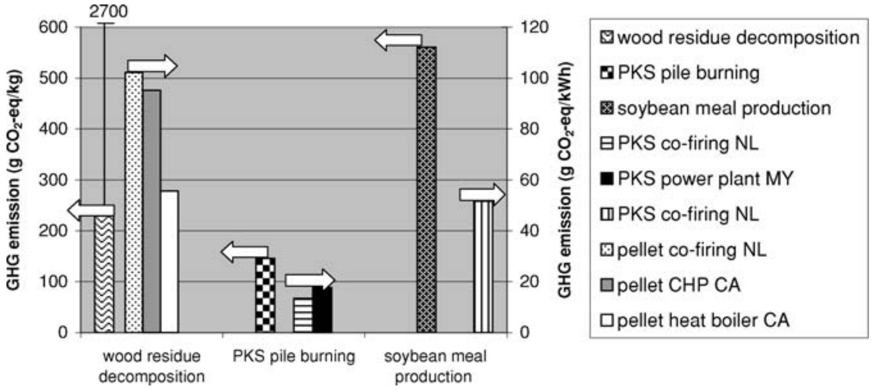


Figure 9. GHG emissions of biomass reference systems. On the left axis, GHG emissions are expressed in g/kg (on dry basis) pellet or palm kernel shell (PKS). On the right axis, GHG emissions are allocated to a kWh of "green" electricity or heat for the different conversion systems considered. NL: Netherlands, CA: Canada, MY: Malaysia.

TABLE VII
Net avoided GHG emissions (g/kWh)

Biomass system	Co-firing share	Vs 100% coal	Vs average electricity/heat
Pellet co-firing NL vs. wood residue decomposition	7%	1007 (2098)	627 (1718)
	20%	881 (2007)	627 (1753)
PKS co-firing NL vs. pile burning	7%	1016	636
	20%	890	636
PKS co-firing NL vs. soya bean meal production	7%	733	352
	20%	598	344
Pellet heat boiler CA vs. wood residue decomposition	–	–	297 (891)
Pellet CHP plant CA vs. wood residue decomposition	–	–	269 (1285)
PKS power plant MY vs. pile burning	–	–	591

power.

For the alternative biomass applications, GHG emissions are expressed per unit of mass and per unit of energy for the various conversion systems. The latter represent the avoided (in case of biomass decomposition and pile burning) or additional (in case of soya bean meal production) GHG emissions per kWh generated by (co-)firing pellets or PKS, if the biomass would not have been applied for energy purposes. The range in GHG emission of wood residue decomposition (extreme left) represents the uncertainty in the amount of carbon that is being decomposed at landfills (3 to 35%). The majority of GHG emissions of soya bean production, transport and crushing are represented by N_2O emissions of fertilizer production and application.

Combining the emissions of the biomass (co-) firing systems with the avoided/ additional emissions of the reference systems gives the net avoided GHG emissions as presented in Figure 10 and Table VII.

Generally, net avoided GHG emissions of pellet and PKS co-firing in the Netherlands are higher than for electricity/heat production in dedicated plants in the country of origin. This can be explained by the large avoided GHG emissions caused by fossil fuel production, transport and combustion and biomass decomposition or pile burning in comparison to additional GHG emissions caused by biomass supply and co-firing. Electricity and heat production in local dedicated plants replaces relatively less GHG intensive electricity/heat.

Avoided methane emissions occurring during residue decomposition at the landfill site contribute significantly to net avoided GHG emissions of pellet co-firing. In the most optimistic case, when 35% of carbon present in the residues would have been decomposed, circa 2100 g CO_2-equivalents can be avoided per kWh "green" electricity. The worst case in terms of avoided GHG emissions is co-firing 20% PKS to replace electricity from the average Dutch fuel mix, provided that the PKS

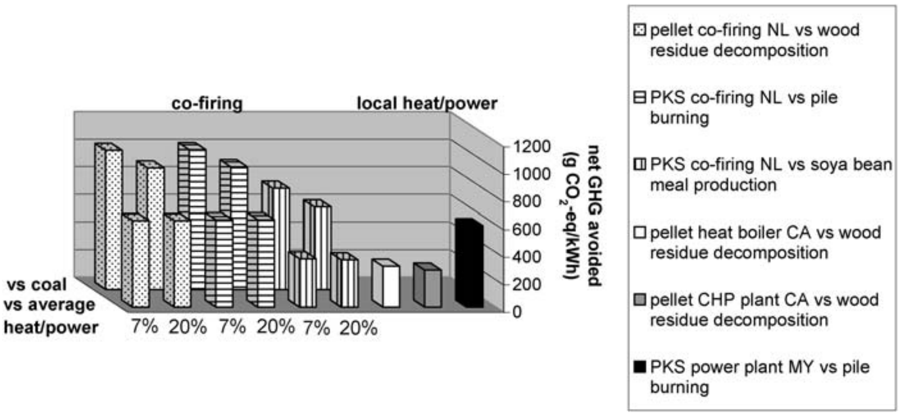


Figure 10. Net avoided GHG emissions (emission of 1 kWh “reference” electricity or heat minus emission of 1 kWh “green” electricity or heat). NL: Netherlands, CA: Canada, MY: Malaysia.

would otherwise be used as resource for animal feed. Considering soya bean meal as alternative resource, produced from soya beans imported from the USA, only 340 g CO_2-equivalents can be avoided per kWh green electricity.

The energy penalty when co-firing 20 wt% instead of 7 wt% (caused by plant de-rating and the higher internal energy use) reduces net avoided GHG emissions per kWh with 12–18%.

When considering local use of biomass, firing PKS in a dedicated power plant in Malaysia has a larger GHG reduction potential than pellet firing in a CHP plant or heat boilers in Canada. This is due to the higher GHG intensity of the average Malaysian electricity production in comparison to the Canadian electricity production.

5. Discussion

In this section, we highlight the main uncertainties in data and assumptions and the impact of these uncertainties on net avoided energy and GHG emissions. Also methodological choices might affect the results, among which allocation rules. These consequences are briefly discussed as well. Finally, we highlight some technological improvements to reduce GHG emissions occurring in the supply chains.

One of the major uncertainties is the efficiency penalty caused by de-rating of the boiler and higher internal energy use when co-firing large quantities of biomass. There is little commercial experience with high co-firing shares at this stage. Both boiler de-rating and internal energy requirements should be considered in more detail, since the reduction in electric efficiency has a significant impact on the total energetic performance and additional emissions allocated to the biomass. A decrease in electric efficiency of 3% versus 100% coal when co-firing 20 wt% pellets as assumed in this analysis reduces the net avoided primary energy with circa 20% in comparison to co-firing without de-rating effects. If the efficiency penalty is limited to 2%, net primary energy avoided of pellet co-firing is reduced with circa 13% in comparison to co-firing without de-rating effects. Net avoided GHG emissions of pellet co-firing decrease with 8% for an efficiency penalty of 2% in comparison to 13% for an efficiency penalty of 3%.

Another important uncertainty is the alternative application of biomass if not applied for (co-)firing. Methane emissions caused by decomposition of surplus wood residues used for pellet production at a landfill site have a large (positive) impact on the avoided GHG emissions. Quantification of these emissions requires more attention, as the carbon decomposition rates given in literature differ substantially. In our analysis, recovery of methane to generate energy is not considered. If 35% of all carbon would decompose and all methane released at the landfill would be burned in a gas motor with an electric efficiency of 30%, the net avoided primary energy would be reduced with 16% compared to current landfill practice without methane capture. Net avoided GHG emissions would be reduced with 57–70% in comparison to current landfill practice.

For the worst-case scenario we consider soya beans imported from the USA to produce soya oil and soya bean meal, the latter used as a resource for animal feed production instead of PKS. Soya bean meal is characterised by a high protein quantity and quality (Hin 2002), whereas PKS have a lower protein content. Currently, soya bean meal is too expensive as alternative for PKS (van Erp and Goelema 2005, personal communication). Alternative resources might be rapeseed, coconut or maize gluten meal, soya bean hulls and sugar beet pulp. Rapeseed meal is generally imported from Germany, coconut meal from East Asia, maize gluten meal from the USA (Neessen et al. 2003), whereas soya bean hulls and sugar beet pulp are produced in the Netherlands. This might have significant impact on the net avoided energy and emissions, as transport distances might potentially be much smaller and other crops may involve other fertilizer regimes. Net avoided GHG emissions of 7 wt% PKS co-firing versus 100% coal increase with circa 11% if soya bean transport is not accounted for.

In this study, we consider biomass resources, which can be considered as (useful) by-products. Wood residues that serve as resource for pellet production are by-product from lumber and wood chip production and PKS are a by-product of palm oil production. Similarly, soya bean meal is a by-product of soya oil production. In this analysis, the energy use and emissions of cultivation/harvesting and transport of the main product (and in the case of soya bean also the crushing process) are allocated to the residues on mass basis. The outcome is not changed significantly if only the energy expenses and emissions from the additional processes required for energetic use are accounted, i.e. setting the system boundary at pelletisation and palm oil plant. However, the allocation of energy inputs and emissions caused by soya bean cultivation, transport and crushing has a strong impact on the energetic performance and net avoided GHG emissions of the worst-case scenario. Considering soya bean meal as a by-product of soya oil production to justify no allocation of energy expenses and emissions would make the picture a lot rosier. In that case, net avoided GHG emissions of 7 wt% PKS co-firing versus 100% coal increase with circa 35% to 990 g CO_2-eq/kWh, which is close to the scenario in which PKS would be pile burned.

GHG emissions occurring in the biomass supply chain are dominated by CO_2 emissions of electricity requirements in the pelletisation process and fuel use in ocean transport. CH_4 and N_2O emissions from the heat boiler in the pelletisation process are significant as well. The heat and electricity requirements of pelletisation could be produced by a CHP plant fuelled with wood residues. Fuel use of ocean transport decreases significantly when increasing the cargo capacity of the vessel. The fuel consumption per tkm of the Panamax vessel (capacity of 60,000 tonnes) used for PKS transport is nearly a third of the fuel consumption of the vessel used to transport pellets (capacity of 9,000 tonnes). The emissions caused by ocean transport can also be reduced by using more efficient ship engines.

6. Conclusion

Primary energy savings of co-firing wood pellets from Canada and palm kernel shells from Malaysia in a state-of-the-art pulverised coal-fired power plant in the Netherlands are between 70% and 100% of the biomass energy content. The performance is strongly depending on the co-firing share and the reference system for energy production and biomass application. Energy losses as a consequence of de-rating and higher internal energy use are negligible when co-firing up to 7 wt% biomass. The net avoided primary energy per unit biomass is reduced with circa 20% when increasing the co-firing share from 7 up to 20 wt% biomass, assuming a penalty of 3% in the electric efficiency of the coal-fired power plant.

The worst case in terms of energy savings represents the scenario of 20 wt% PKS co-firing and soya bean meal as alternative resource for animal feed production, assuming PKS co-firing competes with use as animal feed resource.

The prospects of pellet and PKS transport to the Netherlands for co-firing purposes are generally more promising than utilisation as fuel in dedicated combustion systems in the country where the biomass is produced, in spite of energy use and emissions caused by sea transport over a large distance. This is explained by the high-efficiency of the coal-fired power plant and the relatively high energy use of coal mining and transport to the Netherlands. Another reason that makes export preferable to local use in these cases, is the large share of hydro-electricity in the electricity mix of Canada and natural gas in Malaysia, which are relatively efficient (and less GHG intensive) in comparison to 100% coal or the Dutch electricity mix.

Net avoided GHG emissions are between 340 and 2100 g/kWh for the biomass co-firing chains and between 270 and 590 g/kWh for biomass use in the country where it is produced. The GHG reduction potential is primarily determined by the avoided GHG emissions of fossil fuel production, transport and combustion. The alternative use of biomass may prove beneficial, but can also reduce the net avoided GHG emissions realised by the avoided fossil fuel chain. The avoided emissions of CH_4 caused by decomposition of wood residues at landfills in Canada, and to a lesser extent CH_4 and N_2O emissions caused by PKS burning in the open air in Malaysia, contribute to the positive impact of biomass import for co-firing. However, if increasing competition between energy use and animal feed resource will occur, PKS co-firing might become less attractive in terms of avoided energy and GHG emissions, accounting for the additional energy and emissions required for an alternative resource.

This analysis has identified critical factors, which are decisive for the (avoided) energy use and GHG emissions of biomass trade for co-firing purposes. Based on these findings, some generic lessons can be learned how biomass can be used efficiently to reduce primary energy use and GHG emissions. Whereas focus is generally on composition, availability and price of biomass, also the context in which biomass production and trade occur should be a decisive factor to be considered in biomass import. First, the biomass resource origin and alternative application when not used for (co-) firing might have a strong impact on 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 biomass potential, internal demand application of the biomass and competition with other applications. Generally, biomass resources that are not used for other purposes deserve priority when selecting resources for energy purposes. Second, the energy conversion and energy reference system of importing and exporting country is crucial for the GHG reduction potential. Generally, biomass export for co-firing seems more efficient in reducing GHG emissions in comparison to local application in dedicated plants when replacing imported coal in state-of-the-art PC plants with high electric efficiency and a modest impact on the efficiency as a consequence of de-rating. On the other hand, countries with a biomass supply potential and a relatively GHG intensive energy production system might better use biomass locally.

Whereas this study considered the use of biomass residues, energy crop production may become more important on the longer term. In that case, the use of land and other impacts than solely GHG emissions also become important for assessing the overall sustainability of biomass resources and trade. Large-scale, intensive biomass cultivation may have environmental and socio-economic impacts (deforestation, competition with food production), which might not be in line with sustainability criteria. For such bio-energy production systems, the reference systems are even more complex, as alternative land use needs to be considered. This analysis demonstrated a methodology to account for the impact of reference systems, which can be further extended for more complex bio-energy systems.

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Notes

1. This energy loss is only accounted for when considering 100% coal as reference system.
2. The amount of wood to be harvested to produce 1 Mg pellets is calculated using the total amount of bark required to produce 1 Mg of pellets (1.4 Mg, see Table II) and the bark content of 1 Mg stems (0.136 Mg).
3. MJ/tonne*km, common unit to express fuel economy of transport.
4. In the scenario of pellet use as fuel in a local 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, the transport distance is set at 200 km.
5. Gas volume is kept constant by decreasing total mass input with increasing co-firing share.
6. Exact lifetime is not specified.
7. Conversion efficiency primary into secondary energy carriers: diesel = 88%, heavy fuel oil = 93% (Hekkert et al. 2005).

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