LCA screening of biofuels

- iLUC, biomass manipulation and soil carbon

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1 Introduction

Biofuels were given an important role in the Danish government's energy and climate-change mitigation strategy (Energiaftale 2012).However, following a report questioning the carbon neutrality of different biofuels (Concito 2011), Concito is interested in assessing further the climate impacts of different biofuels. The current report includes Life Cycle Assessment (LCA) screenings for calculating the carbon footprint (CF) of six different biofuels: wood pellets, wood chips, straw, biogas, ethanol and biodiesel. Critical sources of emissions in the product systems of the biofuels, which are often excluded from LCA studies, are addressed in the current study. These include indirect land use changes (iLUC), time dependency of greenhouse gas (GHG) emissions, manipulation of the carbon in biomass and soil carbon.

2 Goal and scope definition

2.1 Purpose of the study and functional unit

Purpose of the study

The purpose of the study is to set-up life cycle inventories and to calculate carbon footprints of different biofuel options for electricity and transport fuels. Recognising that a number of studies with a similar purpose already exist, but that these studies generally do not address significant issues such as indirect land use changes (iLUC) and manipulation of the pools of biogenic carbon, the current study aims at addressing these issues in a consistent and accurate way.

It should be noticed that the emphasis is on accurate modelling rather than obtaining very precise input data. I.e. it has been more important to set-up a causal model than obtaining high quality input data. Therefore, the methodology applied in the current study is regarded as having a relatively low degree of preciseness but a very high degree of accuracy – especially with regard to the modelling of indirect land-use changes, establishment of carbon balances, time accounting for accelerated CO_2 emissions and delayed CO_2 uptake, and nitrogen related field emissions. The results of the comparisons of different biofuel options with the currently dominating mineral fuels is for illustrative purposes rather than for obtaining unambiguous conclusions on the ranking of the different fuel options.

Further, it should be noticed that the current study only show results for the impacts on climate change. This is obvious a relevant impact category when comparing different fuels, but other impact categories such as biodiversity and respiratory inorganics may be just as serious. Therefore, conclusions on the comparison of different biofuels on the basis on only GHG-emissions may not hold true for the overall environmental performance of the different fuels.

ISO 14040/44

The current study is not fully following all requirements set out in the ISO standard on life cycle assessment, ISO 14044. The major deviations are:

- The study only focusses on GHG-emissions
- The study does not fully address uncertainties, e.g. as sensitivity analysis
- The study does not include an interpretation and evaluation phase
- The study has not undergone a critical review

Functional unit

Table 2.1 identifies the functional unit for each biofuel considered, as well as that for their fossil-based counterpart.

Table 2.1: Functional unit.

Electricity based on:	Functional unit
Wood pellets (3 different sources)	1 kWh electricity at power plant
Wood chips based on wood residues (3 different sources)	
Straw	
Biogas (manure, maize, organic waste)	
Coal	
Natural gas	
Wind power	
Solar (photovoltaic)	
Motor fuels based on:	**Functional unit**
Rapeseed biodiesel	1 MJ fuel combusted in engine
Palm oil biodiesel	
Bioethanol, 1st generation (wheat and maize)	
Bioethanol, 2nd generation	
Motor diesel (mineral)	
Motor gasoline (mineral)	

2.2 System boundaries and cut-off criteria

System boundary

The LCA screenings in the current study includes the life cycle stages from extraction or cultivation of raw materials to the point of substitution of the studied energy carriers. For the scenarios concerning electricity, the point of substitution is defined as electricity at power plant, and for motor fuels the point of substitution is defined as released energy in the motor. After this point, there are no differences in environmental impacts relating to the different scenarios for electricity and motor fuel.

Modelling approach

The study models the effects of a change in demand for the functional unit, where this functional unit is supplied by different product systems in different scenarios. This approach for modelling in life cycle inventory is called consequential LCA. The arguments for using this approach, as well as its theoretical foundation and its practical implementation, is described in Weidema et al. (2009), Chrintz and Schmidt (2012) and Schmidt and Dalgaard (2012).

Cut-off criteria

Generally, the same cut-off criteria as in the ecoinvent v2.2 database are used (ecoinvent 2010). This includes raw materials, auxiliary materials, process energy, buildings, machinery and infrastructure (roads, rails, harbours etc.). However, when establishing activities which also requires capital goods, e.g. biogasification (which require a biogas plant), this has generally not been included. This introduces some inconsistences and may favour some biofuel options. However, the relevance of this is not regarded as being significant. Again, notice that the focus of the current study is not to provide unambiguous resultant – the purpose is more to establish consistent and accurate modelling principles for iLUC and manipulation of the carbon pool and apply this to all the assessed biofuel options.

Generally, services (such as cleaning, accounting, lawyers, marketing, business travelling), research and developing (laboratories, equipment, offices etc.), and overhead (overhead energy, office equipment etc.) are not included.

2.3 Life cycle impact assessment (LCIA) method for GHG-emissions

IPCC's Global Warming Potentials (IPCC 2007) in a 100-year perspective (GWP100) are used in the main scenario. A sensitivity analysis is carried out using GWP20.

Generally, no distinction is made between fossil and biogenic carbon. Timing of emissions is accounted for by use of the Bern Carbon Cycle and the IPCC GWP. This is further described in **section 3.1**.

3 Methodology for modelling land use changes and biogenic carbon

As mentioned in the description of the purpose of the study (**section 2.1**), focus is given to indirect land use changes and biogenic carbon. This section describes the methodological approach adopted here for modelling iLUC. It should be noted that all methodologies described in the current chapter are compliant with the ISO 14044 standards on Life Cycle Assessment and with the consequential LCA approach.

3.1 Time-dependent emission factors for CO_2 emissions

In common practice when calculating carbon footprints (and LCAs), no distinction is made between different timings of emissions (although sometimes emissions occurring in the long -term, after more than 100 years, from e.g. landfill leakage, are excluded). However, given that climate-change effects are related to a certain threshold[1] beyond which irreversible changes may occur, and the time-horizon of present climate-action plans (typically 5-10 years), it is evident that the timing of GHG-emissions matters. Postponing GHG-emissions will buy time for technological progress and adaptation, postpones or temporarily avoids radiative forcing, and some delayed emissions may be avoided altogether (Brandão et al., 2012), allowing for a possible increase in the distance between the current GHG concentration in the atmosphere and the currently internationally-agreed threshold of limiting temperature rise to 2°C (which corresponds to a CO_2 concentration of 450 ppm by volume).

The production of biomass is often considered carbon neutral because the CO_2 emitted when burning the biomass corresponds to the CO_2-uptake from the atmosphere by growing biomass. Since there is a time lag between CO_2 sequestration and emissions in which radiative forcing is avoided, the timing CO_2 is uptaken and subsequently emitted is relevant. The same applies to the use of crop residues: if the residues are burned, the associated CO_2 emissions take place instantaneously, while the emissions from biomass decay take place over a longer period. Finally, the effect on deforestation from iLUC is modelled as accelerating deforestation, which is also related to timing of deforestation-related emissions. The principle of iLUC modelling is described in **section 3.2**.

The IPCC Global Warming Potential (GWPs) (IPCC 2007, p 210) are normally used for expressing the relative importance of different GHG-emissions. Most often (or always) this is done relative to CO_2. The GWP of a GHG emission is calculated based on the decay rate of CO_2 and associated radiative forcing over a period (see **Figure 3.1)** against which the cumulative radiative forcing of that GHG emission over the same period is calculated (see **Equation 3.1**: (IPCC 2007, p 210).

Equation 3.1

$$GWP_i = \frac{\int_0^{TH} RF_i(t)dt}{\int_0^{TH} RF_{CO_2}(t)dt}$$

where:

GWP_i is the global warming potential for substance *i*

TH is the applied time horizon

RF_i is the radiative forcing for substance *i*

RF_{CO2} is the radiative forcing for CO_2

[1] Often this is referred to as a 2°C increase in the global average temperature.

When applying a time horizon of 100 years, it can be calculated that 1 kg methane has an equivalent cumulative radiative forcing to 25 kg CO_2 because it has a greater radiative efficiency (despite its shorter residence time in the atmosphere). In order to make this calculation, it is necessary to know how CO_2 is removed from the atmosphere as a function of time. CO_2 is removed from the atmosphere by plants (through photosynthesis) and the oceans. **Figure 3.1** shows the fraction of a pulse emission of CO_2 remaining in the atmosphere as a function of time. According to this equation, of an emission of 1 kg of $CO_{2,}$ 0.5 kg will remain in the atmosphere after 30 years.

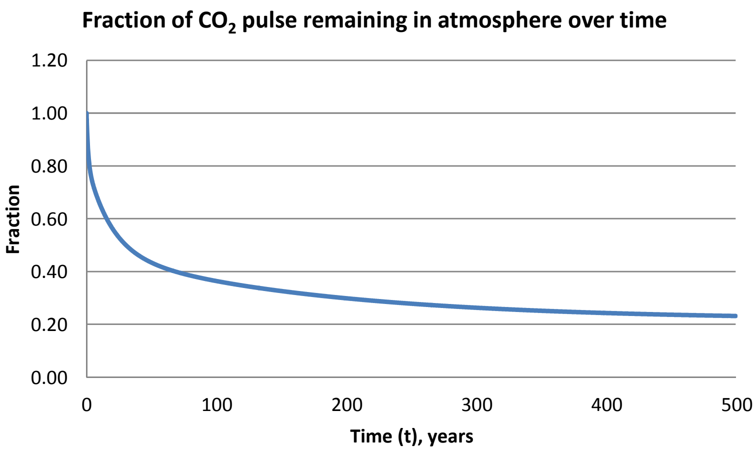

Figure 3.1: Fraction of a CO_2 pulse present in the atmosphere as a function of time. The fraction is calculated using the Bern carbon cycle, see **Equation 3.2**.

The Bern carbon cycle is used to describe the fraction of a pulse emission of CO_2 that remains in the atmosphere over time. The Bern carbon cycle is shown in **Equation 3.2**: (IPCC 2007, table 2.14)

Equation 3.2

$$Fraction(t) = 0.217 + 0.259 \cdot e^{-t/172.9} + 0.338 \cdot e^{-t/18.51} + 0.186 \cdot e^{-t/1.186}$$

In the current study, the GWP approach is expanded to also account for different timing of emissions. **Equation 3.3** applies this to a difference in timing Δt (relative to a reference time t=0) for a substance *i*. **Equation 3.4** shows this applied to CO_2.

Equation 3.3

$$GWP_{i,\Delta t} = \frac{\int_{\Delta t}^{TH} RF_{i,\Delta t}(t-\Delta t)dt}{\int_{0}^{TH} RF_{CO_2,t=0}(t)dt}$$

where:

$GWP_{i,\Delta t}$ is the global warming potential for substance *i* emitted at time Δt relative to t = 0

TH is the applied time horizon

$RF_{i,\Delta t}$ is the radiative forcing for substance *i*, emitted at time Δt relative to t = 0

$RF_{CO2,t=0}$ is the radiative forcing for CO_2 emitted at time t = 0

Equation 3.4

$$GWP_{CO2,\Delta t} = \frac{\int_{\Delta t}^{100} CO_{2,fraction}(t-\Delta t)dt}{\int_{0}^{100} CO_{2,fraction}(t)dt}$$
$$= \frac{\int_{\Delta t}^{100} 0.217+0.259 \cdot e^{-(t-\Delta t)/172.9}+0.338 \cdot e^{-(t-\Delta t)/18.51}+0.186 \cdot e^{-(t-\Delta t)/1.186} dt}{\int_{0}^{100} 0.217+0.259 \cdot e^{-t/172.9}+0.338 \cdot e^{-t/18.51}+0.186 \cdot e^{-t/1.186} dt}$$

The principle of **Equation 3.4** is illustrated in **Figure 3.2**.

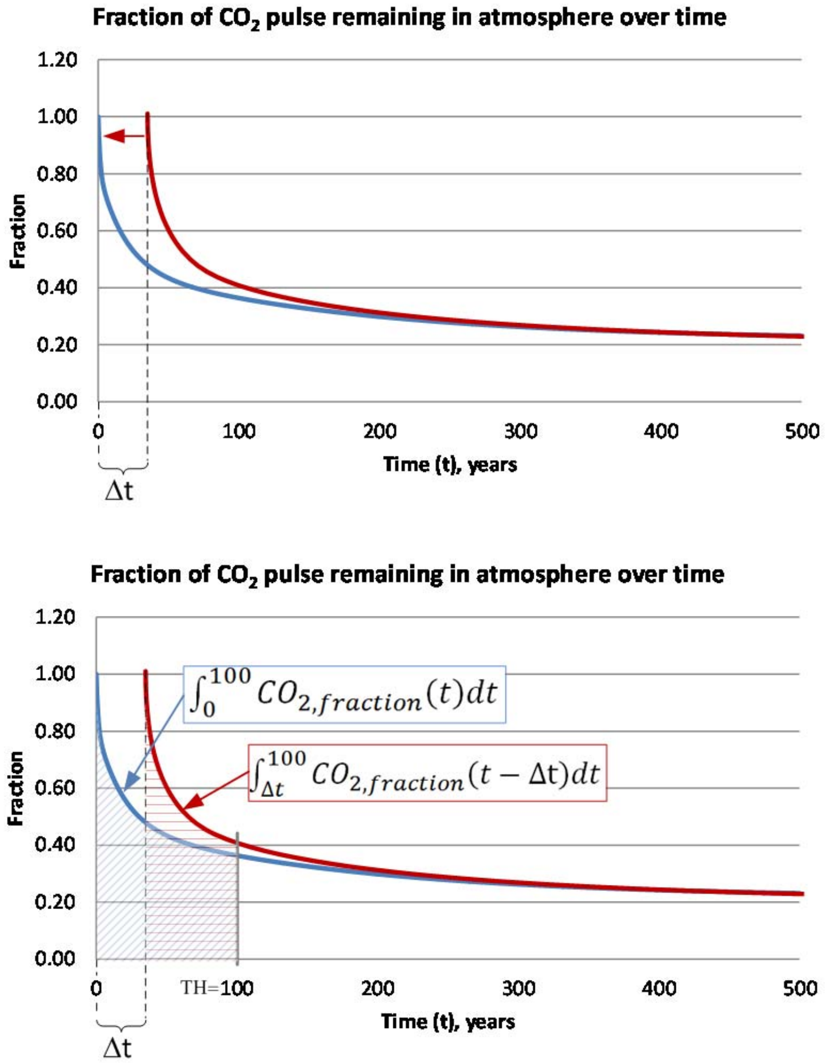

Figure 3.2: ***Top:*** **Effect of emitting a CO_2 pulse at time Δt is illustrated as moving the CO_2 decay curve to the right.** ***Bottom:*** **The denominator in Equation 3.4** is illustrated as the blue shaded area (CO_2 emitted at time 0), and the nominator is illustrated as the red shaded area (CO_2 emitted at time Δt).

By inserting **Equation 3.2** in **Equation 3.4** for CO_2 with Δt = 1 year and TH = 100 years, it can be calculated that:

Equation 3.5

$$GWP_{CO2,\Delta t=0} = 1$$
$$GWP_{CO2,\Delta t=1} = 0.9924$$

This means that emitting 1 kg CO_2 in year 1 has the same GWP100 effect as emitting 0.9924 kg CO_2-eq. in year 0. It also means that speeding up 1 kg CO_2 emission by one year has the following effect: 1 kg CO_2 minus 0.9924 kg CO_2-eq. = 0.00761 kg CO_2-eq.

If the same figures as of **Equation 3.5** are calculated using a time horizon (TH) = 20 years, we have:

Equation 3.6

$$GWP_{CO2,\Delta t=0} = 1$$
$$GWP_{CO2,\Delta t=1} = 0.9586$$

This means that emitting 1 kg CO_2 in year 1 has the same GWP20 effect as emitting 0.9586 kg CO_2-eq. in year 0. It also means that accelerating 1 kg CO_2 emission by one year has the following effect: 1 kg CO_2 minus 0.9586 kg CO_2-eq. = 0.0414 kg CO_2-eq.

Comparing the effects of speeding up or delaying 1 kg CO_2 by one year in **Equation 3.5** and **Equation 3.6** shows that the effect becomes more than fivefold more important when considering the GHG-effects in a 20 years perspective instead of the traditional 100 years perspective.

3.2 Indirect land use changes (iLUC)

The current deforestation and changes in land use are caused by the current demand for productive land. Hence, when a crop for biomass or food requires land, or when land is needed for infrastructure, mines, and housing etc., this affects the overall demand for land. The model used for the calculation of these effects in the current study is the 2.-0 LCA iLUC model (Schmidt et al. 2012a&b; http://www.lca-net.com/projects/iluc_model/).

What is land and how can new productive land be created?

Essentially, this model considers land as capacity for biomass production. This is analogous to the capacity a power plant for electricity production. In order to grow biomass, we also need capacity for cultivation, i.e. land. There exists a market for land; this market is called the land tenure market. Since crops can be grown in different parts of the world and since crops are traded on global markets, it is argued that this market for land is global. The 'product' traded on this global market is capacity for biomass production. It should be noted that this capacity can be created in different ways:

1. Expansion of the area of arable land (deforestation)
2. Intensification of land already in use
3. Crop displacement, i.e. someone reduces consumption, e.g. induced by increases in prices, in order to allow others for using the biomass production capacity (social impacts)

The third point above is assumed to be zero because LCA considers long-term effects of changes in demand. Short-term changes will create imbalances between supply and demand, which leads to effects on prices. But in the long term, suppliers will adjust their production to match demand, and unless the production costs are higher, the prices will remain unchanged.

Markets for land

The relevant functions of land to be modelled is the land's ability to produce products, i.e. food, feed, fibre and timber, and the function to provide area for human structures, i.e. buildings, infrastructure and production facilities such as mines. When forests and human structures occupy land suitable for agriculture, it will have similar land-use-related effects as when crops are grown, because it is related to the acquisition of land from the same land-tenure market. Schmidt et al. 2012a) distinguish five markets for land (all land tenure markets can be used for urban, industrial or infrastructure area):

- Extensive forest land: not fit for more intensive forestry (e.g. clear cutting and reforestation), e.g. because it is too hilly, too remote, or it is growing on very infertile land making intensive forestry uneconomic. Forests grown on extensive forestland are typically harvested after natural regrowth with mixed species.
- Intensive forest land: fit for intensive forestry (e.g. clear cutting, reforestation, species control etc.), but not fit for arable cultivation because the soil cannot be tilled to sustain crops, e.g. because it is too rocky. Forests grown on intensive forestland may be managed as intensive or extensive forestry. Intensive forest land may also be used for other land use, e.g. livestock grazing and extensive forestry.
- Arable land: fit for arable cultivation (annual crops and perennial crops). Arable land may be used for cultivation of annual or perennial crops, for intensive or extensive forestry, and pasture.
- Rangeland: too dry for forestry and arable cultivation. Therefore, when in use, rangeland is most often used for livestock grazing.
- other land: not fit for biomass production; barren land, deserts, ice caps, high mountains etc.

Reference flow of the land tenure market LCA activity

The capacity for biomass production needs to be measured in an appropriate unit. Activities which include occupation of land clearly need a specified area in a specified period of time. This can be measured in hectare-years (ha-yr). An LCA market activity is defined in order to model this. This activity is called 'Market for land tenure'. It is the inputs and outputs of the market for land tenure that consists in the modelling of iLUC. An obvious option for a reference flow of a land-tenure activity would be occupation of land (ha-yr). However, this approach does not take into account that the potential production on 1 ha-yr land in e.g. a dry temperate climate is very different from the potential in wet tropical climate. This could be overcome by operating with a kind of productivity-weighted occupation of land. Another option would be the potential Net Primary Production (NPP_0), measured in kg carbon. Since the latter provides a simple way to include land with different productivities, this option is adopted.

LCA activities in the iLUC model

The change in the demand for arable land is modelled as a mix between intensification of land already in use and expansion of arable land. The land tenure market and its two inputs are illustrated in **Figure 3.3**. Note that the inputs to the land tenure market from land already in use and from crop displacement in **Figure 3.3** are not relevant when modelling iLUC. This is because these two activities are constrained, i.e.

they do not change their output as a consequence of a change in demand. Hence in **Figure 3.3**, a_2 and a_3 are zero, and the flows x and y are not relevant.

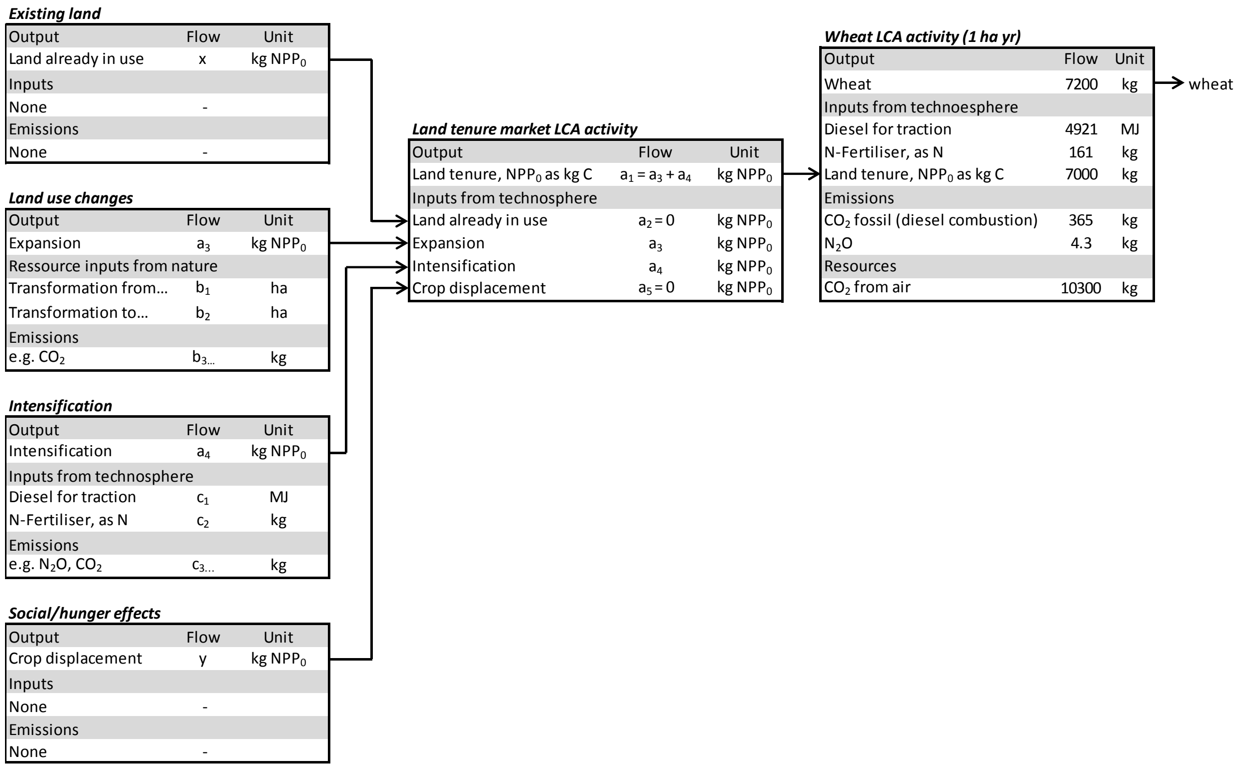

Figure 3.3: Illustration of the land tenure market activity and its inputs and outputs. An agricultural activity, here wheat production, has inputs from the land-tenure market activity. The land-tenure market activity has inputs from four different supplies of biomass production capacity. Only two of these are relevant when modelling iLUC; expansion and intensification. These two activities are associated with emissions. The sum of these emissions is referred to as iLUC emissions. The figure is directly obtained from Schmidt (2012a).

The proportion between the input from expansion and from intensification is calculated based on the total NPP_0 on new arable land and total NPP_0 (carbon in crops) from an increase in fertiliser use in one year. All inflows to the land-market tenure activity are measured in kg NPP_0 (as kg carbon). The NPP_0 from expansion is determined based on general NPP_0 per ha-yr figures (Haberl et al. 2007) and figures on annual increase of arable land (see land-use change transition matrix later in this section). The NPP_0 from intensification is calculated as the carbon in crop produced via intensification during one year. The intensification is determined based on crop yield dose-response figures for fertiliser input (Schmidt 2008) combined with information on which crops and where intensification takes place (data from FAOSTAT 2012) and current fertiliser levels for these crops (IFA 2011).

For forest land, when changing the demand for land, this is modelled as transformation of primary and secondary forests to intensive forest. The proportion of primary and secondary forests being transformed to plantation is determined based on a land-use change transition matrix (see **Table 3.1)**.

The emissions in the expansion activity are determined based on a land-use change transition matrix which specifies which types of new land going into the markets for land (see **Table 3.1**). When the types of land being transformed are known, this is compiled into emissions by tracking the change in carbon stock between the different land-use types in IPCC (2006, chapter 4, 5 and 6) and N_2O model in IPCC (2006, chapter 11). By-products as timber and emissions related to diesel etc. in the deforestation activity are not included in the current version of the iLUC model.

The activity 'Intensification' has inputs of fertilisers and traction, and emissions associated with the use of fertiliser. The inventory data of intensification are described further in Schmidt (2008).

Table 3.1: Land-use change transition matrix, unit: million ha. The global land-use transition matrix is established for an average year in 2000-2010. The top column headings divide the total land into land not in use and land in use. For the land in use there are four land tenure markets. The growth of these markets, which involves deforestation and land degradation, can be seen as inputs in the rows (Schmidt et al. 2012a,b).

Transformation to:	Non use			Markets				
	Primary forest	Secondary forest	Other (grassland, wetland and scrubland)	Extensive forest land	Intensive forest land	Arable land	Rangeland	**Total land use ref. year**
Transformation from:								
Primary forest	1,102	0	0	1.09	0.084	3.02	0	**1,106**
Secondary forest	0.34	1,798	0	0	4.85	9.98	0	**1,813**
Other (grassland, wetland and scrubland)	0	1.30	3,769	0	0	0.60	1.88	**3,773**
Extensive forest	0	0	0	930	0	0	0	**930**
Intensive forest	0	0	0	0	196	0	0	**196**
Arable	0	0	0	0	0	1,624	0	**1,624**
Range	0	0	0	0	0	0	3,569	**3,569**
Total land use ref. year + 1	**1,102**	**1,799**	**3,769**	**931**	**201**	**1,638**	**3,571**	**13,012**

Emissions and timing issues

When the occupation of land causes deforestation, a critical point is often to decide the period of time over which the deforestation emissions should be allocated or 'amortised'. The current model does not operate with amortisation. If only expansion is considered, occupation of 1 ha in 1 year will cause 1 ha deforestation. After the duration of 1 yr, the land is released to the market for land, i.e. to other crops, which can then be grown without deforestation. Hence, the occupation of 1 ha-yr is modelled as 1 ha deforestation in year 0 and -1 ha deforestation in year 1. This is illustrated in **Figure 3.4**. In order to model the GHG effects of this intermediate acceleration of deforestation, the method described in **section 3.1** is used.

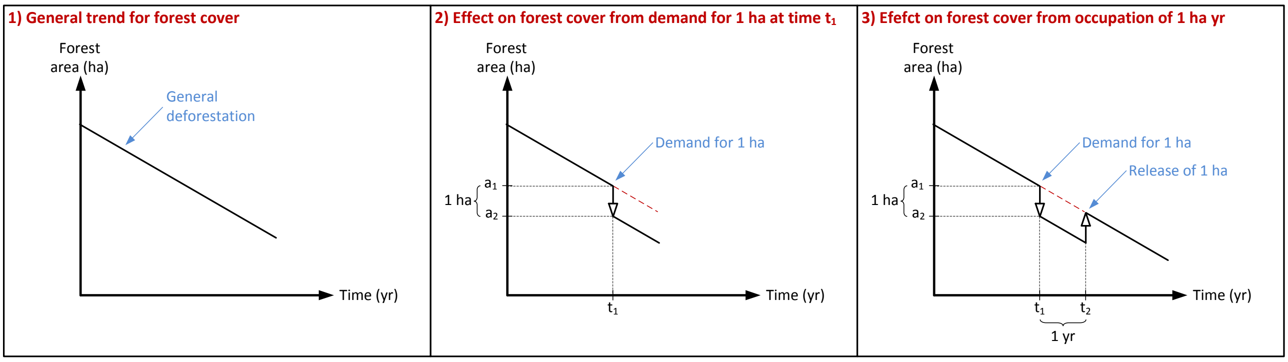

Figure 3.4: Stepwise description of how the occupation of 1 ha in 1 year from t_1 to t_2 affects the global forest cover over time.

3.3 Comparison with other iLUC methods

The current study uses the iLUC model described in Schmidt (2012a,b). **Table 3.2** below summarises the major differences between the Schmidt (2012a,b) model with other models.

Table 3.2: Comparison of iLUC methods.

iLUC methods	Application	Methods	Land types	Carbon stocks	Amortization and allocation
Searchinger et al., 2008	Corn ethanol	Economic modelling, global approach.	Forest and grasslands.	Includes foregone sequestration in young forests	All emissions allocated to the corn ethanol, none to DDGs. No amortization period used, but carbon payback time is determined
Audsley et al., 2010	All commodities used in the UK	Total LUC from IPCC AR4, Not estimating change, but estimating land use for commercial agriculture.	All types.	IPCC total emissions from LUC, IPCC AR4, implicitly taking above and below ground biomass, litter and SOC	Global average yields. Amortization not mentioned
Leip et al., 2011	Livestock commodities in Europe	Change/increase in cropland area (totals and per crop) 1999-2008 in EU countries and non EU countries, used in CAPRI model.	Cropland from grassland and forest.	Carre et al., 2009, based on IPCC, 2006, incl. above and below ground biomass, litter and SOC	All change in cropland area for feed crops is attributed to livestock, intermediate allocation amortization = 20, according IPCC
Cederberg et al. (2011)	Brazilian beef	Regional land use statistics from Brazil 1985 – 2006.	Fearnside et al., 2005, land use transition matrix.	Saatchi et al., 2007 Malhi et al., 2006	Amortization 20 years. Allocation to beef on deforested land, beef in LAR and all beef in Brazil
Economic models (GTAP, FAPRI-CARD, AGLINK-COSIMO, LEITAP, IMPACT, CAPRI	Biofuels	General and partial equilibrium.	Only estimate change in production and marginal supplier.	Only estimate change in production and marginal supplier	Only estimate change in production and marginal supplier
Method applied in current study; Schmidt et al. (2012)	All	Land is capacity for crop/biomass cultivation, land markets, global land use transition matrix. Change in capacity for cultivation is mix of expansion and intensification.	Land tenure markets: Arable land, land for forestry (intensive and extensive) and range land.	IPCC AR4 and estimations to reflect affected land categories.	No amortization. Time dependant characterisation factors based on the IPCC global warming potential (GWP).

3.4 Manipulation of biomass carbon

Two types of biogenic carbon are considered: biogenic carbon fluxes related to plant residues and biogenic carbon fluxes related to carbon in living growing plants. Plant residues include dead organic matter left on field or plantation after harvesting, e.g. straw or forest residues. The effect of plant residues is relevant for climate-impact calculations when residues are used as biomass for energy and when different crops have different carbon quantities and decay times for their residues. Living plants sequester atmospheric carbon as they grow. This is particularly relevant when considering plants with long rotation times, e.g. when trees are cleared for biofuel purposes which causes instantaneous CO_2 emissions while the sequestration from regrowth of new trees takes place over several years. Note that living plants and plant residues cover all plant material considered here.

Plant residue decay (aboveground and in soil)

Plant residues include all non-living biomass, i.e. above-ground, below-ground and harvested plant material. A crop residue can decompose relatively quickly if it is left above ground in the field, while the decay time in soil typically takes significantly longer time, and sometimes some of the carbon stays in the soil permanently. If the crop residue is removed from the field and burned as biofuel, the emissions take place instantaneously. For all residues, a decay function of time can be established. Such a decay function is illustrated in the upper part of **Figure 3.5**. In the current study, it is assumed that the decay function of a certain plant material that starts to decay is not affected by the land management after the time when the plant material becomes a residue. There are some examples where this assumption clearly does not hold , e.g. when plant residues are sealed by asphalt, which significantly delays the decaying process. However, in arable systems, the uncertainties are generally considered as being relatively low, though more research in this area is relevant.

If plant residues are used for energy, the effect on climate is the difference between the emissions profile of the use of the residues (i.e. instantaneous emissions from biofuel) and the emissions time-profile of residues left in the field for decay. An example of this is illustrated as the difference between the red-shaded area and the blue-shaded area in the lower part of **Figure 3.5**.

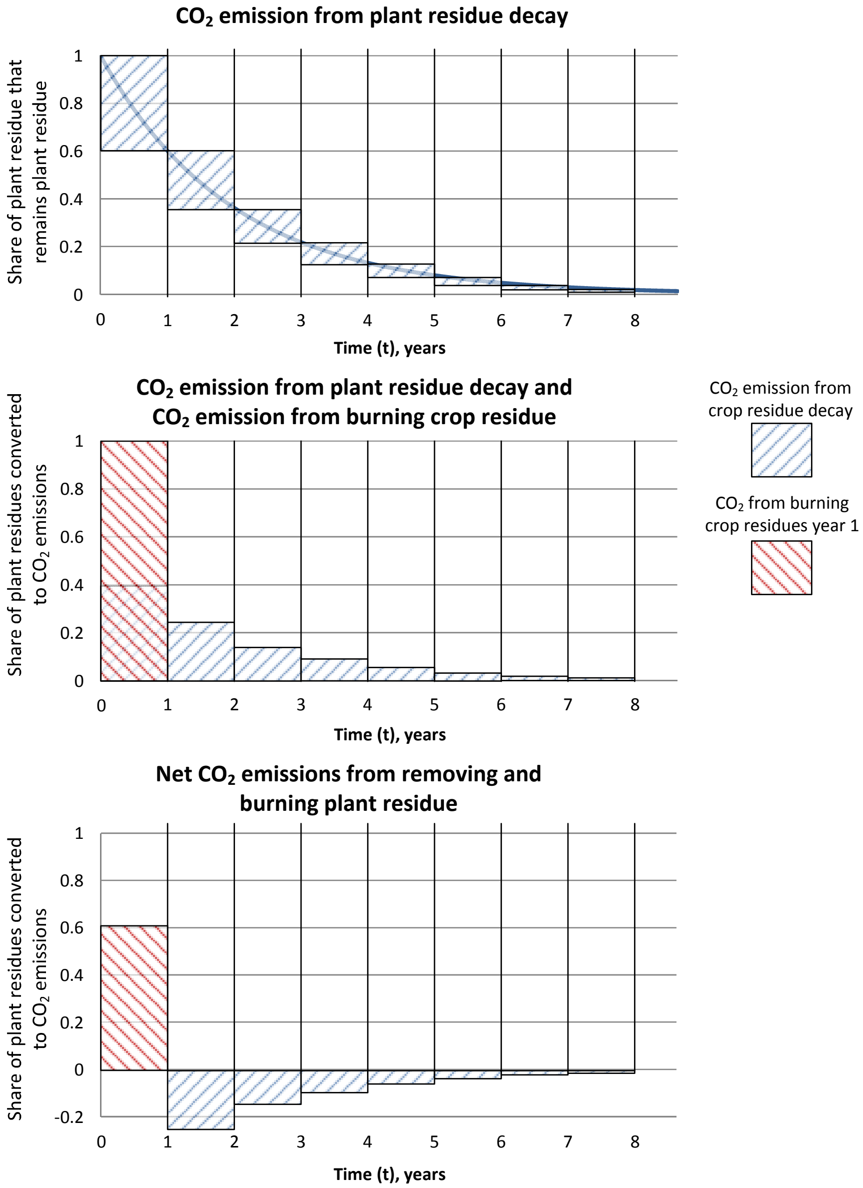

Figure 3.5: ***Top:*** Decay profile of plant residue decay. The graph shows the share of carbon in plant residue (above ground or in soil) that remains a residue as a function of time. The blue-shaded columns illustrate the annual share of the residue that becomes CO_2. ***Middle:*** The blue-shaded columns are the same as in the upper part of the figure – just moved down to the time-axis. The red-shaded columns illustrate that 100% of the residual becomes emissions in year 1. Notice that the height of the red column is the same as the sum of the blue-shaded columns – the only difference is the time-profile of emissions. ***Bottom:*** Net CO_2 emissions = The red-shaded column minus the blue shaded columns in the middle graph.

When modelling the use of plant residues for biofuel purposes, the baseline used here is the situation where the residue is left in the field/plantation/forest under the most likely land management that would have occurred after harvesting the residues, i.e. we model what would have happened with the residues if they were not removed. In case no data on this future management are available, the best assumption is to assume the same land management as before harvesting the residue. This assumption will also be the correct one in most cases, because most land typically remains in the same management system over several years.

Carbon sequestration from live biomass

When plants with long rotation times are harvested for biomass purposes, the harvested biomass is converted to CO_2 emissions instantaneously. Subsequently, another crop is planted on that land which, in many cases, will be similar to the one just harvested. When no data on the succeeding crop are available, it is assumed that the same crops with same rotation time follow. The regrowth profile with carbon sequestration and the instantaneous emissions from burning biomass are illustrated in **Figure 3.6**. When considering annual crops no difference in timing of emissions from burning biomass and from sequestration from regrowth is considered.

It is important to note that harvesting biomass today does not lead to historical carbon sequestration. Clearly, the trees harvested today have sequestered carbon during a period of time up until the point of harvest. However, the effect of the decision to fell a tree today has no effects back in time. A change in demand for wood today can only be met by felling trees today. Similarly, an increase in demand today will also result in an increase in the area covered by plantations. Hence, replanting is often done towards a more high yielding system (intensified forestry).

When modelling the use of crops with long rotation times for biofuel purposes, two baselines need to be considered: 1) the regrowth of new plants as described above, and 2) what would have happened with the trees if not felled. Regarding the second baseline, it is assumed that the trees will be felled for other purposes. This is not related to the demand for the studied biofuel, and therefore this baseline can be ignored.

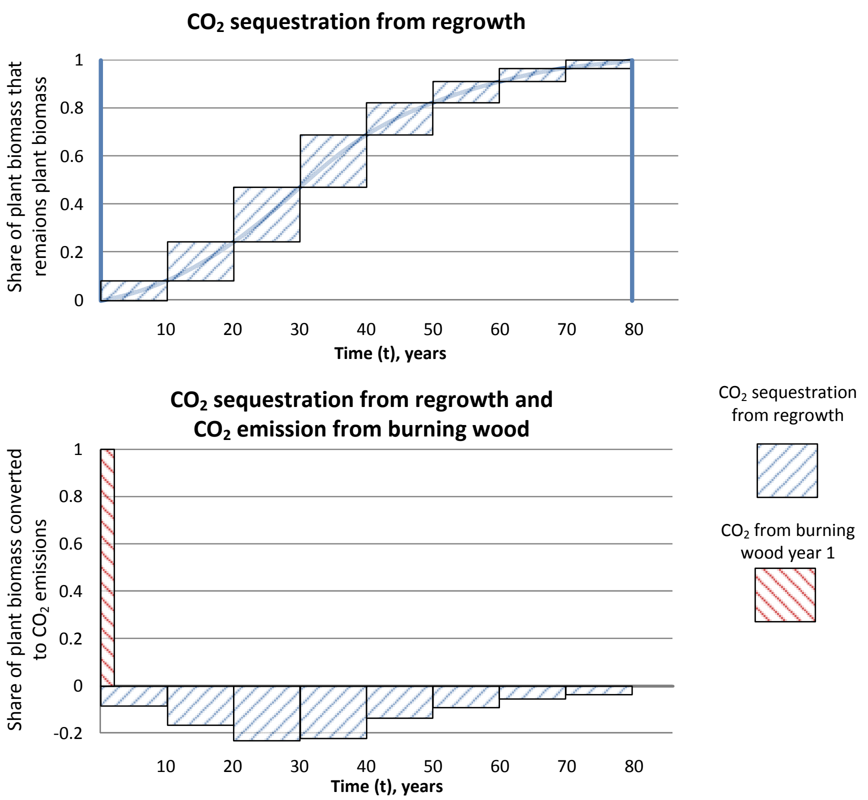

Figure 3.6: ***Top:*** Regrowth profile for new plants after harvesting. The blue shaded boxes illustrate the quantity of carbon sequestration along with the regrowth. ***Bottom:*** Instantaneous emissions from burning biomass and subsequent carbon sequestration from regrowth of new plants.

3.5 Material and fuel properties

Table 3.3 specifies the relevant basic physical properties for the inventoried fuels and materials in the current study.

Table 3.3: Physical properties of the fuels and materials included in the current study.

Fuel/material	Basic wood density (kg dm/m^3)	Dry matter (%)	Lower heating value (LHV)	
Eucalyptus	0.51	50%	-	Density: (IPCC 2006, table 4.13), Dry matter: Assumed (data only used for transport).
Loblolly pine	0.42	50%	-	
Pine	0.42	50%	-	
Wood pellets	-	90%	17.5 MJ/kg	DM%: (Prapaspongsa et al. 2011, appendix 3) LHV: (Nielsen et al. 2012, p 840)
Wood chips	-	75%	13.6 MJ/kg	DM% and LHV: Biomass Energy Centre (2012). Average of wood chips (70% dm) and log wood (80% dm)
Straw	-	85%	14.5 MJ/kg	DM%: Møller et al. (2005) LHV: Nielsen et al. (2012, p 840)
Maize ensilage	-	33%	-	(Møller et al. 2005)
Organic municipal waste	-	40%	5.10 MJ/kg	DM% and LHV: (Jungbluth et al. 2007, p 630)
Purified biogas (96% methane)	-	-	34.5 MJ/Nm^3	LHV: (Jungbluth et al. 2007, p 244)
Diesel	-	-	43.0 MJ/kg	LHV: Renewable Energy Directive (2009)
Rapeseed biodiesel	-	-	37.0 MJ/kg	LHV: Renewable Energy Directive (2009)
Palm oil biodiesel	-	-	37.0 MJ/kg	LHV: Renewable Energy Directive (2009)
Petrol			43.0 MJ/kg	LHV: Renewable Energy Directive (2009)
Bioethanol	-	-	27.0 MJ/kg	LHV: Renewable Energy Directive (2009)
Coal	-	-	24.4 MJ/kg	LHV: Nielsen et al. (2012, p 840)

4 Inventory of electricity from combustion of wood pellets

Wood pellets can be sourced from dedicated plantations forests or as saw dust/chips from saw mills (or other waste wood). Since saw dust from saw mills is a dependant by-product of the sawn wood production, a change in demand for saw dust will not change the production volume of sawn wood. Instead dedicated plantations will be affected as source of wood. This is illustrated in **Figure 4.1**.

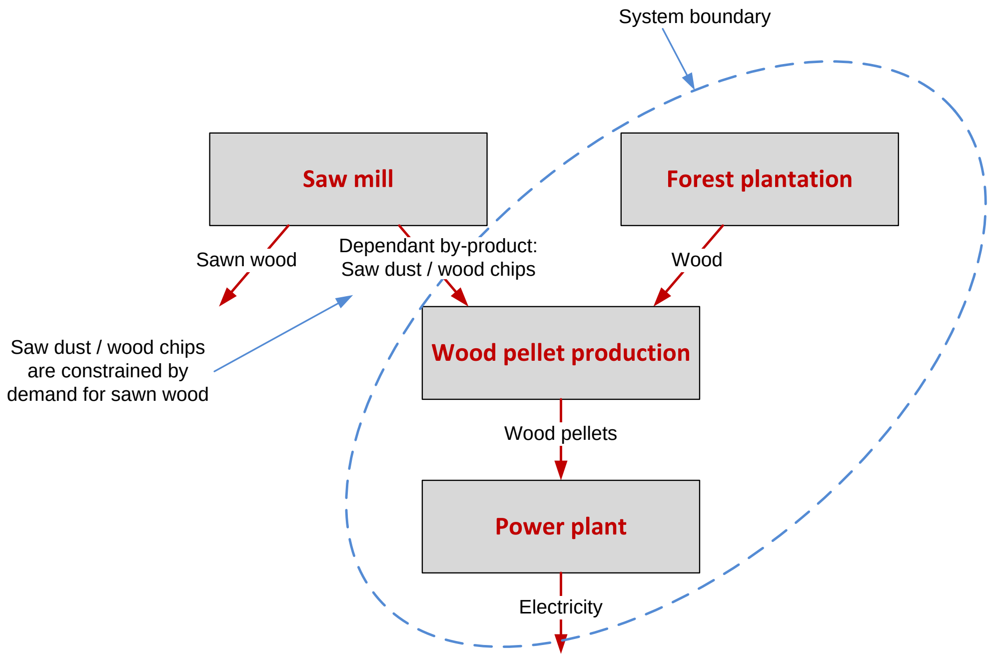

Figure 4.1: System boundary for the inventory of electricity production based on wood pellets.

Wood pellet is the fastest growing source of wood biomass in the EU27 (Cocchi et al. 2011). A local EU scenario and two import scenarios are included. Latvia is regarded as the most likely EU supplier of wood pellets to Denmark (see more description of this in the following). The Main current exporters to the EU are Canada, the United States and the Russian Federation (Cocchi et al. 2011, p 146). The major future suppliers are predicted to be Canada, the United States and Brazil. The suppliers which are expected to increase their production the most are United States and Brazil. Therefore, wood pellets from the United States and Brazil are included in the current study.

Scenario 1: Eucalyptus from Brazil representing marginal supply to global market

According to outlook scenarios for bioenergy between 2010 and 2020, pine from South-East USA and eucalyptus from Brazil are forecasted to be the suppliers that will most increase their production (Cocchi et al. 2011). The main reason that South-East USA increases its wood-pellet production is a decline in domestic demand for roundwood for construction due to the financial/housing crisis (Cocchi et al. 2011, p 144). Hence, the trends in South-East USA may rather reflect regional short-time changes in demand for roundwood than it reflects that the region represents the marginal supplier of wood to the global market for wood pellets. In contrast to the trends in the South-East USA described above, the forecasted increase in North Eastern Brazilian production is based on new investments in Eucalyptus plantations (Cocchi et al. 2011, p 138, 145). Therefore, Brazil is regarded as a more likely representative for the marginal supplier to the global market for wood pellets. In contrast to the eucalyptus plantations for pulp wood, which typically have rotation times of seven years, the Brazilian plantations of eucalyptus for energy abide by a very short rotation cycle down to 2-3 years (Cocchi et al. 2011, p 138).

Brazilian eucalyptus:

- Rotation time: 6 years (Couto et al., 2011)
- Annual increment: 50 m^3 ha^{-1} $year^{-1}$ (Couto et al., 2011)
- Amount of thinned wood: Total increment is modelled as if it was harvested at the end of rotation.
- Amount of removed wood at felling: 300 m^3 (Almeida et al., 2007)
- Times of thinning: 2-3 $year^{-1}$. Total increment is modelled as if it was harvested at the end of rotation.

Scenario 2: Loblolly pine (Pinus taeda) from South East USA representing marginal supply to global market (shorter term and less likely compared to eucalyptus from Brazil).
According to Dickens and Jackson (2011), Loblolly pine is financially the best choice of the tree species for wood pellets in Georgia. Therefore, this species is adopted in this study. The peak in the annual increment is 10-15 years, and the average yield of six trials of Loblolly pine between 8 and 19 years is 9.5 (fresh) tonnes/acre-yr which corresponds to 23.5 (fresh) tonnes /ha-yr (Dickens and Jackson 2011, p 6). According to Meyer (2012) the moisture content in fresh loblolly pine is approximately 50%, hence the mean average increment is 11.7 (dry) tonnes /ha-yr, and it is assumed that this is valid for harvest after 12 years.

Loblolly pine:

- Rotation time: 12 years
- Annual increment: 14 m^3 ha^{-1} $year^{-1}$ (Dickens and Jackson 2011)
- Amount of thinned wood: Total increment is modelled as if it was harvested at the end of rotation.
- Amount of removed wood at felling: 168 m^3
- Times of thinning: Unknown, total increment is modelled as if it was harvested at the end of rotation.

Scenario 3: Pine from Latvia representing marginal supplier among the Baltic countries from which Denmark imports its majority of wood pellets
In 2010 Denmark imported 1.6 million tonnes of wood pellets, of which approximately 40% came from the Baltic countries (IEA 2012, p 30-31). According to IEA (2012, p 97) Latvia is the Baltic Country that has faced the largest growth in wood pellet production from 2007 to 2009.

Latvian pine

- Rotation time: 63 years
- Annual increment: 6 m^3 ha^{-1} $year^{-1}$
- Amount of thinned wood: 64,000 kg C ha^{-1} (Total increment is modelled as if it was harvested at the end of rotation)
- Amount of removed wood at felling: 378 m^3
- Times of thinning: years 30, 35, 40, 45, 50, 55. Total increment is modelled as if it was harvested at the end of rotation.

4.1 Electricity production

The inventory of electricity production at plant is presented in **Table 4.1**. According to Prapaspongsa et al. (2011, appendix 1), the electricity-to-fuel efficiency for a planned new biomass power plant in the UK is 37.9%. This figure is assumed to be representative for the electricity based on wood pellets in the current study.

Table 4.1: LCI-data: Electricity production using wood pellets.

Exchanges	Unit	Electricity production based on wood pellets	LCI data
Reference flow			
Electricity from wood pellets	MJ	1	Reference flow
Energy inputs			
Wood pellets, burned in power plant	MJ	2.639	See **Table 4.2**

In **Table 4.2**, the inventory data for the burning of wood pellets in power plant are presented. The table also includes the burning of wood pellets in industrial boilers. These figures are used when wood pellets are burned as fuel for drying wood in the process of wood pellet production. The input of wood pellets is based on calorific value (LHV) from **Table 3.3**.

Table 4.2: LCI-data: Wood pellets burned in power plant and in the wood pellet industry.

Exchanges	Unit	Wood pellets burned in power plant, DK	Wood pellets burned in small industrial boiler, at wood pellet producer	LCI data
Reference flow				
Wood pellets, burned in power plant	MJ	1		Reference flow
Wood pellets, burned in small industrial boiler	MJ		1	Reference flow
Material inputs				
Wood pellets (90% dm))	kg	0.0571	0.0571	See **Table 4.3**
Transport				
Transport, lorry	tkm	0.0114	0.0114	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Transport, freight ship for wood pellets from BR to DK: 8510 km	tkm	0.486	-	Transport, transoceanic freight ship/OCE (ecoinvent 2010). Distances are based on www.searates.com
Transport, freight ship for wood pellets from US to DK: 9980 km	tkm	0.570	-	
Transport, freight ship for wood pellets from LV to DK: 845 km	tkm	0.0483	-	
Emissions				
CO_2 (biogenic)	kg	0.0886	0.0886	Calculated based on carbon balance of forest activity (**Table 4.4**), flows in wood pellet production (**Table 4.3**) and the calorific value of wood pellets
CH_4	kg	3.1E-6	15E-6	Nielsen et al. (2012, p 845)
N_2O	kg	0.80E-6	4.0E-6	Nielsen et al. (2012, p 848)

4.2 Wood pellet production

The LCI data for the production of wood pellets include pelletization and drying to 7-12% moisture content (Yorwoods 2008). A moisture content at 10% is assumed (as in Prapaspongsa et al. 2011, appendix 3).

The input of wood is determined based on the dry-matter content of wood pellets at 90% (see above), and the assumption that there is no loss in the process. 1 kg wood pellets contain 0.1 kg of water. Thus, 1 kg wood pellets require an input of 0.9 kg dry-matter wood.

The inputs of diesel for mechanical energy, electricity and wood pellets for heat energy are obtained from Mani (2005, p 99). It has been assumed that wood pellets are used as source of heat for drying.

Table 4.3: LCI-data for the production of wood pellets.

Exchanges	Unit	Wood pellets			LCI data
		Brazil	USA	Latvia	
Reference flow					
Wood pellets (90% dm), eucalyptus, BR	kg	1			Reference flow
Wood pellets (90% dm), loblolly pine, US	kg		1		Reference flow
Wood pellets (90% dm), pine, LV	kg			1	Reference flow
Material inputs					
Wood, eucalyptus, BR	kg dm	0.900			See **Table 4.4**
Wood, loblolly pine, US	kg dm		0.900		
Wood, pine, LV	kg dm			0.900	
Energy inputs					
Fuel for mechanical energy	MJ	0.206	0.206	0.206	Diesel, burned in building machine/GLO (ecoinvent 2010)
Wood pellets, burned in furnace, BR	MJ	2.75			See **Table 4.2**
Wood pellets, burned in furnace, US	MJ		2.75		
Wood pellets, burned in furnace, LV	MJ			2.75	
Electricity, medium voltage, BR	MJ	0.430			See **section 12.1**
Electricity, medium voltage, US	MJ		0.430		See **section 12.1**
Electricity, medium voltage, CZ	MJ			0.430	See **section 12.1**
Transport					
Transport, lorry 16-32 t	tkm	0.361	0.361	0.361	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs.

4.3 Wood production in forest plantation

The rate of biomass growth of all forestry crops is based on the general logistic (S-shape or sigmoid) equation:

Equation 4.1

$$NPP(t) = \frac{NPP_T}{1 + 100^{\frac{T/2-t}{T/2}}}$$

where:

- NPP(t) is the yield in a specific year *t* (kgC or kg biomass),
- NPP_T is the total yield over the whole rotation (kgC or kg biomass),
- t = time (year), variable,
- T = rotation length in years.

Figure 4.2 shows the application of this equation to a rotation of Sitka spruce on a 80-year rotation and a total yield of 220 tonnes of carbon per hectare. Three distinct phases of growth or carbon sequestration can be noted: establishment phase (0-20 years), full-vigour phase (20-60 years), and mature phase (60-80 years). The estimates are representative of a stand of general yield class 12 Sitka spruce and have been made using the CARBINE carbon accounting model (Broadmeadow and Matthews, 2003).

We assume that 80% of both above-ground and below-ground wood residues are recovered from the plantation during the course and at the end of the rotation at harvest. The decay functions and rates for the three species in the three countries are described in **section 5.3**.

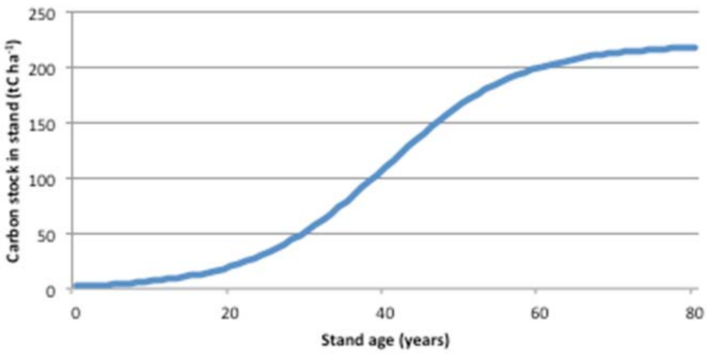

Figure 4.2: An example of carbon accumulation in a newly created stand of trees.

Data on the use of diesel and fertiliser throughout the rotation time in forestry from Brazilian eucalyptus is obtained from Romanelli and Milan (2010). The same fuel and fertiliser consumption per rotation period is assumed for South-East US loblolly pine and Latvian pine.

The input of land tenure (measured in units of potential net primary production) is calculated as the annual potential net primary production, NPP_0, for the three locations (obtained from Haberl et al. 2007) multiplied by the rotation time.

The transport inputs, measured as tkm, are estimated assuming a standard distance at 200 km for all material inputs. The fertiliser nutrients are converted to total fertiliser weight by use of standard factors from IFA (2012).

Table 4.4: LCI-data for forest plantations. The data collection unit is 1 ha over the entire rotation period for each species.

Exchanges	Unit	Plantation			LCI data
		Eucalyptus, BR	Loblolly pine, US	Pine, LV	
Reference flow					
Wood, as dry matter weight	kg	227,016	102,816	285,768	Reference flow, calculated as annual increment multiplied with rotation time
Land tenure					
Market for land, intensive forest land, NPP_0 as C	kg C	54,000	84,000	441,000	Schmidt et al. (2012) – also see **section 3.2**
Materials					
N-fertiliser, as N	kg	164	164	164	Ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
P-fertiliser, as P2O5	kg	78	78	78	Triple superphosphate, as P2O5, at regional storehouse/RER (ecoinvent 2010)
K-fertiliser, as KCl	kg	254	254	254	Potassium chloride, as K2O, at regional storehouse/RER (ecoinvent 2010)
Lime	kg	1,000	1,000	1,000	Limestone, milled, loose, at plant/CH (ecoinvent 2010)
Energy					
Diesel burned in forest machinery	MJ	20,400	20,400	20,400	Diesel, burned in building machine/GLO (ecoinvent 2010)
Transport					
Transport, lorry 16-32 t	tkm	512	512	512	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs.
Emissions					
CO2-emission from residue decay, as GWP100	kg	30,127	12,323	32,207	Calculated based on **Equation** 3.4 and **Table 4.5**, **Table 4.6** and **Table 4.7**.
CO2-uptake from biomass growth, as GWP100	kg	-408,652	-180,160	-403,498	Calculated based on **Equation** 3.4 and **Table 4.5**, **Table 4.6** and **Table 4.7**

In **Table 4.5** and **Table 4.7** the carbon balances of the three plantations are shown.

Table 4.5: Time dependant carbon balance for 1 hectare eucalyptus plantation in Brazil. The balance includes harvest in year 0, regrowth of new trees from year 1-7 and residue decay until year 500. (AG = above around and BG = below ground). Time is given in years, and carbon flows are specified in units of kg C.

Time after harvest	Inputs:					Outputs:			Balance
	Uptake as AG, roundwood for harvest	Uptake as AG, residues for harvest	Uptake as AG, residue for non-use	Uptake as BG, residue for harvest	Uptake as BG, residue for non-use	Decay of AG residues	Decay of BG residues	Removed wood	inputs - outputs
0	0	0	0	0	0	0	0	106,698	-106,698
1	719	169	42	179	45	2,021	2,134		-3,001
2	2,503	589	147	622	155	280	295		3,441
3	9,652	2,271	568	2,398	600	165	174		15,150
4	23,441	5,515	1,379	5,824	1,456	146	154		37,315
5	23,441	5,515	1,379	5,824	1,456	134	141		37,341
6	9,652	2,271	568	2,398	600	123	129		15,237
7	2,503	589	147	622	155	112	119		3,785
8						219	231		-212
9						195	206		-195
10						181	191		-179
…	…	…	…	…	…	…	…	…	…
11-500						965	1,019		-1,984
Sum	**71,910**	**16,920**	**4,230**	**17,868**	**4,467**	**4,230**	**4,467**	**106,698**	**0**

Table 4.6: Time dependant carbon balance for 1 hectare loblolly pine plantation in South East USA. The balance includes harvest in year 0, regrowth of new trees from year 1-13 and residue decay until year 500. (AG = above around and BG = below ground). Time is given in years, and carbon flows are specified in units of kg C.

Time after harvest	Inputs:					Outputs:			Balance
	Uptake as AG, roundwood for harvest	Uptake as AG, residues for harvest	Uptake as AG, residue for non-use	Uptake as BG, residue for harvest	Uptake as BG, residue for non-use	Decay of AG residues	Decay of BG residues	Removed wood	inputs - outputs
0	0	0	0	0	0	0	0	48,324	-48,324
1	332	82	21	69	17	749	634		-862
2	375	93	23	79	20	222	188		178
3	779	193	48	163	41	87	74		1,064
4	1,559	386	97	327	82	51	43		2,355
5	2,892	716	179	606	151	41	35		4,469
6	4,681	1,159	290	981	245	37	32		7,287
7	6,129	1,518	379	1,284	321	35	30		9,566
8	6,129	1,518	379	1,284	321	34	29		9,569
9	4,681	1,159	290	981	245	32	27		7,296
10	2,892	716	179	606	151	31	26		4,488
11	1,559	386	97	327	82	30	25		2,395
12	779	193	48	163	41	29	24		1,172
13	375	93	23	79	20	27	23		538
14						26	22		-48
15						25	21		-47
…	…	…	…	…	…	…	…	…	…
16-500						595	504		-1,099
Sum	**33,163**	**8,212**	**2,053**	**6,948**	**1,737**	**2,053**	**1,737**	**48,324**	**0**

Table 4.7: Time dependant carbon balance for 1 hectare pine plantation in Latvia. The balance includes harvest in year 0, regrowth of new trees from year 1-64 and residue decay until year 500. (AG = above around and BG = below ground). Time is given in years, and carbon flows are specified in units of kg C.

Time after harvest	Inputs:					Outputs:			Balance
	Uptake as AG, roundwood for harvest	Uptake as AG, residues for harvest	Uptake as AG, residue for non-use	Uptake as BG, residue for harvest	Uptake as BG, residue for non-use	Decay of AG residues	Decay of BG residues	Removed wood	inputs - outputs
0	0	0	0	0	0	0	0	134,311	-134,311
1	746	398	99	199	50	858	429		205
2	116	62	15	31	8	709	354		-831
3	134	71	18	36	9	587	293		-612
4	154	82	21	41	10	486	243		-421
5	178	95	24	47	12	404	202		-250
6	205	109	27	55	14	337	168		-95
7	236	126	31	63	16	281	141		49
8	271	145	36	72	18	236	118		188
9	311	166	41	83	21	199	99		324
10	357	190	48	95	24	168	84		461
…	…	…	…	…	…	…	…	…	…
11-62	71,659	38,218	9,555	19,109	4,777	1,987	994		140,337
…	…	…	…	…	…	…	…	…	…
63	134	71	18	36	9	22	11		235
64	116	62	15	31	8	22	11		199
65						22	11		-33
66						22	11		-33
67						22	11		-33
68						22	11		-32
69						21	11		-32
70						21	11		-32
…	…	…	…	…	…	…	…	…	…
71-500						3,389	1,694		-5,083
>500						263	132		-395
Sum	**74,617**	**39,796**	**9,949**	**19,898**	**4,974**	**9,686**	**4,843**	**134,311**	**0**

5 Inventory of electricity from combustion of wood chips

The production of wood chips, as well as their combustion for electricity production, is reported here. It should be noted that it has been assumed that all wood chips are produced from forest residues and that these residues are not constraint by e.g. the demand for ordinary timber. I.e. an optimistic scenario where additional residues are regarded as available is assumed. Hence, the wood chips are sourced by an increase in residue harvest without affecting the forested area or the timber harvest.

5.1 Electricity production

The inventory of electricity production at plant is presented in **Table 5.1**. It has been assumed that electricity from wood chips can be produced at an efficiency of 35%. The calculations made here assume a simulated wood-fired power only plant, consuming 132,808 oven-dried tonnes (25% moisture content) of wood chip per year, based on an equivalent straw-fired power only plant with a net electrical output rating of 20.0 MW and a load factor of 65% (Grant et al., 1995).

In an alternative scenario that is not considered here, where the wood chips are recovered from residues and not from dedicated crops, the transformation of chunks into chips would be regarded as a means of valorisation; therefore, all inputs related to chipping of chunks would be allocated to the chips. However, the diversion of waste wood chunks from landfilling with energy recovery would result in the use of extra coal to compensate for the foregone electricity (627 kWh/t, AEA and NEA, 2008). This would be counterbalanced by the avoided use of coal due to the alternative recovery of energy from this waste.

Table 5.1: LCI-data: Electricity production using wood chips.

Exchanges	Unit	Electricity production based on wood pellets	LCI data
Reference flow			
Electricity from wood chips	MJ	1	Reference flow
Energy inputs			
Wood chips, burned in power plant	MJ	2.86	See **Table 5.2**

In **Table 5.2**, the inventory data for the burning of wood chips in power plant are presented. The input of wood chip is based on calorific value (LHV) specified in **Table 3.3**.

According to **Table 3.3**, wood chips have a dry-matter content of 75% and a lower calorific value of 13.6 MJ/kg (Biomass Energy Centre 2012). On a dry-matter basis, this corresponds to 0.50 kg C/kg dry matter. The input of wood chips to the 'wood chips, burned in power plant' activity is determined based on the calorific value at 13.6 MJ/kg.

The input of transport, measured as tkm, is estimated assuming a standard distance at 200 km and by using the calorific value of wood chips.

Table 5.2: LCI-data: Wood chips burned in power plant.

Exchanges	Unit	power plant, DK	LCI data
Reference flow			
Wood chips, burned in power plant	MJ	1	Reference flow
Material inputs			
Wood chips (75% dm)	kg	0.0735	See **Table 5.3**
Transport			
Transport, lorry	tkm	0.0147	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Emissions			
CO_2 (biogenic)	kg	0.101	Calculated based on carbon in forest residues removed from plantation
CH_4	kg	0.47E-6	Nielsen et al. (2012, p 845)
N_2O	kg	1.1E-6	Nielsen et al. (2012, p 848)

5.2 Wood chips production

The LCI data for the production of wood chips include chipping and drying to 25% moisture content (Elsayed et al., 2003). The input of wood is determined based on the dry-matter content of wood chips at 75% (see above), and the assumption that there is no loss in the process. 1 kg wood chips contain 0.25 kg of water. Thus, 1 kg chips require an input of 0.75 kg dry-matter wood.

The passive drying (from 50% to 25%) and storage of wood chips are assumed to require minimal facilities. The input of diesel for mechanical energy for chipping is obtained from Elsayed et al. (2003, p 112).

Table 5.3: LCI-data for the production of wood chips.

Exchanges	Unit	Wood chips	LCI data
Reference flow			
Wood chips (75% dm)	kg	1	Reference flow
Material inputs			
Forest residues (100% dm), removed from plantation	kg dm	0.75	See **Table 5.6**
Energy inputs			
Fuel for mechanical energy	MJ	0.04	Diesel, burned in building machine/GLO (ecoinvent 2010)
Transport			
Transport, lorry 16-32 t	tkm	0.361	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs.

5.3 Wood residues removal from plantation

When wood residues are removed from the plantation, they are modelled compared to a baseline, where the wood residues are left in the plantation. Removing wood residues from the plantation has a number of effects:

- When wood residues are removed, they will not be left in the plantation for decay over a period of time. Hence, the CO_2 emissions from decay are avoided. This includes the effects on organic material in the soil, as well as more slowly degradable soil carbon. The carbon content in the wood residues will be released at time t=0 in the 'Wood chips, burned in power plant' activity instead (see **Table 5.2**)
- Unlike straw, when wood residues are removed, no additional mineral fertiliser is assumed to be used to counterbalance the nutrient content of the removed wood residues.

The effect on the decay of wood residues is modelled with reference to a negative exponential model as proposed by Freschet et al. (2012) (section 4.3).

The effect on the decay of wood is modelled using the 'ROTHC-26.3' model (Coleman and Jenkinson 2008). In , the decay of wood and associated CO_2 emissions are illustrated. According to this model, 46% of the wood carbon goes to form part of the microbial-biomass pool and 54% to the humified-organic-matter pool. Subsequently, the carbon in these two pools decays at a rate constant (k) of 0.66 and 0.02, respectively, taking into account three rate modifying factors representing temperature, moisture and soil cover (a, b, c, respectively). The general equation for the amount of the material in a pool that remains in a particular year is thus:

Equation 5.1

$$Y(t) = e^{-\frac{t}{a*b*c*k}}$$

where:

- Y is the amount of the material in a pool that remains in a particular year
- k is a constant
- t is time after wood removal in years
- a is the rate modifying factor for temperature
- b is the rate modifying factor for moisture
- c is the soil cover rate modifying factor

The decay rate of wood residues of Brazilian eucalyptus, US loblolly pine and Latvian pine account for the climatic parameters (i.e. mainly temperature and humidity) that determine the rate of decomposition of the different species. The half-lives (the time by which half the residues are decomposed) are 1, 3 and 18 years, respectively. The climate parameters for each region are show in **Table 5.4** and in **Equation 5.2**.

Table 5.4: Climate parameters for the decay of wood residues in different countries.

Parameters	Denmark	Brazil	South-East US	Latvia
a	0.9	4.3	2.1	0.6
b	0.5	1.0	1.0	0.5
c	1.0	1.0	1.0	1.0
T (average annual temperature)	8.6	27.5	15.9	6.0

Equation 5.2

$$a = \frac{47.9}{1 + e^{\frac{106}{T+18.3}}}$$

where:

- a is the rate modifying factor for temperature
- T is the average annual air temperature (°C)

Table 5.5 shows the decay of wood residues, as well as the corresponding CO_2 emissions.

Table 5.5: Decay of wood residues left in the plantation and the corresponding CO_2 emissions (based on decay function, dm% and carbon%). The CO_2 emissions are shown as CO_2 as well as time-dependent GWP100 and GWP20 (based on **section 3.1**). TH = time horizon for GWP.

	Decay function Y(t), see Equation 5.1			**GWP(TH) from CO_2 from decay of 1 kg wood residues (100% dm) left in plantation**					
				GWP100 (kg CO_2-eq.)			**GWP20 (kg CO_2-eq.)**		
Time, t (year)	Eucalyptus, BR	Loblolly pine, US	Pine, LV	Eucalyptus, BR	Loblolly pine, US	Pine, LV	Eucalyptus, BR	Loblolly pine, US	Pine, LV
0	1.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.522	0.635	0.914	0.869	0.664	0.314	0.839	0.641	0.152
2	0.456	0.527	0.842	0.119	0.196	0.257	0.111	0.182	0.120
3	0.417	0.484	0.784	0.070	0.076	0.211	0.062	0.068	0.094
4	0.383	0.459	0.735	0.061	0.044	0.174	0.052	0.038	0.074
5	0.351	0.439	0.694	0.056	0.035	0.143	0.045	0.029	0.058
6	0.322	0.421	0.660	0.051	0.032	0.118	0.039	0.025	0.046
7	0.295	0.404	0.632	0.046	0.030	0.098	0.034	0.022	0.036
8	0.271	0.388	0.608	0.042	0.028	0.082	0.029	0.020	0.028
9	0.249	0.372	0.588	0.038	0.027	0.068	0.025	0.017	0.022
10	0.228	0.357	0.571	0.035	0.026	0.057	0.021	0.015	0.017
11	0.209	0.342	0.557	0.032	0.024	0.048	0.017	0.013	0.013
12	0.192	0.328	0.545	0.029	0.023	0.041	0.014	0.012	0.010
13	0.176	0.315	0.534	0.026	0.022	0.035	0.012	0.010	0.008
14	0.162	0.302	0.525	0.024	0.021	0.030	0.009	0.008	0.006
15	0.148	0.290	0.517	0.022	0.020	0.026	0.007	0.007	0.004
…	…	…	…	…	…	…	…	…	…
100	0.000	0.009	0.295	0.000	0.000	0.000	0.000	0.000	0.000
…	…	…	…	…	…	…	…	…	…
500	0.000	0.000	0.026	0.000	0.000	0.000	0.000	0.000	0.000
Sum	-	-	-	**1.732**	**1.626**	**1.079**	**1.332**	**1.119**	**0.697**

In addition to the calculated inventory data in **Table 5.5**, inputs of fuel for plantation operations and handling of wood chips are included. According to Elsayed et al. (2003), the fuel consumption for converting wood residues into chips per tonne of dried wood chips is 54 MJ/t wood residues (100% dm). The inventory data for removal of forest residues are summarised in **Table 5.6**.

Table 5.6: LCI-data for forest residue removal. The data collection unit is 1 ha yr^{-1}.

Exchanges	Unit	Species, region			LCI data
		Eucalyptus, BR	Loblolly pine, US	Pine, LV	
Reference flow					
Forest residues (100% dm), removed from plantation	kg	1	1	1	Reference flow
Land tenure					
Market for land, arable land, NPP_0 as C	kg C	0	0	0	Schmidt et al. (2012) – also see **section 3.2**
Energy					
Diesel burned in machinery for collection, baling and extraction	MJ	0.054	0.054	0.054	Elsayed et al. (2003)
Transport					
Transport, lorry 16-32 t	tkm	0.000251	0.000251	0.000251	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Emissions					
CO2-emission from residue decay, as GWP100	kg	-1.73	-1.63	-1.08	Calculated based on **Table 5.5**.
CO2-emission from residue decay, as GWP20	kg	-1.33	-1.12	-0.70	Calculated based on principle in **Table 5.5**.

6 Inventory of electricity from combustion of straw

Straw is considered as a so-called second generation biofuel, which is based on residues. Hence, as long as the potential for straw removal is not fully utilised, a change in demand for straw for biofuel purposes will not affect the cultivation of any crops. The only effect is that the straw is combusted instantaneously instead of being left in the field for decomposition, i.e. the carbon content of the straw will be converted to CO_2 instantly instead of throughout a period of several years.

The production of electricity based on straw is modelled using two LCA activities; removal of straw from field and power plant.

As for wood pellets, the power plant activity is subdivided into two activities in order to be more transparent about the conversion of straw to thermal energy (combustion; key parameter is calorific value of straw) and the conversion of thermal energy to electricity (turbine: key parameter is electricity to fuel efficiency). The two power plant LCA activities are described in **section 6.1**.

6.1 Electricity production

The inventory of electricity production at plant is presented in **Table 6.1**. No specific data on electricity-to-fuel efficiencies have been identified. Since the calorific value of straw is significantly lower than that of coal, it is expected that the same efficiency as coal-based electricity generation cannot be achieved. Therefore, it has been assumed that electricity from straw can be produced at the same efficiency as that of wood pellets, i.e 37.9% (see **section 4.1**).

Table 6.1: LCI-data: Electricity production using straw.

Exchanges	Unit	Electricity production based on wood pellets	LCI data
Reference flow			
Electricity from straw	MJ	1	Reference flow
Energy inputs			
Straw, burned in power plant	MJ	2.639	See **Table 6.2**

In **Table 6.2**, the inventory data for the burning of straw in power plant are presented. The input of straw is based on calorific value (LHV) from **Table 3.3**.

Straw has a dry-matter content of 85% (Møller et al. 2005), a lower calorific value at 14.5 MJ/kg (Nielsen et al. 2012, p 840) and a CO_2 emission factor of 0.110 kg CO_2/MJ. Considering further the molar mass of carbon and CO_2, it can be calculated that the carbon content of straw is 43.5% on a wet weight (85% dry matter) basis. On a dry-matter basis, this corresponds to 51.2% C/kg dry matter. The input of straw to the 'wood pellets, burned in power plant' activity is determined based on the calorific value of 14.5 MJ/kg.

The input of transport, measured as tkm, is estimated assuming a standard distance at 200 km and by using the calorific value of straw.

Table 6.2: LCI-data: Straw burned in power plant.

Exchanges	Unit	power plant, DK	LCI data
Reference flow			
Straw, burned in power plant	MJ	1	Reference flow
Material inputs			
Straw (85% dm)	kg	0.0690	See **Table 6.5**
Transport			
Transport, lorry	tkm	0.0138	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Emissions			
CO_2 (biogenic)	kg	0.110	Nielsen et al. (2012, p 842)
CH_4	kg	0.47E-6	Nielsen et al. (2012, p 845)
N_2O	kg	1.1E-6	Nielsen et al. (2012, p 848)

6.2 Straw removal from field

The removal of straw from the field is modelled compared to a baseline where the straw is left in the field. Removing straw from the field has a number of effects:

- When straw is removed, it will not be left in the field for decay over a period of time. Hence, the CO_2 emissions from decay are avoided. This includes the effects on organic material in the soil, as well as more slowly degradable soil carbon. The carbon content in the straw will be released at time t=0 in the 'Straw, burned in power plant' activity instead (see **Table 6.2**)
- When straw is removed, also the nutrient content of the straw is removed. It is assumed that the farmer will counter balance this by adding additional mineral fertiliser. The effect of straw as N-fertiliser relative to mineral N-fertiliser is assumed to be 45% which is similar to deep litter (based on Plantedirektoratet 2004). Similar effects of straw as phosphorous and potassium fertilisers are assumed.

The effect on the decay of straw is modelled using the 'ROTHC-26.3' model (Coleman and Jenkinson 2008). In **Table 6.3,** the decay of straw and associated CO_2 emissions are illustrated. According to this model, 46% of the straw carbon goes to form part of the microbial-biomass pool and 54% to the humified-organic-matter pool. Subsequently, the carbon in these two pools decays at a rate constant (k) of 0.66 and 0.02, respectively, taking into account three rate modifying factors representing temperature, moisture and soil cover (a, b, c, respectively). The general equation for the amount of the material in a pool that remains in a particular year is thus:

Equation 6.1

$$Y(t) = e^{-\frac{t}{a*b*c*k}}$$

where:

- Y is the amount of the material in a pool that remains in a particular year
- k is a constant
- t is time after straw removal in years
- a is the rate modifying factor for temperature
- b is the rate modifying factor for moisture
- c is the soil cover rate modifying factor

The climate parameters for Denmark are show in **Table 5.4** and in **Equation 5.2**.

Table 6.3: Decay of straw left in the field (based on Coleman and Jenkinson 2008) and the corresponding CO_2 emissions (based on decay function, dm% and carbon%). The CO_2 emissions are shown as CO_2 as well as time-dependent GWP100 (based on **section 3.1**).

Time, t (year)	Decay function Y(t), see Equation 6.1	CO_2 from 1 kg straw (85% dm) left in field (kg CO_2)	GWP100 from CO_2 from 1 kg straw (85% dm) left in field (kg CO_2-eq.)	GWP20 from CO_2 from 1 kg straw (85% dm) left in field (kg CO_2-eq.)
0	1.000	0.000	0.000	0.000
1	0.740	0.415	0.369	0.398
2	0.547	0.307	0.197	0.281
3	0.405	0.227	0.109	0.198
4	0.300	0.168	0.063	0.139
5	0.222	0.124	0.039	0.098
6	0.164	0.092	0.027	0.068
7	0.121	0.068	0.021	0.047
8	0.090	0.050	0.017	0.033
9	0.066	0.037	0.015	0.022
10	0.049	0.028	0.014	0.015
11	0.036	0.020	0.013	0.010
12	0.027	0.015	0.013	0.007
13	0.020	0.011	0.012	0.005
14	0.015	0.008	0.012	0.003
15	0.011	0.006	0.011	0.002
…	…	…	…	
100	8.14E-14	4.56E-14	0.000	0.000
…	…	…	…	
500	0.000	0.000	0.000	0.000
Sum	-	**1.595**	**1.548**	**1.329**

In **Table 6.4** the N-balance for straw removal is shown. The N-balance is established for an average Danish wheat field in 2005. All relevant inventory data are documented in Dalgaard and Schmidt (2012, p 55-80). The N-balance is established based on IPCC (2006) emissions models. In the table, the straw-related effect on the N-balance is calculated as the difference between a situation where all above-ground residues are removed and additional mineral fertiliser to account for removed nutrients (first column with data), and a situation where all crop residues are left in the field (second column with data).

Table 6.4: N-balance for two practises of wheat cultivation: 1) cultivation with removal of straw and additional fertiliser input, and 2) cultivation practise with no straw removal (baseline). The effect of straw removal is calculated as the difference between the two. The unit for the N-balance data kg N ha^{-1} yr^{-1}.

Exchanges	Wheat DK2005, all above ground residues removed	Wheat DK2005, all above ground residues left in field	Effect of removing straw
Cultivation data	**Straw removed**	**Baseline**	
Yield, wheat (85% dm)	7,296 kg ha^{-1} yr^{-1}	7,296 kg ha^{-1} yr^{-1}	
Above ground residues (85% dm)	11,629 kg ha^{-1} yr^{-1}	11,629 kg ha^{-1} yr^{-1}	
N-inputs	**Straw removed**	**Baseline**	
Synthetic fertiliser	112.8	99.0	13.9
Organic fertiliser and manure	99.2	99.2	0.0
Crop residues returned to soils	48.1	78.9	-30.8
Total inputs	**260.1**	**277.0**	**-17.0**
N-outputs			
Harvested crop	114.1	114.1	0.0
Crop residues removed from soils	15.2	0.0	15.2
N_2O-N_direct	2.6	2.8	-0.2
N_2O-N_indirect	0.9	0.9	0.0
NO_x-N	0.4	0.4	0.0
NH_3-N	30.7	29.3	1.4
NO_3-N	78.0	83.1	-5.1
N_2-N	18.1	46.4	-28.2
Total outputs	**260.1**	**277.0**	**-17.0**
N-balance			
Inputs minus outputs	**0**	**0**	**0**

In addition to the calculated inventory data in **Table 6.3** and **Table 6.4**, inputs of fuel for field operations and handling of straw are included. According to Dalgaard et al. (2001), the fuel consumption per tonne of straw for baling (high pressure) and handling is 2.0 litre. By using the calorific value of diesel (see **Table 3.3**), it can be found that this corresponds to 0.0854 MJ/kg straw (85% dm). The use of additional N-fertiliser is distributed on different fertiliser types based on Dalgaard and Schmidt (2012, p 67). The amount of removed phosphorus (P) and potassium (K) is calculated based on the P and K content of wheat straw. According to Møller et al. (2005), this is 0.0009 kg P/kg dm straw and 0.015 kg K/km dm straw. By using the dry-matter content of straw (see **Table 3.3**) and molecular weights, this can be converted to 0.018 kg P_2O_5/kg straw (85% dm) and 0.015 kg K_2O/kg straw (85% dm) which are the common units for expressing P and K fertiliser. Only 45% (assumed fertiliser efficiency of straw relative to mineral fertiliser) of this need to be counter-balanced by additional mineral P and K fertilisers.

Table 6.5: LCI-data for straw removal. The data collection unit is 1 ha yr^{-1}.

Exchanges	Unit	Straw	LCI data
Reference flow			
Straw (85% dm), removed from field	kg	11,629	Reference flow
Land tenure			
Market for land, arable land, NPP_0 as C	kg C	0	Schmidt et al. (2012) – also see **section 3.2**
Materials			
N-fertiliser (A), as N	kg	0.680	Ammonia, liquid, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (Urea), as N	kg	1.09	Urea, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AN), as N	kg	1.50	Ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (CAN), as N	kg	10.2	Calcium ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AS), as N	kg	0.408	Ammonium sulphate, as N, at regional storehouse/RER (ecoinvent 2010)
Phosphorus, as P_2O_5	kg	9.17	Triple superphosphate, as P2O5, at regional storehouse/RER (ecoinvent 2010)
Potassium chloride, as K_2O	kg	80.4	Potassium chloride, as K2O, at regional storehouse/RER (ecoinvent 2010)
Energy			
Diesel burned in tractor	MJ	993	Diesel, burned in building machine/GLO (ecoinvent 2010)
Transport			
Transport, lorry 16-32 t	tkm	44.9	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Emissions			
CO_2-emission from residue decay, as GWP100	kg	-18,001	Emission to air. Based on **Table 6.3**
CO_2-emission from residue decay, as GWP20	kg	-15,450	
N_2O	kg	-0.305	Emission to air

7 Inventory of electricity from biogas (maize, manure, organic waste)

Biogas can be used for the production of electricity and heat. Any organic material is a potential feedstock for this purpose; its anaerobic digestion results in the production of methane (CH_4). Three feedstocks are assessed here: manure, maize and organic waste (i.e. sorted organic fraction of municipal solid waste).

According to Energistyrelsen (2012), there is an upper limit of allowable input of energy crops in biogas production in Denmark. In the period 2015-2017, maximum 70% of the biogas is allowed to come from maize ensilage (or other crops), and in the period 2018-2020, this maximum is 48%. The following scenarios for biogas-based electricity are inventoried:

- **70% maize / 30% manure mix**
- **48% maize / 52% manure mix**
- **100% sorted organic municipal waste**

7.1 Electricity production

The inventory of electricity production at plant is presented in **Table 7.1**. According to Jungbluth et al. (2007), the electricity-to-fuel efficiency for a planned new biogas power plant is 37.9%. This figure is assumed to be representative for the electricity based on biogas from organic waste, manure and maize in the current study.

Table 7.1: LCI-data: Electricity production using biogas.

Exchanges	Unit	Electricity production based on biogas	LCI data
Reference flow			
Electricity from biogas	MJ	1	Reference flow
Material inputs			
Purified biogas (96% methane), burned in power plant	MJ	2.65	See **Table 7.2**

Table 7.2 shows the inventory of purified biogas burned in power plant. The input of purified biogas is based on a calorific value at 34.5 MJ/Nm^3 (see **Table 3.3**) and the shares of sources of biogas as specified in the scenarios. The emissions are obtained from Nielsen et al. (2012, p 845, 848).

Table 7.2: LCI-data: Biogas burned in power plant.

Exchanges	Unit	Scenario			LCI data
		70% maize / 30% manure	48% maize / 52% manure	Organic waste	
Reference flow					
Biogas, burned in power plant	MJ	1	1	1	Reference flow
Energy inputs					
Purified biogas (96% methane), from manure	m^3	0.0230	0.0398		See **Table 7.3**
Purified biogas (96% methane), from maize	m^3	0.0536	0.0368		See **Table 7.3**
Purified biogas (96% methane), from organic waste	m^3			0.0766	See **Table 7.3**
Emissions					
Methane	kg	0.000434	0.000434	0.000434	
Nitrous oxide	kg	1.6E-6	1.6E-6	1.6E-6	

7.2 Biogas production

The LCI data for the production of biogas from maize, manure and organic waste refers to a 100% dry-matter content. **Sections 7.3**, **7.4** and **7.5** show the inventory for the three biogas feedstocks considered: maize, manure and organic municipal waste, respectively.

In **Table 7.3**, the inventory data for the purification of the raw biogas is presented. In the purification process the methane content at 55% vol. for biogas from maize (Jørgensen 2009, p 23) and 65% vol. for biogas from manure and organic waste (Jørgensen 2009, p 23) is increased to 96%. This is done by CO_2 removal. The energy use and emissions related to this process are based on Jungbluth et al. (2007, 244-248). The required input of biogas is calculated based on the difference in methane content between the raw biogas (55-65% vol. methane) and the purified biogas (96% vol. methane). The CH_4 loss from the purification as of Jungbluth et al. (2007) corresponds to 2% of input of CH_4 in biogas. This is calculated based on density of biogas at 1.16 kg/Nm^3 (Jensen and Jensen 2000) and the specified CH_4 contents at 55% and 65%.

Table 7.3: LCI-data: Purification of biogas into natural gas quality (96% methane) which can be transmitted via the natural gas grid.

Exchanges	Unit	Biogas from			LCI data (source)
		Manure (cattle)	Maize (cob and stalk)	Organic household waste	
Reference flow					
Purified biogas (96% methane), from manure	m^3	1			Reference flow
Purified biogas (96% methane), from maize	m^3		1		Reference flow
Purified biogas (96% methane), from organic waste	m^3			1	Reference flow
Material inputs					
Biogas, from manure (65% CH_4)	m^3	1.48			See **Table 7.5**
Biogas, from maize (55% CH_4)	m^3		1.75		See **Table 7.5**
Biogas, from organic waste (65% CH_4)	m^3			1.48	See **Table 7.5**
Energy inputs					
Electricity, medium voltage, DK	MJ	1.80	1.80	1.80	See **section 12.1**
Emissions					
CH_4	kg	0.0223	0.0223	0.0223	

Table 7.5 shows the inventory data for the conversion of feedstocks to biogas. The input of maize, manure and organic waste is based on their biogas potentials from Jørgensen (2009, p 23). The figure for maize is consistent with that reported by Larsen and Madsen (2009), which report a yield of 0.312 m^3 CH_4 kg dm^{-1} crop which corresponds to 1.76 kg dm maize at a methane content of the biogas at 55%. Transport for the manure and maize is estimated based on distances at 20 km, and transport for organic waste is obtained from same data source as for the energy inputs and emissions – see below. The energy inputs and N_2O emissions from the digestion process are obtained from the following ecoinvent processes:

- Maize: Data for this are assumed to be similar to biogasification of organic waste, see bullet below
- Manure: 'Biogas, from slurry, at agricultural co-fermentation, covered/CH' (ecoinvent 2010)
- Organic waste: 'Biogas, from biowaste, at storage/CH' (ecoinvent 2010)

The use of heat in the biogas production process is based on the data in the ecoinvent processes referred to above, and that the heat is generated by burning biogas with a fuel to heat efficiency at 90%.

CH_4 emission (fugitive losses) from the digestion process is assumed to be 1% of the produced CH_4. According to Hamelin et al (2010, p 239) literature specifies values in a range between 1% and 4%. 1% is assumed here which is in accordance with Hamelin et al (2010, p 239) and Jungbluth et al. (2007, p 206). In order to calculate the CH_4 emission in mass unit (kg), the CH_4% (specified in the table) and density of biogas at 1.16 kg/Nm3 (Jensen and Jensen 2000) are used.

A by-product of the biogasification activity is the compost from maize and organic waste (there are no impacts on manure because it is already applied on land). It has been assumed that the compost will not displace any products (sphagnum and mineral fertilisers). Generally, the effect of displaced fertilisers from compost as a by-product from biogas is relatively insignificant (Kromann et al. 2004). Regarding the displacement of sphagnum, no displacement is assumed because the two products generally provide different services, i.e. they do not belong to the same market, and hence thee is very limited substitution. When the compost is applied on land, the decay function is assumed to be similar as of straw (see **section 6.2**). The amount of carbon that is not regarded as being uptaken or released in year t=0, i.e. the carbon in compost, is estimated based on the carbon in the feedstock minus the carbon in the biogas, see **Table 7.4**. All other carbon than the compost carbon is assumed to be uptaken or released at time t=0, and therefore these CO_2 exchanges are not included in the inventory tables. The carbon in biogas is calculated based on a density at 1.15 kg/Nm^3 and on carbon content in the biogas at 0.49 kg C/kg biogas (estimated based on composition at 55% CH_4 and 45% CO_2 and molar masses of CH_4 and CO_2). The carbon in feedstock is estimated as 0.5 kg C/kg dm. The carbon in the compost will be converted to CO_2 as the compost decays. A decay function similar to straw (see **Table 6.3**) has been assumed.

Table 7.4: Carbon balance of biogas production to calculate carbon in compost. The carbon balance is established per m^3 biogas produced.

Inputs and outputs	Unit	Carbon balance: biogasification maize	Carbon balance: biogasification maize
Inputs			
Feedstock	kg C/m^3 biogas	0.820	1.17
Outputs			
Carbon in biogas	kg C/m^3 biogas	0.564	0.564
Rest = carbon in compost	kg C/m^3 biogas	0.256	0.606

Table 7.5: LCI-data: Conversion of biogas in biogas plant.

Exchanges	Unit	Biogas from			LCI data (source)
		Maize (cob and stalk)	Manure (cattle)	Organic household waste	
Reference flow					
Biogas, from maize (55% CH_4)	m^3	1			Reference flow
Biogas, from manure (65% CH_4)	m^3		1		Reference flow
Biogas, from organic waste (65% CH_4)	m^3			1	Reference flow
Material inputs					
Maize	kg dm	1.64			See **Table 7.6**
Manure	kg dm		4.17		See **Table 7.7**
Organic waste	kg dm			2.33	See **Table 7.8**
Energy inputs					
Electricity	MJ	0.309	0.504	0.443	See **section 12.1**
Heat: Burning biogas from maize	MJ	1.57	7.90	1.83	Based on **Table 7.2**
Transport					
Transport, lorry	tkm	0.253	0.700	0.0306	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010)
Transport, waste collection	tkm	-	-	0.0270	Transport, municipal waste collection, lorry 21t/CH (ecoinvent 2010)
Emissions					
CH_4	kg	0.0064	0.0075	0.0075	
N_2O	kg	0.308E-3	2.04E-3	0.308E-3	

Delayed CO_2-emission from compost decay, as GWP100	kg	-0.205	-	-0.484	
Delayed CO_2-emission from compost decay, as GWP20	kg	-0.454	-	-1.074	

7.3 Biogas feedstock: Production of maize (cob + stalk)

Inventory data for the production of maize are obtained from Dalgaard and Schmidt (2012, p 78). In Dalgaard and Schmidt (2012), the maize field has input of manure as fertiliser. This has been converted to mineral fertilisers and reduced N_2O emissions using the data in Dalgaard and Schmidt (2012, p 36-39). Maize ensilage has dry matter content at 33% (Dalgaard and Schmidt 2012).

Table 7.6: LCI-data for maize ensilage production, DK average 2005. The data collection unit is 1 ha yr^{-1}. (Dalgaard and Schmidt 2012, p 78)

Exchanges	Unit	Amount	LCI data
Reference flow			
Maize ensilage (100% dm)	kg	12,647	Reference flow
Land tenure			
Market for land, arable land, NPP_0 as C	kg C	7000	Schmidt et al. (2012) – also see **section** 3.2
Materials			
N-fertiliser (A), as N	kg	4.93	Ammonia, liquid, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (Urea), as N	kg	7.88	Urea, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AN), as N	kg	10.8	Ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (CAN), as N	kg	73.9	Calcium ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AS), as N	kg	2.96	Ammonium sulphate, as N, at regional storehouse/RER (ecoinvent 2010)
Phosphorus, as P_2O_5	kg	46.1	Triple superphosphate, as P2O5, at regional storehouse/RER (ecoinvent 2010)
Potassium chloride, as K_2O	kg	260	Potassium chloride, as K2O, at regional storehouse/RER (ecoinvent 2010)
Energy			
Diesel burned in tractor	MJ	3,715	Diesel, burned in building machine/GLO (ecoinvent 2010)
Transport			
Transport, lorry 16-32 t	tkm	131	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Emissions			
N_2O	kg	3.66	emission to air

The transport inputs, measured as tkm, are estimated assuming a standard distance at 200 km for all material inputs. The fertiliser nutrients are converted to total fertiliser weight by use of standard factors from IFA (2012).

7.4 Biogas feedstock: Effect of diverting manure for biogas treatment

Diverting manure for biogas has been modelled as raw manure sent directly to biogas plant without any special pre-treatment of manure, e.g. separation.

CH_4 from storage (after in-house storage of manure) is affected when the manure is sent to biogas. The in-door storage of manure is not affected. The outdoor storage time is heavily reduced when the manure is sent to biogas treatment. According to Wesnæs et al. (2009, p 168) CH4 emission per 1000 kg slurry (wet) is 1.68 kg. Applying a dm% at 11.9% (Poulsen et al. 2001, p 50, 147), this corresponds to 0.014 kg CH_4/kg dm manure. The CH_4 emission from outdoor storage, when the manure is sent to biogas, is assumed to be negligible. This assumption is in accordance with Hamelin et al. (2010, p 298,326).

The net effect on N_2O emissions of diverting manure from storage to a biogas plant before applying the manure on land is described in Dalgaard and Schmidt (2012, p 38). In general, the emissions from manure application on land are the same regardless of where the manure has been between collection and application. However, according to Mikkelsen et al. (2011, p 81), the field emissions of direct N_2O from applied manure will be reduced by 64% if the manure has been sent through a biogas plant before being applied on land. According to Dalgaard and Schmidt (2012, p 38), the N_2O emission per kg N in manure is 0.010 kg N_2O-N for non-biogasified manure and 0.0064 kg N_2O-N for biogasified manure. Hence, the effect is 0.0064 kg N_2O-N minus 0.010 kg N_2O-N = -0.0036 kg N_2O-N / kg N in manure. By use of molar masses this can be converted to -0.0057 kg N_2O / kg N in manure. According to Poulsen et al. (2001, p 50, 147), the dry matter content in manure (liquid slurry, cattle) is 11.9% and the N content in manure (liquid slurry, cattle) is

-5.75 kg N/tonne. 1 kg N in manure corresponds to 174 kg manure (11.9% dm) and 20.7 kg manure (100% dm). Hence, the -5.75 kg N_2O/kg N in manure can be converted to -0.000273 kg N2O/kg dm manure.

The IPCC (2006, section 10) methodology for calculating methane from manure management and land application does not include methane from manure in soils. Based on this, and on the fact that the soils are not anaerobic, it is assumed that there is no methane emissions from manure applied on land.

The transport of the manure to the biogas plant and back to the farm is included in the biogas LCA activity.

The inventory data for the acquisition of manure as a biogas feedstock are presented in **Table 7.7**.

Table 7.7: LCI-data for manure for biogas. The LCA activity represents the difference between applying manure to land without biogas and with biogas. (Dalgaard and Schmidt 2012, p 38)

Exchanges	Unit	Amount	LCI data
Reference flow			
Manaure for biogas (100% dm)	kg	1	Reference flow
Emissions			
CH_4	kg	-0.014	emission to air
N_2O	kg	-0.000273	emission to air

7.5 Biogas feedstock: Organic municipal waste

Currently, all non-sorted municipal waste in Denmark is sent to waste incineration with electricity and heat recovery. When organic municipal waste in Denmark is sorted out for biogasification, the effect of organic waste acquisition is avoided incineration. LCI data on incineration of organic waste in Denmark is modelled using the ecoinvent data set: 'Disposal, biowaste, 60% H2O, to municipal incineration, allocation price/CH' (ecoinvent 2010). It should be noted that this dataset is an allocated dataset (allocated between waste disposal service, electricity and heat), where 71.39% is allocated to the waste disposal service (Jungbluth et al. 2007, p 636). In order to comply with ISO 14044 on allocation (which shall be avoided), all inputs and outputs of the activity are multiplied with 1/0.7139 (to create an unallocated LCA activity) and the generated electricity and heat are included as substituted products. The lower calorific value of organic municipal waste (40% dm) is 5.10 MJ/kg (Jungbluth et al. 2007, p 630); this corresponds to 12.8 MJ/kg dm. According to Schmidt (2012, p 91), the energy recovery rates for waste incineration in Denmark in 2005 for heat and electricity were 64.9% and 16.1% respectively.

It has been assumed that the sorting of organic waste from the remaining municipal waste can be carried out without any additional inputs. This is clearly not possible since it would require waste bins for the additional fraction, as well as probably some extra transportation due to less efficient utilisation of the load capacity of the waste collection vehicles. However, this is regarded as having minimal effect (estimated based on Kromann et al. 2004) and it has been omitted.

The inventory data for the acquisition of organic municipal waste as a biogas feedstock are presented in **Table 7.8**.

Table 7.8: LCI-data for organic municipal waste. The LCA activity represents the avoidance of incinerating the waste.

Exchanges	Unit	Amount	LCI data
Reference flow			

Organic municipal waste (100% dm)	kg	1	Reference flow
By-products			
Electricity	MJ	2.05	The input is calculated as 16.1% of 12.8 MJ. LCI data: see **section 12.1**.
District heating	MJ	8.28	The input is calculated as 64.9% of 12.8 MJ. LCI data: see **section 12.2**..
Inputs			
Incineration: Inputs and emissions	kg	-3.50	The input is calculated as (1/0.7139) / 0.40 in order to have unallocated data for 100% dm organic waste. LCI data: Disposal, biowaste, 60% H2O, to municipal incineration, allocation price/CH (ecoinvent 2010)

8 Inventory of 1st and 2nd generation ethanol (wheat, maize and straw)

8.1 Bioethanol production incl. combustion

The inventory data of wheat- and maize-cob-based bioethanol is based on Jensen et al. (2007). Only inputs of feedstock, electricity and heat are considered. And for the outputs only the ethanol, DDGS, and energy from biogas (co-product) are considered. The biogas co-product output is assumed to be converted to electricity and heat at efficiencies of 30% and 60%, respectively. The electricity and heat in **Table 8.1** is the net input, i.e. the input minus the output (related to the co-product of biogas). All other exchanges are omitted in the current screening LCA. Jensen et al. (2007) does not include data for wheat-based bioethanol, so the bioethanol production is assumed to be similar in terms of quantities of flow exchanges.

Note that there are no emissions. The carbon contained in the feedstocks is converted to carbon dioxide. However, the time between uptake in agriculture and emission in vehicle motor is assumed to be negligible.

Second generation bioethanol is modelled based on straw. The modelled technology represents the Integrated Biomass Utilisation System (IBUS) concept developed by DONG Energy A/S (briefly described in Jensen et al. 2007). The inventory of bioethanol production is based on Jensen et al. (2007). Only inputs of feedstock, electricity and heat are considered. And for the outputs only the ethanol, C5 molasses, and energy from biogas (co-product) are considered. The biogas co-product output is assumed to be converted to electricity and heat at efficiencies at 30% and 60% respectively. The electricity and heat in **Table 8.1** is the net input, i.e. the input minus the output (related to the co-product of biogas). All other exchanges are omitted in the current screening LCA.

As opposed to bioethanol based on wheat and maize, CO_2 emissions (GWP time weighted) originating from the conversion of the carbon in the straw to CO_2 are considered. Exactly the same amount of CO_2 is avoided in the field, when the straw is removed – the only difference is the timing of the emissions.

Table 8.1: Biotethanol production. (Jensen et al. 2007)

Exchanges	Unit	Bioethanol production			LCI data
		Wheat	Maize	Straw	
Reference flow					
Bioethanol, from wheat	MJ	1			Reference flow
Bioethanol, from maize	MJ		1		
Bioethanol, from straw	MJ			1	
By-products					
DDGS (wheat)	kg	0.0488			See **section 12.3**
DDGS (maize)	kg		0.0488		
C5 molasses used as animal feed	kg			0.0438	
Materials					
Wheat	kg	0.131			See **Table 8.2**
Maize	kg		0.131		See **Table 8.2**
Straw	kg			0.172	See **Table 5.6**
Enzymes, Termamyl	kg	0.0000223	0.0000223	-	Blackbox GWP100/20 at ~1.2 kg CO_2-eq/kg (Nielsen et al. 2007)
Enzymes, Spirizyme	kg	0.0000916	0.0000916	-	Blackbox GWP100/20 at ~7.6 kg CO_2-eq/kg (Nielsen et al. 2007)
Enzymes, Cellulasse	kg	-	-	0.000190	Estimated: GWP100/20 at 10 kg CO_2-eq./kg
Sulphuric acid (94%)	kg	0.000898	0.000898	0.00118	Sulphuric acid, liquid, at plant/RER (ecoinvent)
Phosphorous acid (74%)	kg	0.000165	0.000165	0.000217	Phosphoric acid, fertiliser grade, 70% in H2O, at plant/GLO (ecoinvent 2010)
Sodiom hydroxide (49%)	kg	0.000071	0.000071	0.0000929	Sodium hydroxide, 50% in H2O, membrane cell, at plant/RER (ecoinvent 2010)
Ammonia water (25%)	kg	0.000115	0.000115	0.000151	Ammonia, liquid, at regional storehouse/RER (ecoinvent 2010)
Urea (45%)	kg	0.000100	0.000100	0.000132	Urea, as N, at regional storehouse/RER (ecoinvent 2010)
Calcium chloride (68%)	kg	0.000031	0.000031	0.0000410	Calcium chloride, CaCl2, at plant/RER (ecoinvent 2010)
Energy					
Electricity	MJ	0.0645	0.0645	0.117	Net = input (elec): 0.066 MJ minus output (elec from biogas): 0.0015 MJ. LCI data for electricity, see **section 12.1**
Heat (modelled as district heat)	MJ	0.454	0.454	0.682	Net = input (steam): 0.457 MJ minus output (heat from biogas): 0.003 MJ. LCI data for heat, see **section 12.2**
Transport					
Transport, lorry 16-32 t	tkm	0.0262	0.0262	0.0262	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs.
Emissions					
CO_2 (GWP100 for emissions taking place at time t=0)	kg	not relevant	not relevant	0.275	Calculated based on carbon content in straw to ensure carbon balance (see carbon in straw in **section 5.3**).
CO_2 (GWP20 for emissions taking place at time t=0)	kg	not relevant	not relevant	0.275	

8.2 1st generation bioethanol feedstock: wheat and maize

Inventory data for wheat production in Denmark and European maize production are obtained from Dalgaard and Schmidt (2012, p 75).

Table 8.2: LCI-data for wheat and maize cultivation. The data collection unit is 1 ha yr^{-1}.

Exchanges	Unit	Cultivation		LCI data
		Wheat (DK)	Maize (EU)	
Reference flow				
Wheat	kg	7,296		Reference flow
Maize	kg		6,577	Reference flow
Material for treatment				
Straw removed for biofuel purposes	kg	2,552	0	
Land tenure				
Market for land, intensive forest land, NPP_0 as C	kg C	7000	7000	Schmidt et al. (2012) – also see **section 3.2**
Materials				
N-fertiliser (A), as N	kg	8.25	0.173	Ammonia, liquid, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (Urea), as N	kg	13.2	40.5	Urea, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AN), as N	kg	18.2	47.1	Ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (CAN), as N	kg	124	56.2	Calcium ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AS), as N	kg	4.95	8.23	Ammonium sulphate, as N, at regional storehouse/RER (ecoinvent 2010)
P-fertiliser: Triple super phosphate, as P_2O_5	kg	37.8	51.7	Triple superphosphate, as P2O5, at regional storehouse/RER (ecoinvent 2010)
K-fertiliser: Potassium chloride, as K_2O	kg	164	153	Potassium chloride, as K2O, at regional storehouse/RER (ecoinvent 2010)
Energy				
Diesel burned in tractor	MJ	3,306	3,306	Diesel, burned in building machine/GLO (ecoinvent 2010)
Transport				
Transport, lorry 16-32 t	tkm	219	210	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs.

9 Inventory of biodiesel

Two sources of biodiesel are included in the current study: palm oil and rapeseed oil methyl esters. The inventory data for the production of the fuels are based on Schmidt (2007), which are comprehensive and transparent life cycle inventories of refined (NBD[2]) palm oil and rapeseed oil. These inventory data have been consolidated and updated at several occasions, and the most recent and updated data, which are used in the current study, are documented in Schmidt and Dalgaard (2012, chapter 7-9) and Dalgaard and Schmidt (2012, chapter 4-5).

It should be noted that the inventories are for NBD oil, which is vegetable oil for food purposes, and not methyl-esters which are used for fuel purposes. However, the refining process (for producing NBD oil) and the trans-esterification process (for producing methyl-ester) are associated with approximately the same types and amounts of inputs, losses and by-products. Further, according to Schmidt (2010), the refining process only accounts for a minor part of the overall GHG-emissions related to the production of NBD vegetable oil.

Table 9.1: LCI data for the cultivation of rapeseed in Denmark and oil palm in Malaysia. The data represent 1 ha year. Data are obtained from Dalgaard and Schmidt (2012, chapter 4). *FFB = Fresh fruit bunches.

Exchanges	Unit	Rapeseed	Oil palm	LCI data
Output of products				
Determining product: rapeseed / oil palm (FFB*)	kg	3,351	20,407	Reference flow
Material for treatment: straw	kg	277	-	
Input of products				
N-fertiliser (A), as N	kg N	8.29	-	Ammonia, liquid, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (Urea), as N	kg N	13.3	151	Urea, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AN), as N	kg N	18.2	10.8	Ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (CAN), as N	kg N	124	-	Calcium ammonium nitrate, as N, at regional storehouse/RER (ecoinvent 2010)
N-fertiliser (AS), as N	kg N	4.98	-	Ammonium sulphate, as N, at regional storehouse/RER (ecoinvent 2010)
P-fertiliser: Triple super phosphate, as P_2O_5	kg P_2O_5	41.8	-	Triple superphosphate, as P2O5, at regional storehouse/RER U
P-fertiliser: Rock phosphate	kg P_2O_5	-	35.7	Phosphate rock, as P2O5, beneficiated, wet, at plant/US (ecoinvent 2010)
K-fertiliser: Potassium chloride, as K_2O	kg K_2O	174	223	Potassium chloride, as K2O, at regional storehouse/RER (ecoinvent 2010)
Transport, lorry 16-32 t	tkm	124	198	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs.
Diesel	MJ	3,195	1,710	Diesel, burned in building machine/GLO (ecoinvent 2010)
Light fuel oil for drying	MJ	1.10	0	Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER (ecoinvent 2010)
Land tenure, arable	kg C	7,000	11,000	
Emissions				
Carbon dioxide from peat decay	kg CO_2		2,613	
Nitrous oxide	kg N_2O	4.16	9.59	

[2] NBD oil: Neutralised, bleached and deodorised oil.

10 Inventory of coal, gas, wind and photovoltaic power

The current study focuses on energy produced from different biofuels. In order to compare this with other fossil-based and renewable sources of energy, data for electricity based on coal, natural gas, wind and photovoltaic power are described in this chapter. The inventories of these sources of electricity are obtained directly from the ecoinvent database (ecoinvent 2010). Generally, the level of completeness in ecoinvent is similar to the current study (see **section 2.2**). The current version of ecoinvent uses allocation for the modelling of multi-functional LCA activities. This is different from what is required in ISO 14044 and the current study. However, since none of the datasets of electricity based on coal, natural gas, wind and photovoltaic power are associated with by-products (only very minor in the upstream product system) this does not affect the results.

The used LCI data are:

- **Electricity based on coal:** 'Electricity, hard coal, at power plant/NORDEL' (ecoinvent 2010). This LCA activity represents coal based electricity in Scandinavia
- **Electricity based on natural gas:** 'Electricity, natural gas, at power plant/NORDEL' (ecoinvent 2010). This LCA activity represents coal based electricity in Scandinavia
- **Electricity based on wind:** 'Electricity, at wind power plant 2MW, offshore/OCE' (ecoinvent 2010). This LCA activity represents wind based electricity in a 2 MW off-shore wind power mill at Middelgrunden in Denmark. Transmission lines to land are not included.
- **Electricity based on photovoltaic power:** 'Electricity, production mix photovoltaic, at plant/DK' (ecoinvent 2010). This LCA activity represents solar based electricity in Denmark.

The electricity based on solar power is based on an ecoinvent dataset representing the production of grid-connected low voltage electricity with a 3 kWp building integrated photovoltaic (PV) module in Denmark in 2008. The 3 kWp module has been chosen as basic module for building integrated PV electricity production. Larger modules can easily be built with these 3 kWp modules without producing a significant error in environmental impact calculations. The module is a single-Si panel installed on a slanted roof. An inverter is used to convert the low voltage DC power into AC power. An average yield of 850 kWh/kWp was assumed for the calculations.

Annual output of grid-connected PV power plants differentiated for Roof-Top and Facade plants. Literature data for optimum installation and not real performance in the country have been corrected with a factor of 92% according to experiences in Switzerland for average production. Mix of PV-plants based on worldwide average and own assumptions. A lifetime of 30 years is taken into account for the PV installation. The assume life time of 30 years may not apply to Denmark, where a 20 year time-frame may be more realistic due to the presence of snow, algae, etc. Similarly, solar cells today may be more efficient than those in 2008.

11 Inventory of mineral based diesel and gasoline

The current study focuses on energy produced from different biofuels. In order to compare this with other fossil-based sources of energy, data for production and combustion of mineral diesel and petrol are described in this chapter. The inventories of these sources of liquid motor vehicle fuels are obtained directly from the ecoinvent database (ecoinvent 2010). Generally, the level of completeness in ecoinvent is similar to the current study (see **section 2.2**). The current version of ecoinvent uses allocation for the modelling of multi-functional LCA activities. This is different from what is required in ISO 14044 and the current study. However, since no of the data sets on electricity based on coal, natural gas, wind and photovoltaic power are associated with by-products (only very minor in the upstream product system) this does not affect the results.

The used LCI data are:

- **Production and combustion of mineral diesel:** Modified version of 'Diesel, burned in building machine/GLO' (ecoinvent 2010). This LCA activity represents the production of diesel and combustion in a building machine (e.g. excavator). However, the data set also includes the excavator (capital goods), as well as lubricating oil and disposal of this oil, which is excluded here. Since the current study only focuses on GHG-emissions, the type of engine where the diesel is combusted does not affect the global-warming effect from combustion emissions.
- **Production and combustion of mineral petrol:** Modified version of 'Operation, passenger car, petrol, EURO4/CH' (ecoinvent 2010). This LCA activity represents the production of petrol and combustion in a passenger car. The reference flow of the LCA activity is 1 km. This is converted to MJ combusted fuel. Calorific value of petrol at 43 MJ/kg (see **Table 3.3**) and input of kg petrol to the car operation activity are used for this conversion. Since the current study only focuses on GHG-emissions the type of engine (e.g. EURO norm) where the petrol is combusted does not affect the global-warming effect from combustion emissions.

12 Inventory of common activities: Electricity, heat and animal feed

Many activities throughout the product systems of the inventoried biofuels use electricity and some of the activities are also associated with district heating (mainly because this is supplied as a by-product). In this chapter, the inventory data for electricity and district heating are described. Further, many biofuel production systems are associated with by-products that are used as animal feeds. Inventory data for animal feed on the global market is also described in this chapter.

12.1 Electricity

The current study is associated with the use of electricity in the following countries:

- Denmark (used in several activities) (Merciai et al. 2011a)
- USA (used in wood pellet production in US) (Merciai et al. 2011b)
- Malaysia (used in palm oil system in MY) (Merciai et al. 2011c)
- Brazil (used in wood pellet production and soy system in BR) (Merciai et al. 2011d)
- Latvia (used in wood pellet production in LT – modelled as Czech electricity due to lack of data on Latvian electricity) (Merciai et al. 2011e)

All electricity data represents the so-called marginal source of electricity – based on future outlooks of national electricity supplies. The methodology for identifying marginal electricity is comprehensively described in Schmidt et al. (2011). The applied electricity mixes are presented below in **Table 12.1**.

For biomass based electricity, Schmidt et al. (2011) contains LCI data for wood pellets burned in power plant (including forestry, wood pellet production and combustion). In the current project, these data have been replaced by the average of the three '*wood pellets burned in power plant*' data sets (eucalyptus BR, loblolly pine US and pine LV) documented in **Table 4.2**, **Table 4.3** and **Table 4.4**.

Table 12.1: Electricity mixes.

Source of electricity	DK	US	MY	BR	LT
Coal			0.605	0.075	
Oil	0.004				0.065
Gas	0.197	0.063	0.348	0.353	0.401
Biomass	0.403	0.169		0.052	0.304
Nuclear		0.147		0.058	0.031
Hydro	0.003	0.018	0.046	0.405	
Wind	0.393	0.492		0.046	0.085
Geothermal		0.044			0.001
Solar		0.068		0.012	0.113
Marine					
Total	**1.000**	**1.000**	**1.000**	**1.000**	**1.000**

12.2 District heating

Based on Schmidt (2012, 80-83), 1 MJ district heat at plant uses 1.69 MJ biofuel (assumed to be wood chips from Latvia, see **sections 5.2** and **5.3**), and it is associated with the co-production of 0.475 MJ electricity. This electricity substitutes electricity at grid in Denmark.

12.3 Animal feed

Animal feed is constituted by feed energy and feed protein. When a co-product from biofuel production is utilised as feed, it substitutes the marginal sources of feed energy and feed protein. These can be identified as soybean meal from Brazil (marginal source of protein) and barley from Ukraine (marginal source of feed energy) (Schmidt and Dalgaard 2012). The inventory data for the barley and soy systems are comprehensively described in Schmidt and Dalgaard (2012, p 85) and Dalgaard and Schmidt (2012). The modelling approach is also described in Schmidt et al. (2009).

The relevant co-products that are utilised as animal feed are listed in **Table 12.2** where the relevant feed properties are also listed.

Table 12.2: Animal feed properties relevant for the modelling of co-products. Data are from Møller et al. (2005). C5 molasses is based on Jensen et al. (2007, appendix D). Scandinavian feed units (SFU) are converted to MJ net energy by multiplying with 7.82 MJ/SFU (Volden 2011).

Source of electricity	DM%	Protein (% of DM)	Energy (MJ net/kg dm)
Marginal source of feed energy: Barley	85.0%	10.8%	8.68
Marginal source of feed protein: Soybean meal	87.4%	53.5%	10.9
By-product: Rapeseed meal	88.9%	35.0%	9.31
By-product: Palm kernel meal	90.6%	17.0%	6.49
By-product: DDGS (wheat)	90.0%	32.0%	8.45
By-product: DDGS (maize)	89.0%	29.2%	10.0
By-product: C5 molasses	70.0%	5.9%	8.05

13 Life cycle impact assessment, electricity

In this chapter the LCIA results for global warming are shown for the inventoried electricity scenarios. All results are shown with two different time horizons, i.e. 100 years (GWP100) and 20 years (GWP20). **Section 13.1** compares all electricity scenarios, and **section 13.2** to **13.4** present detailed process contributions for each scenario.

13.1 Electricity, all

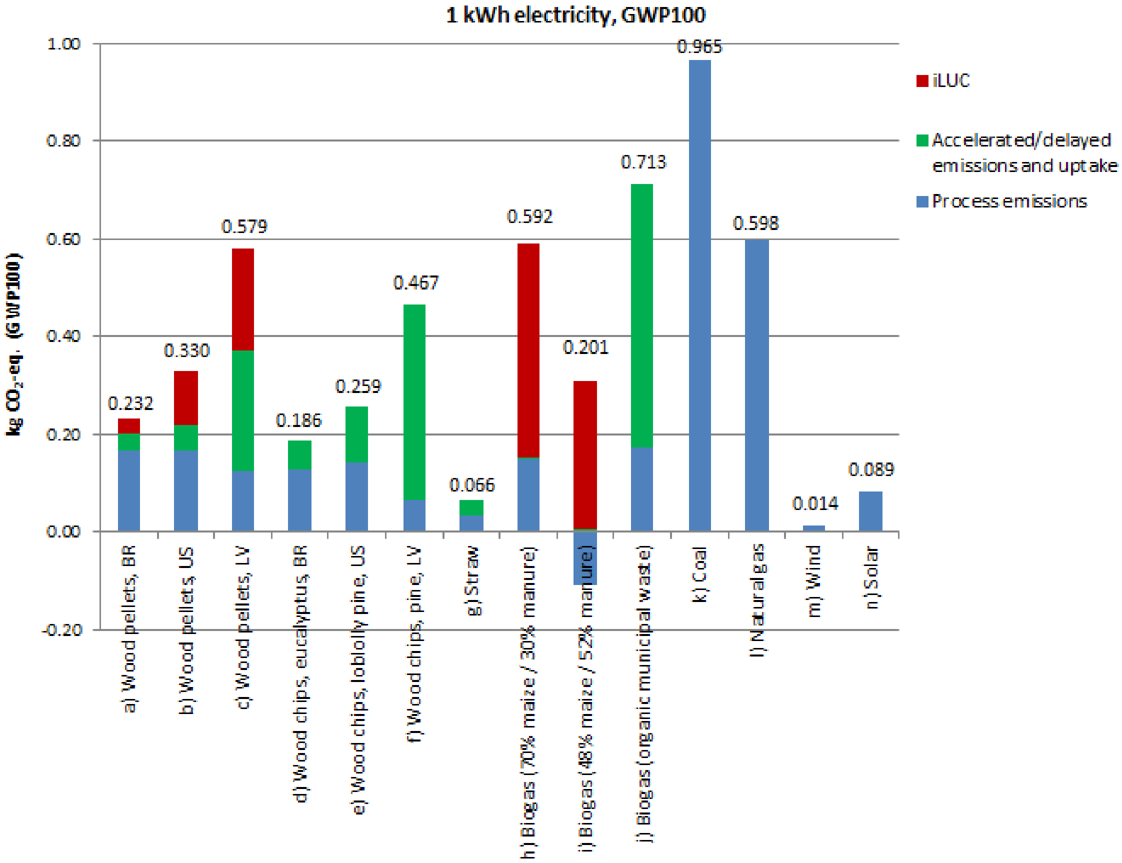

Figure 13.1, Comparison of all electricity scenarios (**GWP100**). The functional unit is 1 kWh.

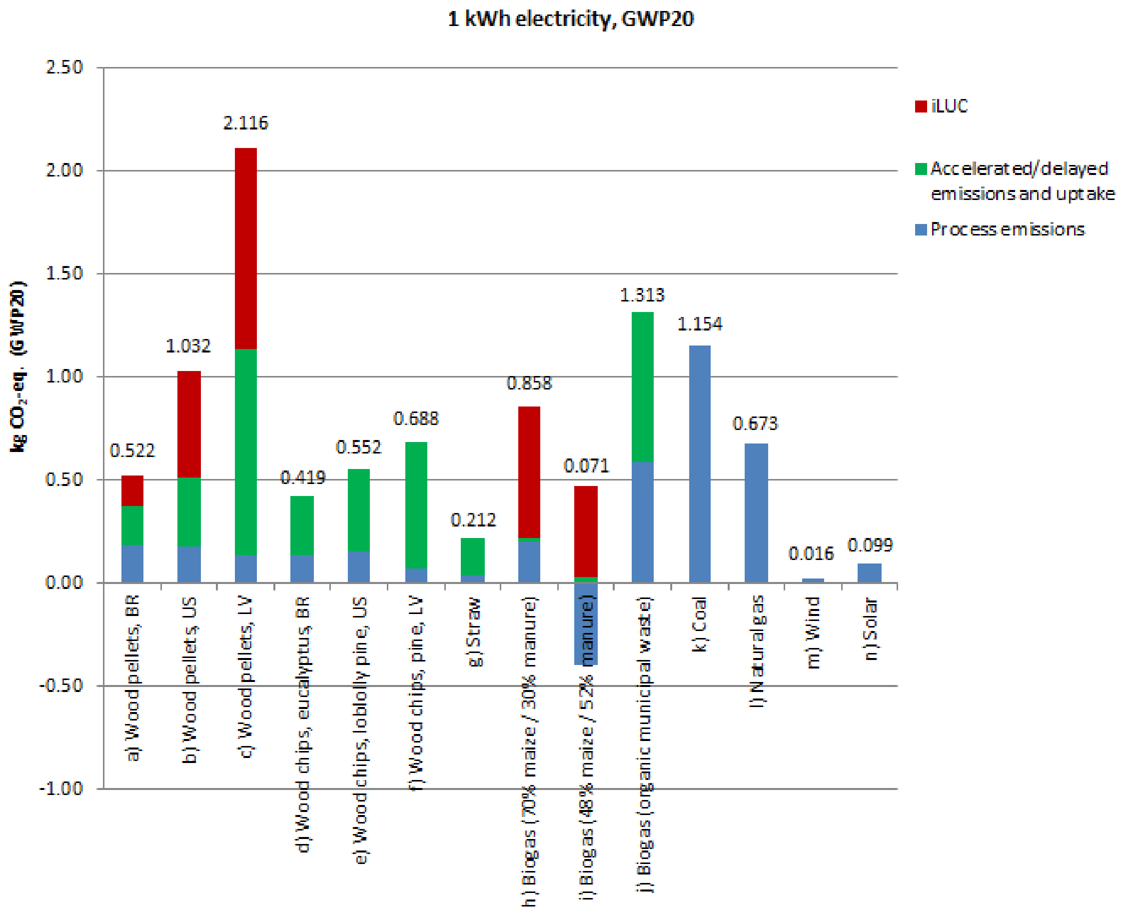

Figure 13.2, Comparison of all electricity scenarios (**GWP20**). The functional unit is 1 kWh.

General summary of important assumptions in the data affecting the results for biofuel based electricity:

- Wood pellets:
  - All parts of the harvested wood (stem + residues) are used for wood pellets.
  - Wood yields are optimistically estimated because of high removal rates of above and below ground residues (90% of all residues are assumed to be harvested).
  - Rotation time for eucalyptus in BR, loblolly pine in US and pine in LV are 6, 12 and 63 years respectively. Latvian figures may be in the high end for energy forests.
  - Drying of wood pellets is based on biofuel (wood pellets).
  - iLUC only accounts for accelerated transformation of primary and secondary forests to plantations – no net transformations are assumed.
  - iLUC is modelled as if the affected land is forest land, i.e. land not suitable for arable cultivation. If arable land was affected, the iLUC impact would increase by more than a factor two.
- Wood chips
  - Wood chips are purely based on forest residues (no dedicated cultivation), and the alternative pathway of the residues is modelled as residues left in the forest. Hence, it has been assumed that residues are currently and in the future being left in the forest, i.e. the residue resource is flexible – this may not be the case and this should be investigated

further. If the residues would have been harvested anyway, the effects of wood chips would be similar to the ones as of wood pellets (without drying).
    - No iLUC.
- Straw
    - It has been assumed that straw is currently and in the future being left in the field unused, i.e. the residue resource is flexible – this may not be the case and it should be investigated further. If the straw would have been harvested anyway, the impact can be expected to be significant higher because the marginally affected technology would be something else.
    - No iLUC
- Biogas
    - iLUC is only related to maize. iLUC is modelled as the affected land is arable land. The effect is a combination of intensification and accelerated deforestation. Intensification is associated with significant uncertainties: N_2O from fertiliser production is overestimated because nitric acid today is produced with catalytic N_2O (this is not addressed in the used data from the ecoinvent database). Further, intensification is modelled as intensification of average barley in Canada. This may not be a good representative of where intensification is going to take place in reality. This issue will be further addressed in the next version of the iLUC model (Schmidt et al. 2012a,b).
    - Losses of methane in the biogas production and upgrading/refining for the natural gas grid are 1% and 2% respectively.
    - Biogas based on separated municipal organic waste is modelled as substituted waste incineration. This leads to avoided avoided, i.e. induced, heat and electricity which would have been supplied by the waste incineration. The induced district heating is assumed to be based CHP based on Latvian wood chips. Notice that the result concerns 1 kWh electricity (no heat by-product), and that the alternative use of the municipal waste is combined heat and power production. Hence the presented result represents a situation where the overall energy recovery is lower (only electricity) than the alternative use (heat and electricity from waste incineration). However, since the overall efficiency of heat production (which is almost always co-produced with electricity) is much higher than for stand-alone electricity production (condensation mode), this difference in energy recovery is not significant for the results.

13.2 Electricity, wood pellets

Wood pellets, eucalyptus, BR

The green arrows represent CO_2 uptake, while the red arrows represent CO_2 emissions. The major contributor is the transport of pellets to DK, iLUC and electricity in the wood pellet production.

The differences between the GWP100 and GWP20 results can mainly be explained by the fact that the delayed uptake (emissions from combustion in year t=0 and uptake the subsequent 6 years) becomes more significant when applying a shorter time horizon, and also that the accelerated deforestation accounted for by the iLUC becomes more significant.

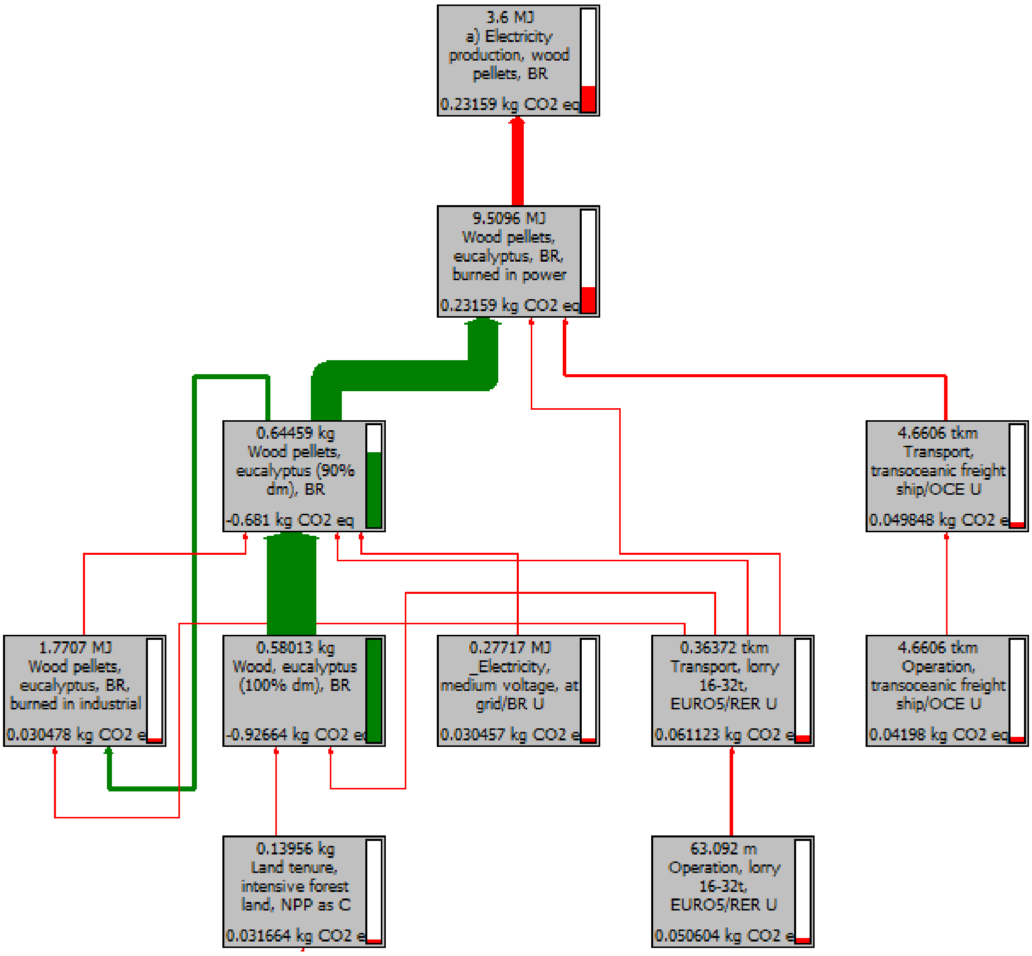

Figure 13.3, Process contribution to **GWP100** for electricity from wood pellets, eucalyptus, Brazil. The functional unit is 1 kWh.

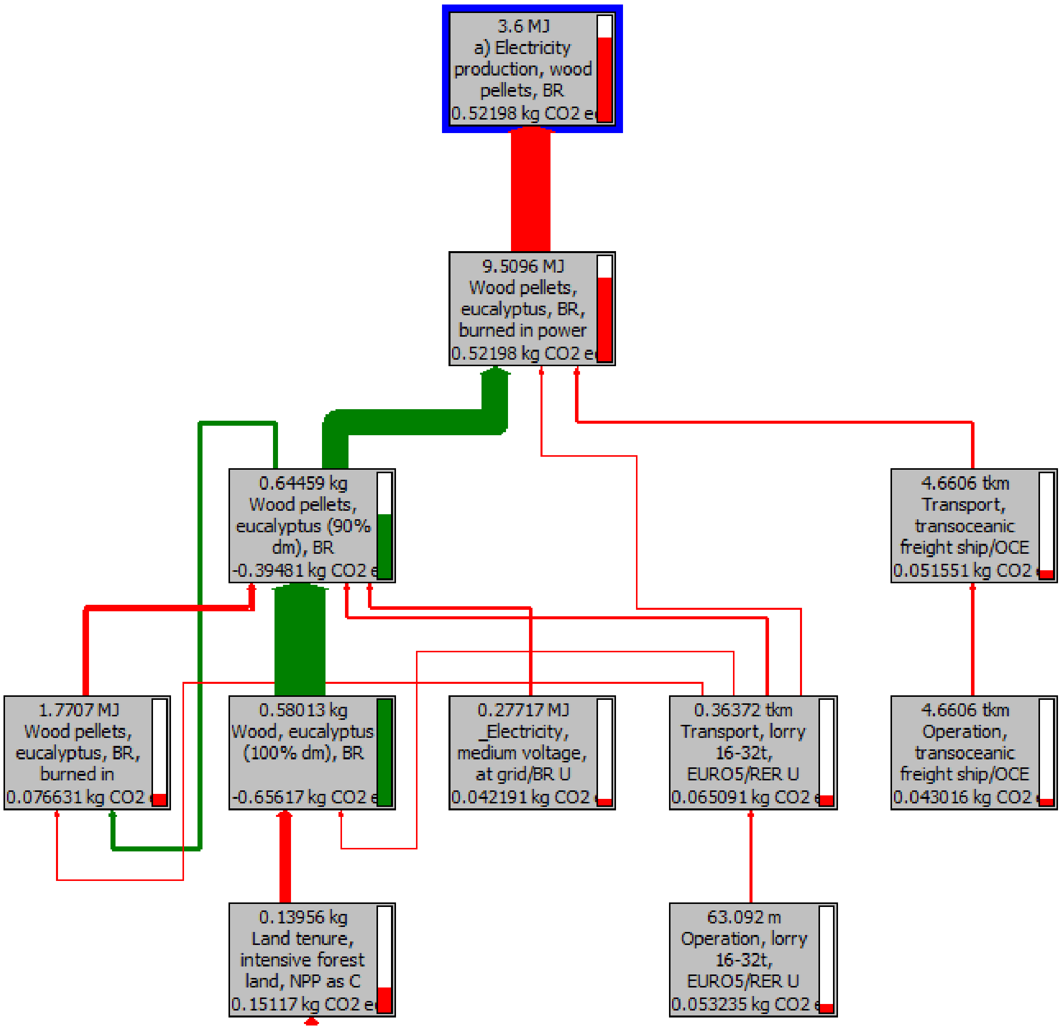

Figure 13.4, Process contribution to **GWP20** for electricity from wood pellets, eucalyptus, Brazil. The functional unit is 1 kWh.

Wood pellets, loblolly pine, US

Electricity from loblolly pine in US is associated with the same hot spots as eucalyptus in Brazil. Loblolly pine in US shows higher results than eucalyptus from Brazil. The reason for this is partly that the delayed uptake (emissions from combustion in year t=0 and uptake the subsequent 12 years) becomes more pronounced because the rotation time is longer, and partly because the overall yield is lower which increases the iLUC.

The differences between the GWP100 and GWP20 results can be explained by the same reasons as for eucalyptus from Brazil. It should be noticed that the difference is significant.

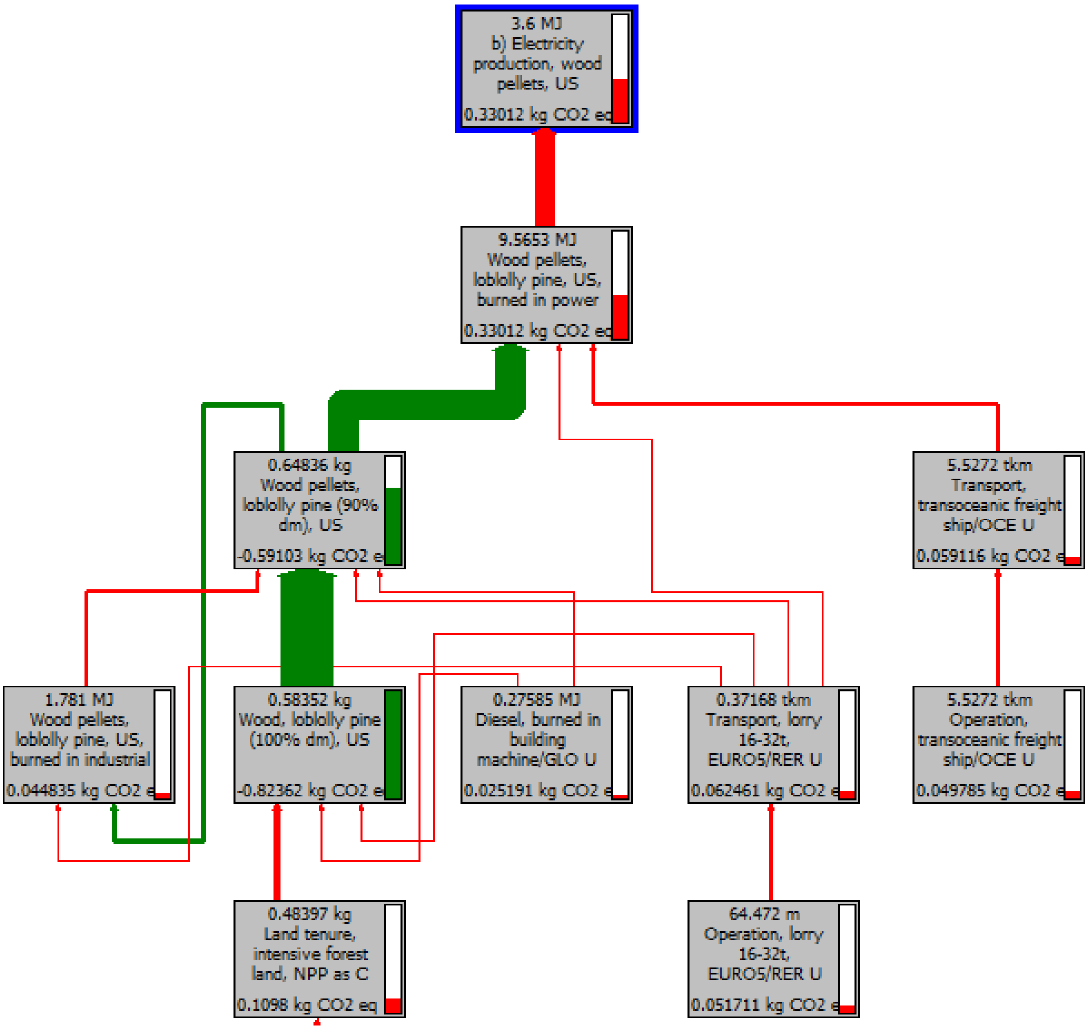

Figure 13.5, Process contribution to **GWP100** for electricity from wood pellets, Loblolly pine, United States. The functional unit is 1 kWh.

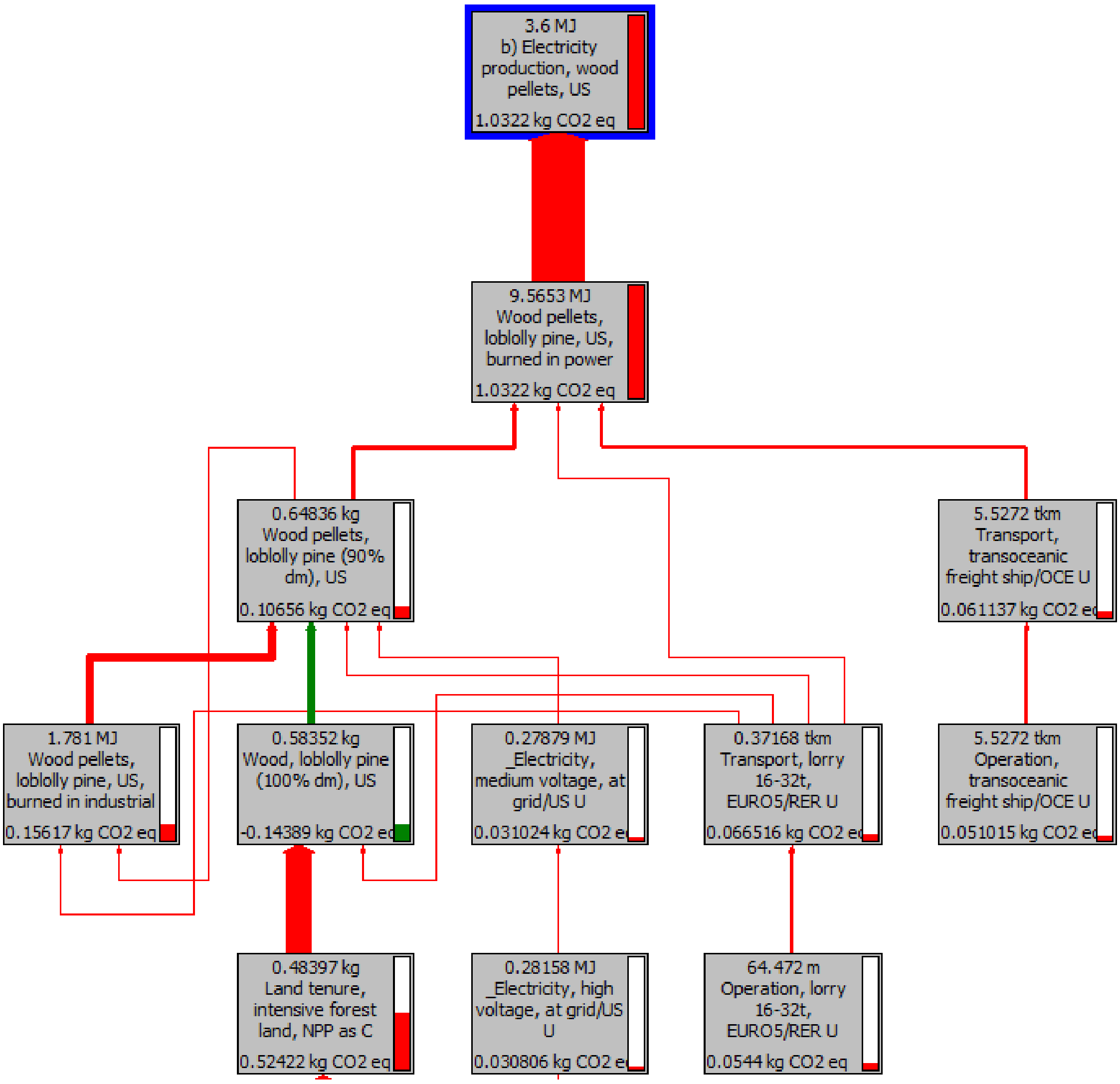

Figure 13.6, Process contribution to **GWP20** for electricity from wood pellets, Loblolly pine, United States. The functional unit is 1 kWh.

Wood pellets, pine, LV

Electricity from pine in Latvia is associated with the same hot spots as eucalyptus in Brazil and loblolly pine in US. Pine in Latvia shows higher results than the other two wood pellet sources. . The reason for this is partly that the delayed uptake (emissions from combustion in year t=0 and uptake the subsequent 63 years) becomes more pronounced because the rotation time is longer, and partly because the overall yield is lower which increases the iLUC.

The differences between the GWP100 and GWP20 results can be explained by the same reasons as for the other two wood pellet sources. It should be noticed that the difference is significant.

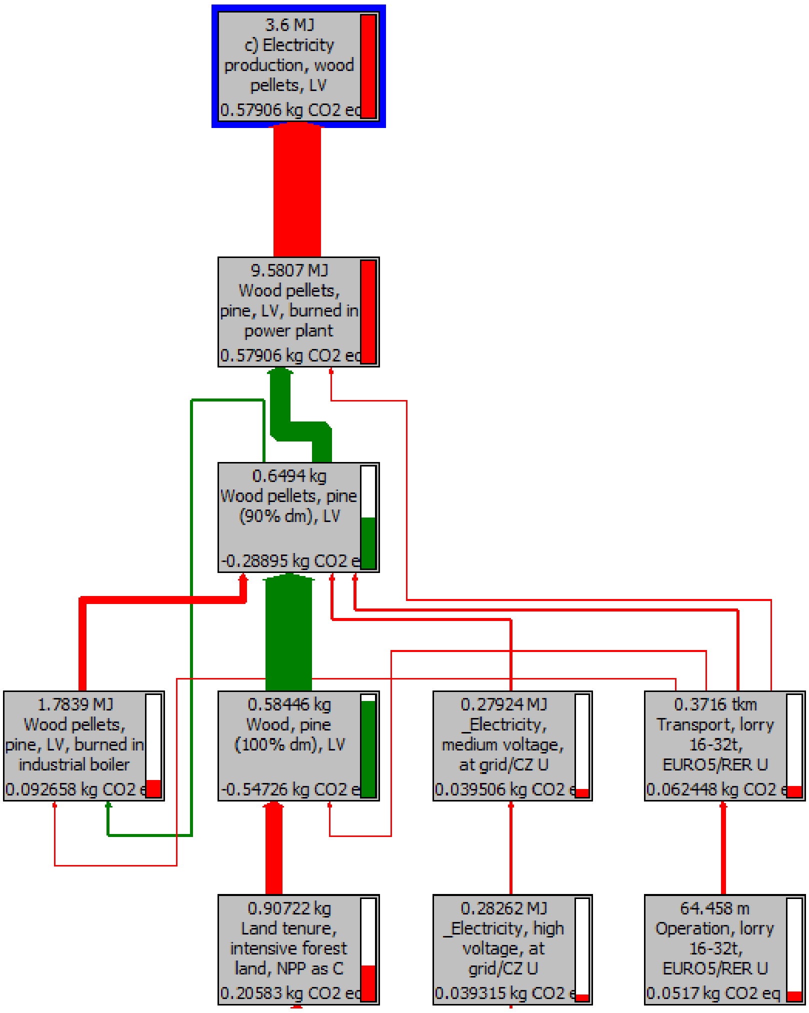

Figure 13.7, Process contribution to **GWP100** for electricity from wood pellets, pine, Latvia. The functional unit is 1 kWh.

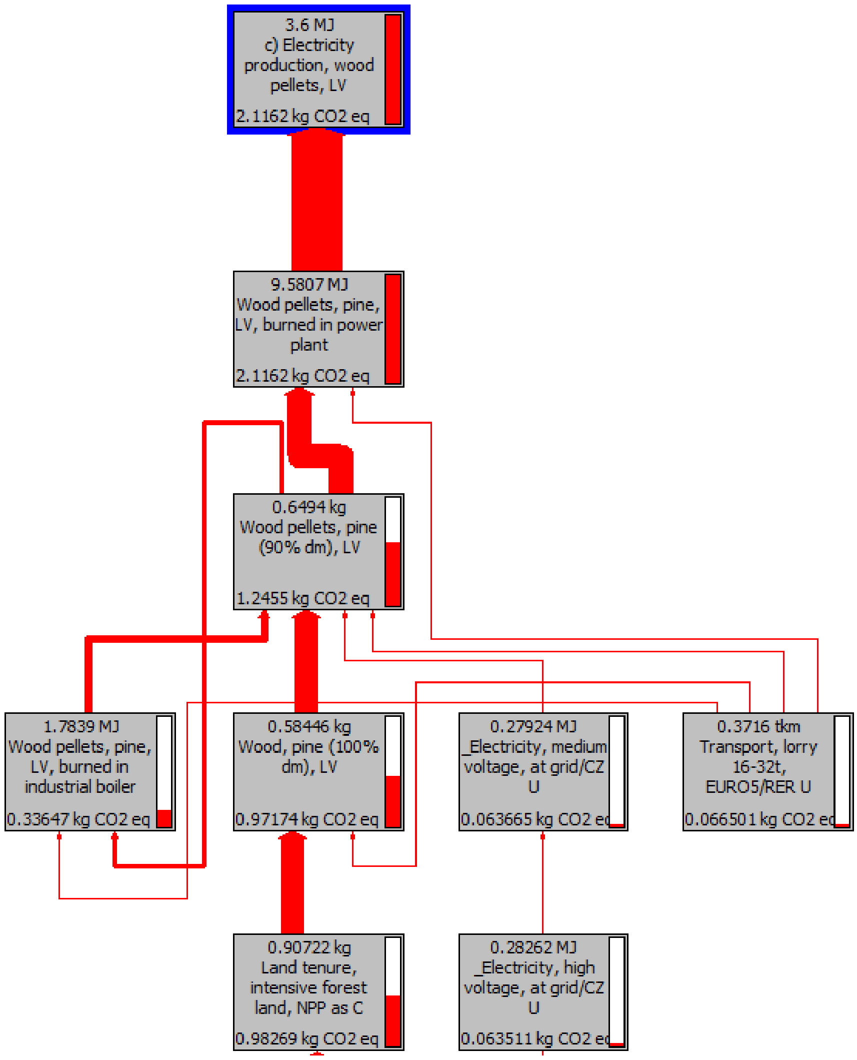

Figure 13.8, Process contribution to **GWP20** for electricity from wood pellets, pine, Latvia. The functional unit is 1 kWh.

13.3 Electricity, wood chips (residues)

Wood chips (residues), eucalyptus, BR

The hot spot from electricity from wood chips is the avoided "natural" decay of forest residues. Transport emissions also contribute.

The difference between the GWP100 and GWP20 results is related to the fact that the avoided decay of forest residues becomes more significant when applying a shorter time horizon. The difference between the GWP100 and GWP20 results is significant.

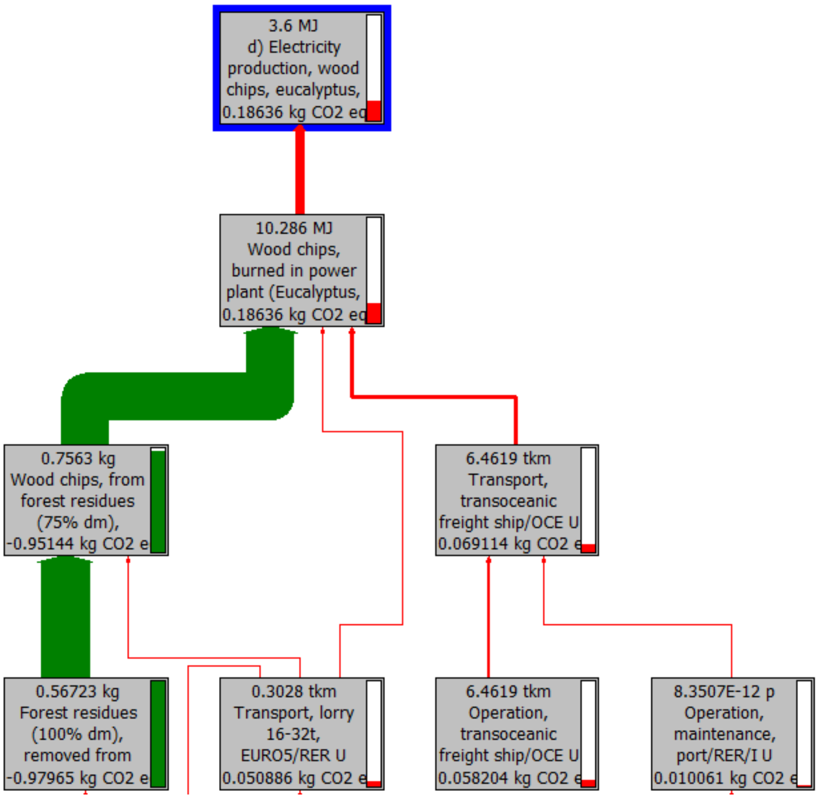

Figure 13.9, Process contribution to **GWP100** for electricity from wood chips, eucalyptus, Brazil. The functional unit is 1 kWh.

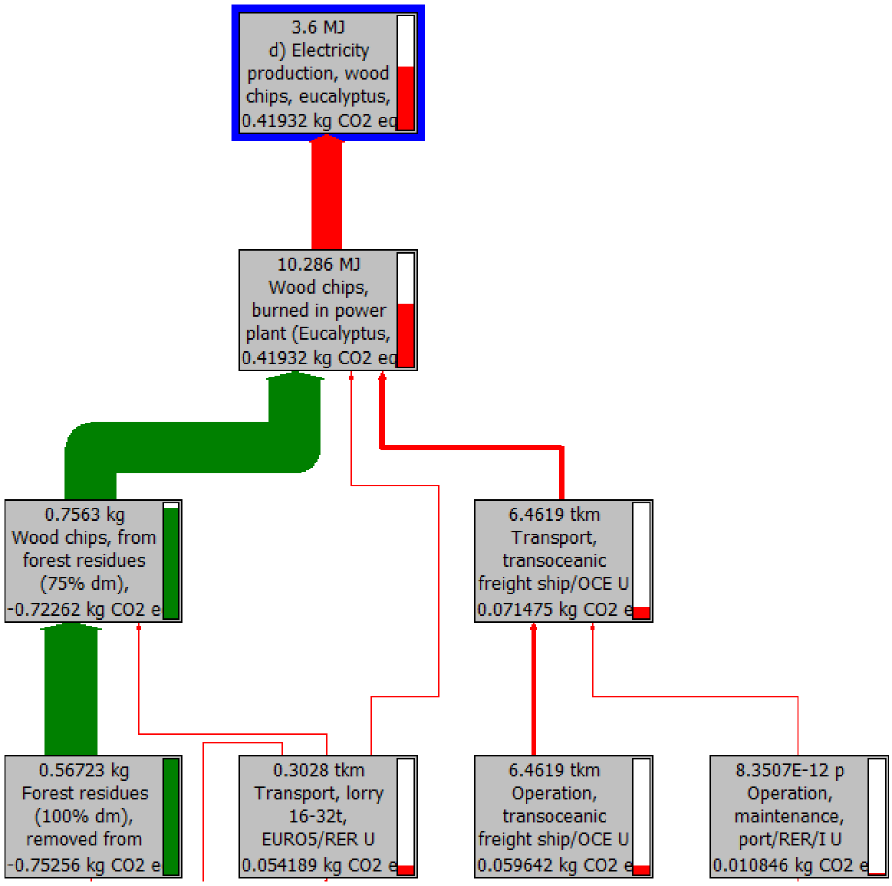

Figure 13.10, Process contribution to **GWP20** for electricity from wood chips, eucalyptus, Brazil. The functional unit is 1 kWh.

Wood chips (residues), loblolly pine, US

The hot spot from electricity from wood chips is the avoided "natural" decay of forest residues. Transport emissions also contribute.

The difference between the GWP100 and GWP20 results is related to the fact that the avoided decay of forest residues becomes more significant when applying a shorter time horizon. The difference between the GWP100 and GWP20 results is significant.

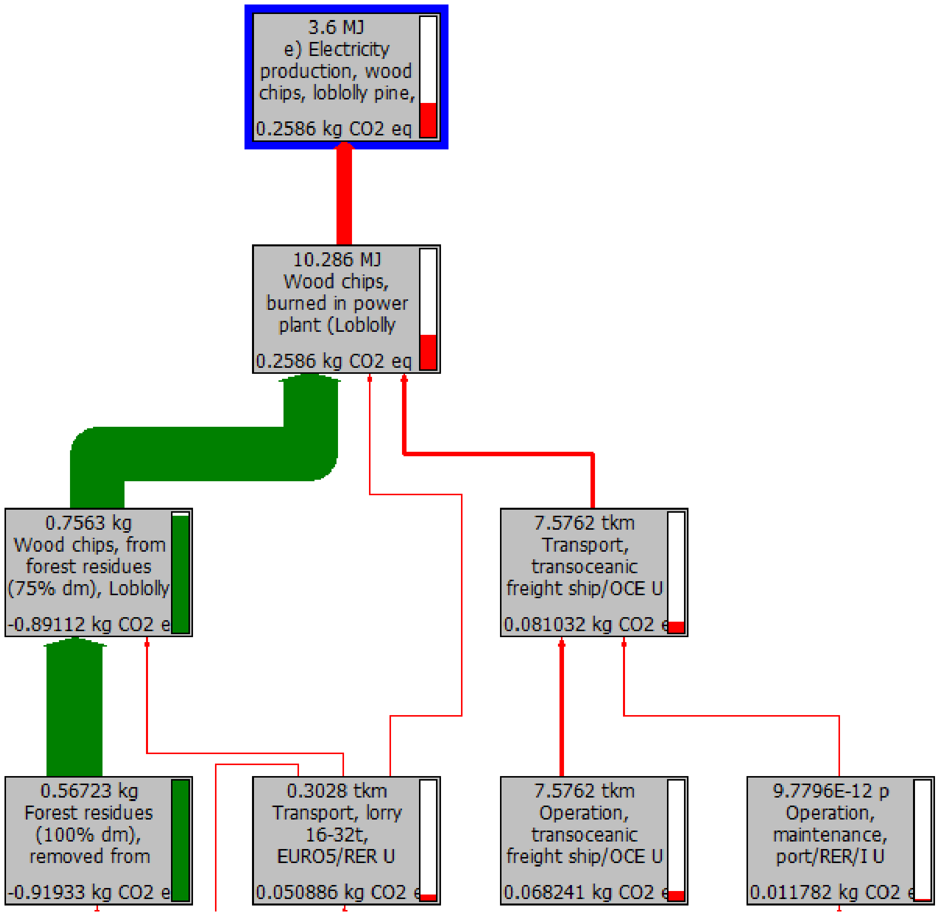

Figure 13.11, Process contribution to **GWP100** for electricity from wood chips, loblolly pine, United States. The functional unit is 1 kWh.

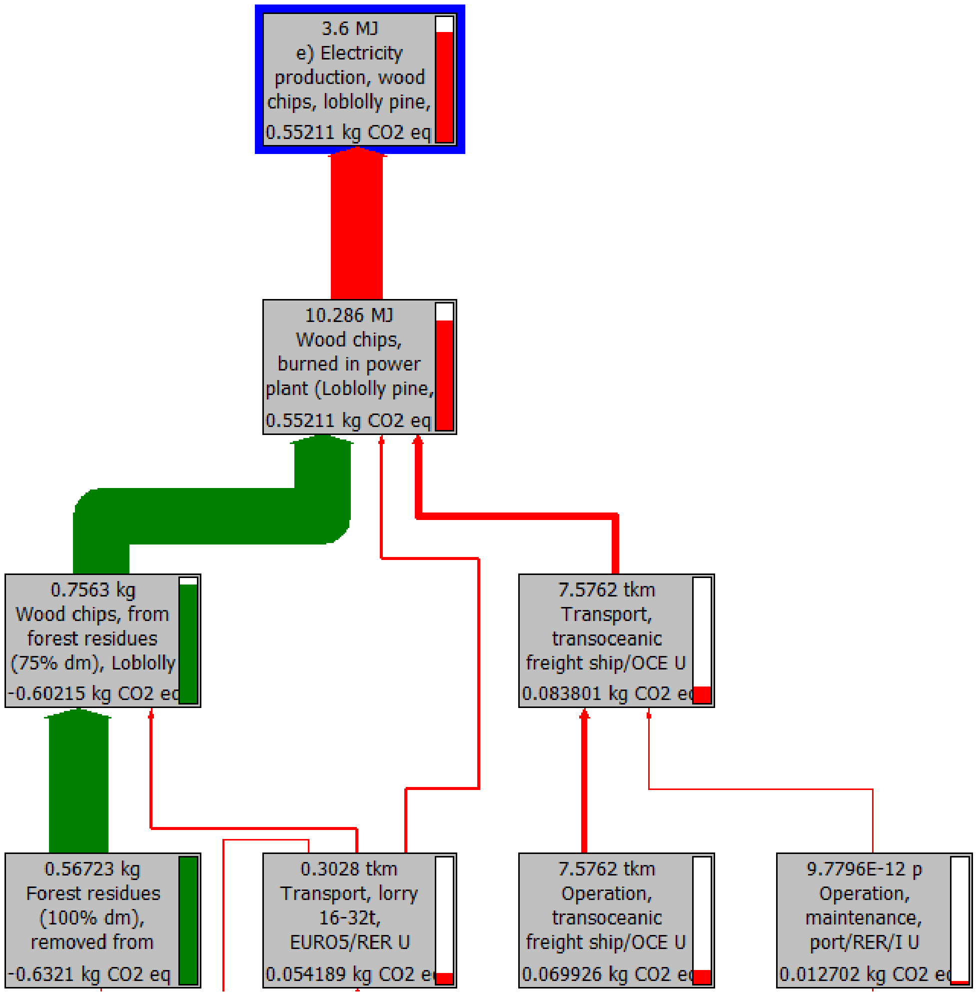

Figure 13.12, Process contribution to **GWP20** for electricity from wood chips, loblolly pine, United States. The functional unit is 1 kWh.

Wood chips (residues), pine, LV

The hot spot from electricity from wood chips is the avoided “natural” decay of forest residues. Transport emissions also contribute.

The difference between the GWP100 and GWP20 results is related to the fact that the avoided decay of forest residues becomes more significant when applying a shorter time horizon. The difference between the GWP100 and GWP20 results is significant.

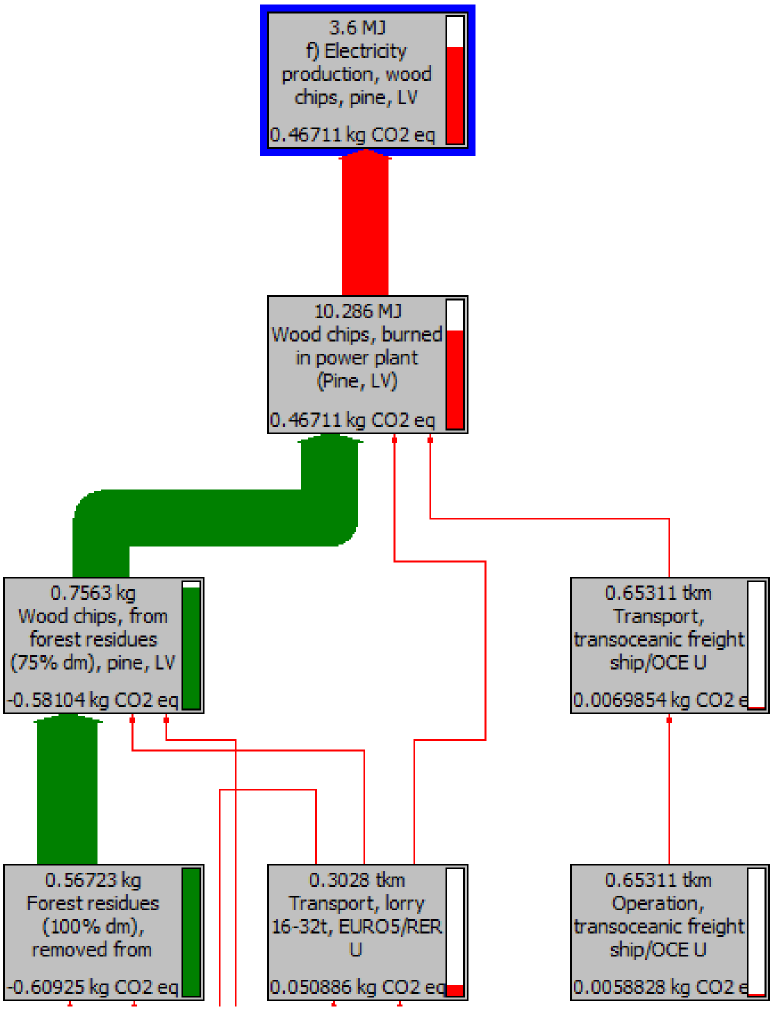

Figure 13.13, Process contribution to **GWP100** for electricity from wood chips, pine, Latvia. The functional unit is 1 kWh.

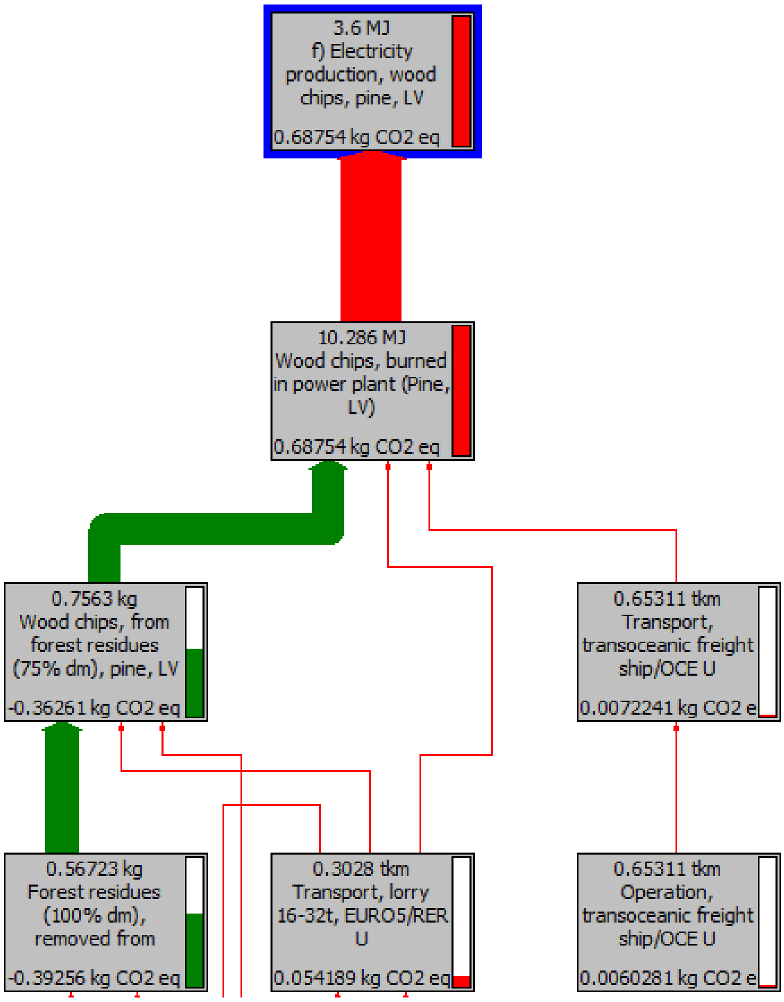

Figure 13.14, Process contribution to **GWP20** for electricity from wood chips, pine, Latvia. The functional unit is 1 kWh.

Straw

The hotspot in the production of electricity from straw is, as for the wood chips (forest residues), the avoided decay of the straw in the field.

The difference between the GWP100 and GWP20 results is related to the fact that the avoided decay of straw becomes more significant when applying a shorter time horizon. The difference between the GWP100 and GWP20 results is significant.

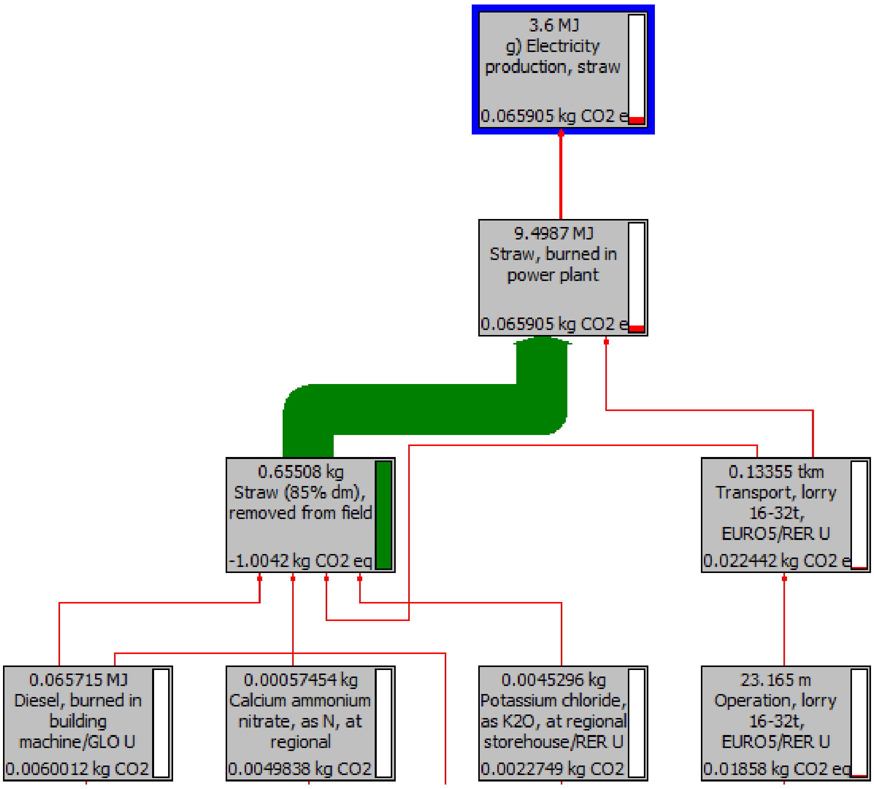

Figure 13.15, Process contribution to **GWP100** for electricity from straw. The functional unit is 1 kWh.

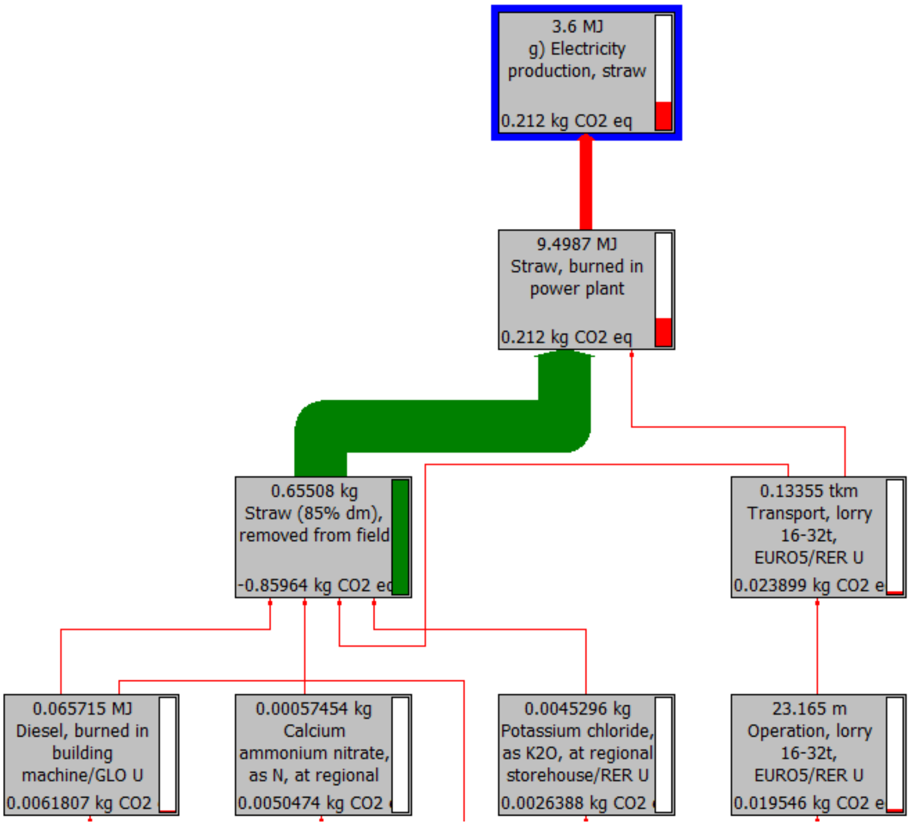

Figure 13.16, Process contribution to **GWP20** for electricity from straw. The functional unit is 1 kWh.

13.4 Electricity, biogas

Biogas, 70% maize / 30% manure

The hotspots in the product system for electricity from biogas (70% maize / 30% manure) are: iLUC related to maize cultivation, N_2O field emissions from maize cultivation, heat for biogas process and leakage of CH_4 in the biogas process and in the purification process.

The overall CH_4 leakage is around 3%, which is consistent with the data found in general literature, e.g. Liebetrau et al. (2010).

Negative contributions are seen from the use of manure for biogas because of avoided outdoor storage and associated CH_4 emissions.

The difference between the GWP100 and GWP20 results is mainly associated to different global warming potential for CH_4 (leakage), higher GWP from iLUC (accelerated deforestation), and higher GWP from heat input because this is based on forest residues which are sensitive to time horizon because of avoided decay.

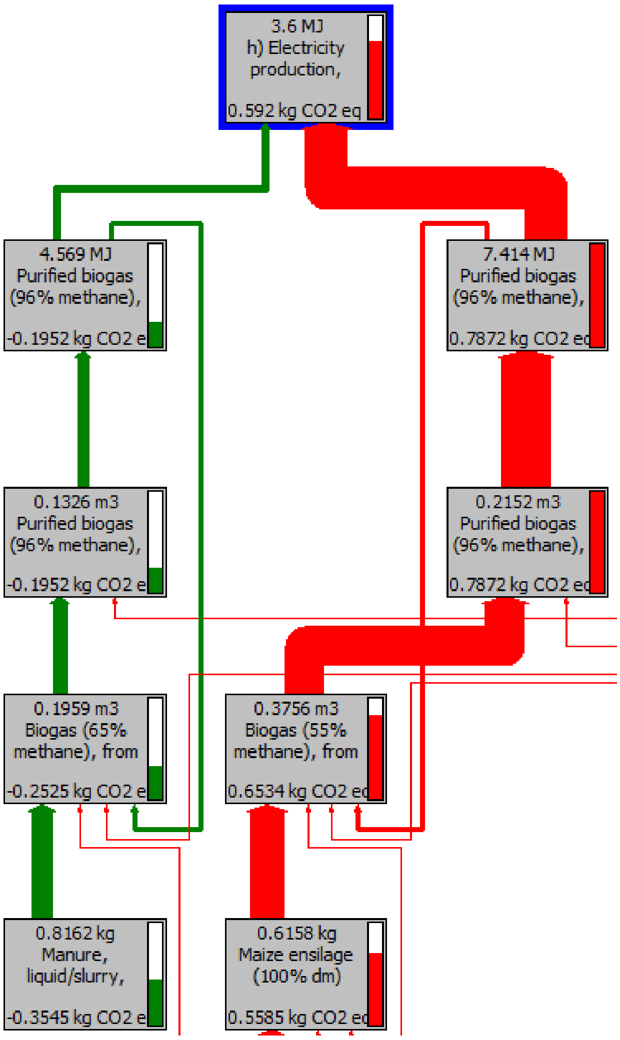

Figure 13.17, Process contribution to **GWP100** for electricity from biogas (70% maize / 30% manure). The functional unit is 1 kWh.

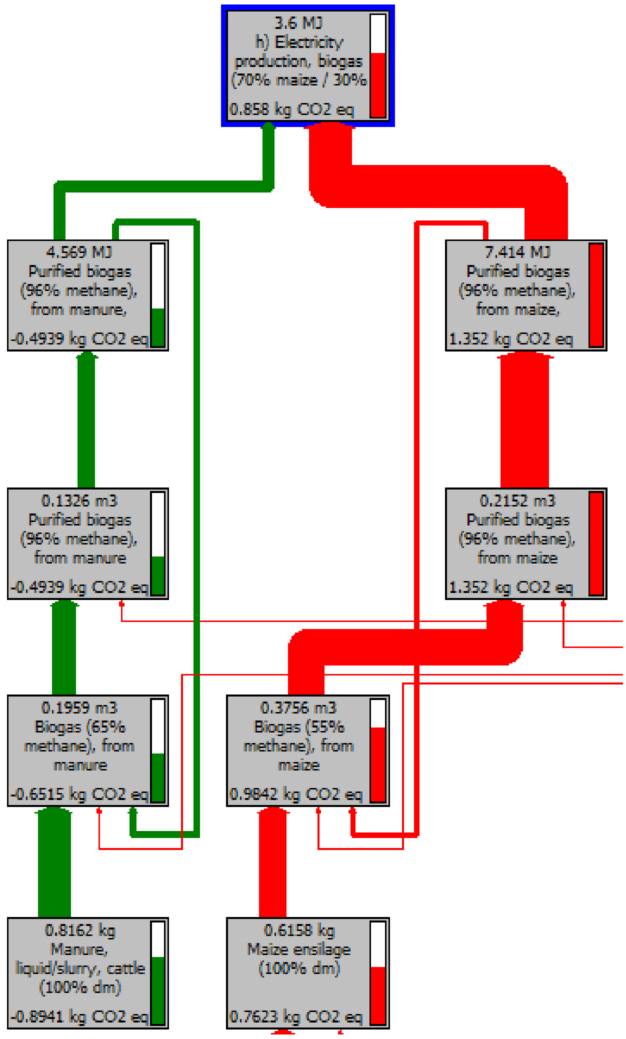

Figure 13.18, Process contribution to **GWP20** for electricity from biogas (70% maize / 30% manure). The functional unit is 1 kWh.

Biogas, 52% maize / 48% manure

The hotspots are the same as for the 70% maize/ 30% manure scenario, but the GHG-emissions are generally lower. This is because the share of manure based biogas is higher. Manure based biogas is not associated with iLUC and field emissions as maize. And in addition the higher share of manure based biogas means more avoided CH_4 emissions from avoided outdoor storage of manure when sending the manure to biogasification.

The difference between the GWP100 and GWP20 results is the same as for the 70% maize/ 30% manure scenario.

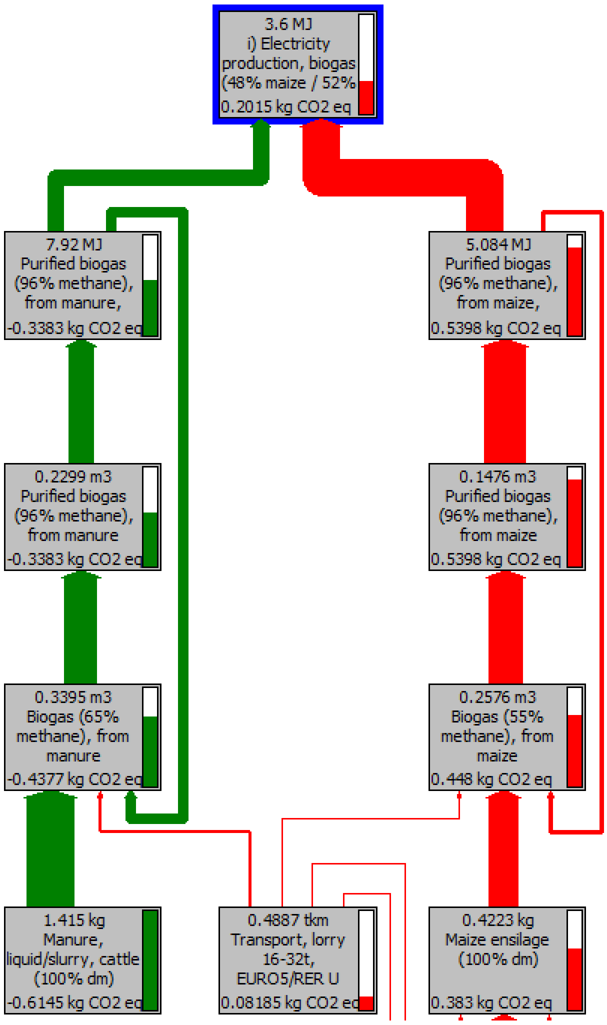

Figure 13.19, Process contribution to **GWP100** for electricity from biogas (52% maize / 48% manure). The functional unit is 1 kWh.

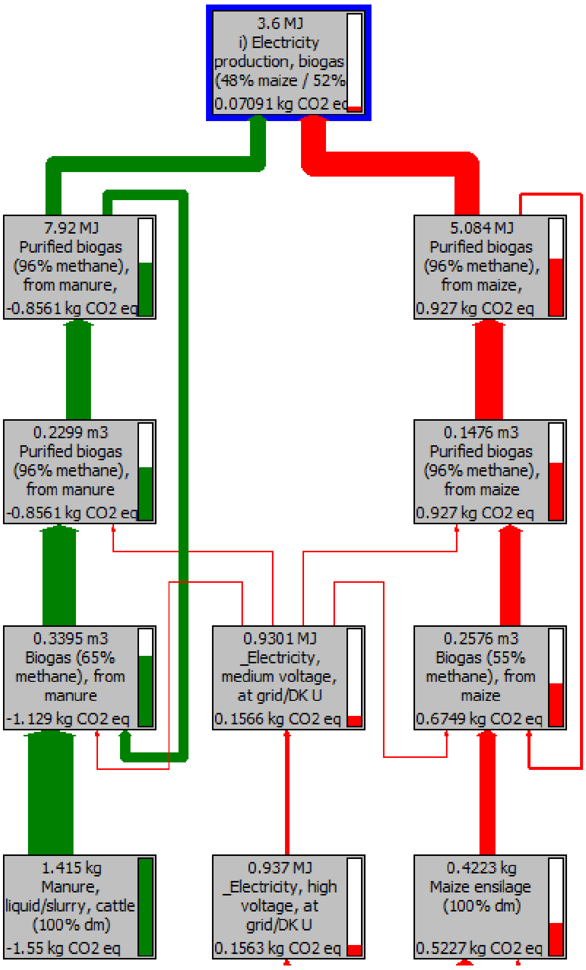

Figure 13.20, Process contribution to **GWP20** for electricity from biogas (52% maize / 48% manure). The functional unit is 1 kWh.

Biogas, organic waste

The hotspots related to electricity from organic waste based biogas are the missed benefit of heat production from waste incineration, and leakage in the biogas process and in the purification process. It should be noticed that the use of waste is moved from relatively efficient heat and power utilisation in incineration to lower efficient only power production in biogas scenario. This also explains a large part of the high GHG-emissions. If the functional unit was just the production and combustion of the gas, the result would be lower.

The main reason for the difference between the GWP100 and the GWP20 result is the difference in global warming potential for CH_4 (leaking).

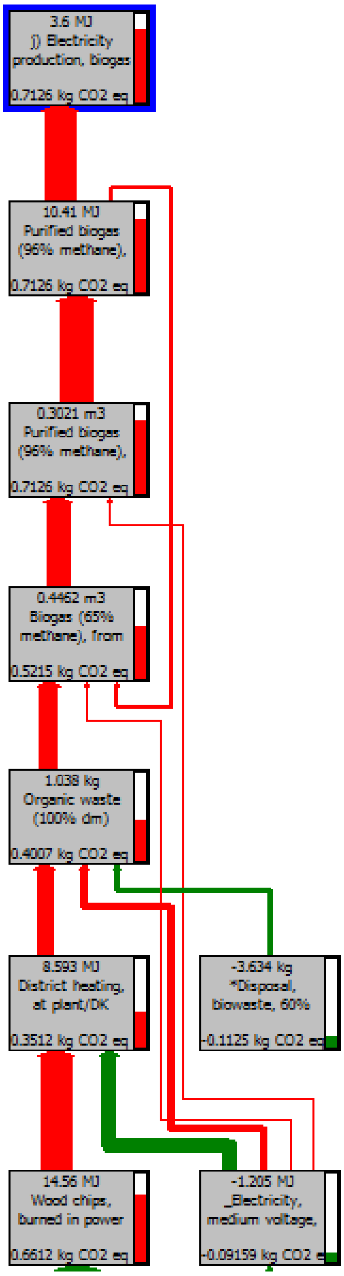

Figure 13.21, Process contribution to **GWP100** for electricity from biogas (organic waste). The functional unit is 1 kWh.

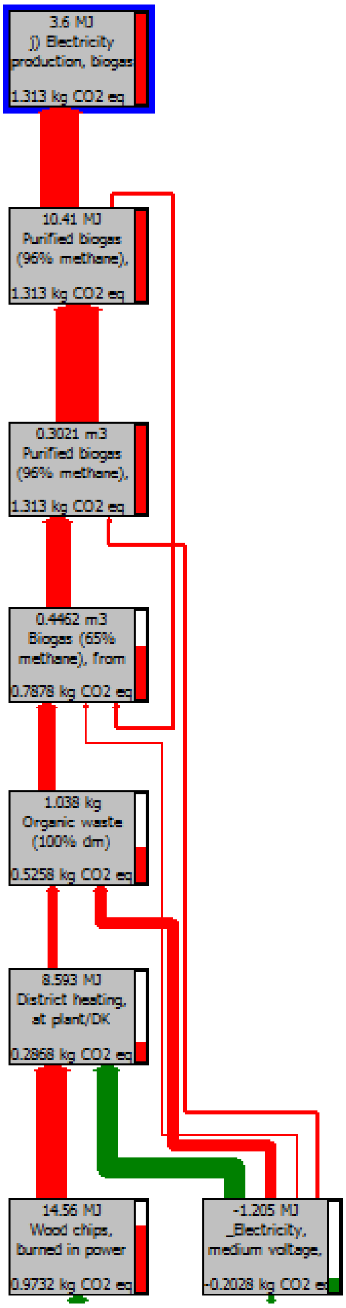

Figure 13.22, Process contribution to **GWP20** for electricity from biogas (organic waste). The functional unit is 1 kWh.

14 Life cycle impact assessment, liquid fuels

In this chapter the LCIA results for global warming are shown for the inventoried liquid fuels scenarios. All results are shown with two different time horizons, i.e. 100 years (GWP100) and 20 years (GWP20). **Section 14.1** compares all electricity scenarios, and **section 0** and **14.3** present detailed process contributions for each scenario.

14.1 Liquid fuels, all

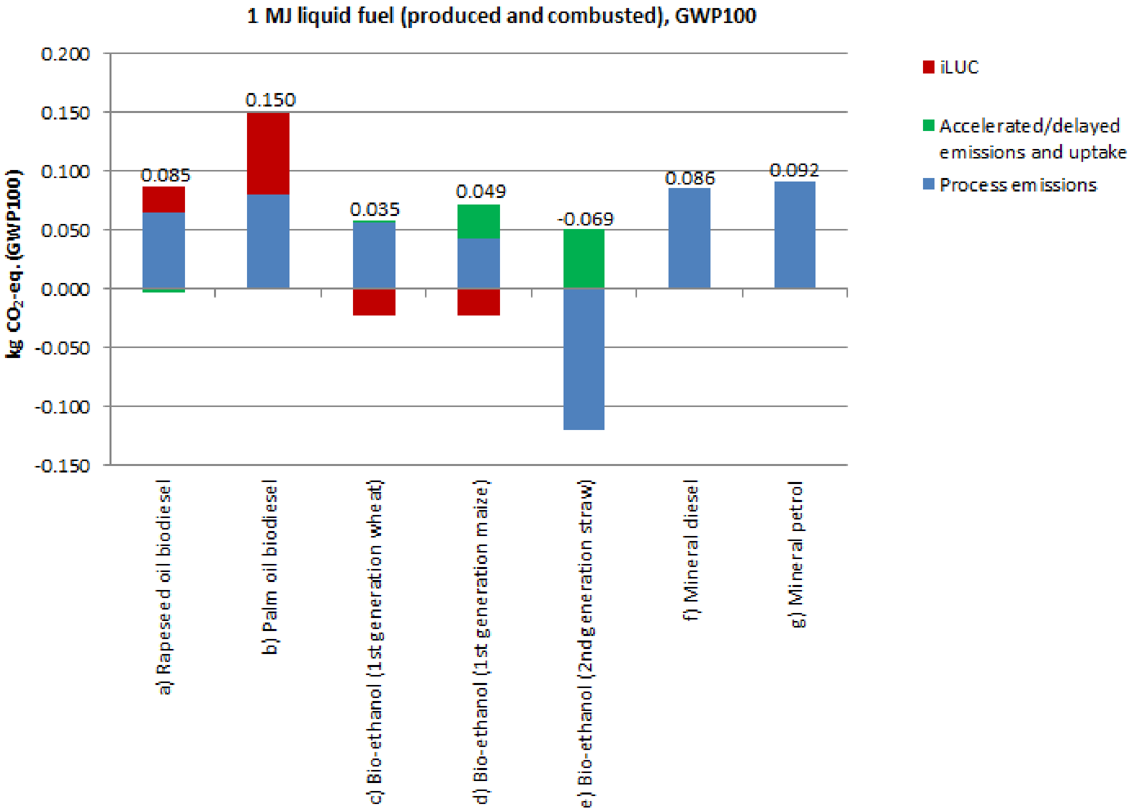

Figure 14.1, Comparison of all liquid fuels scenarios (**GWP100**). The functional unit is 1 MJ produced and combusted fuel.

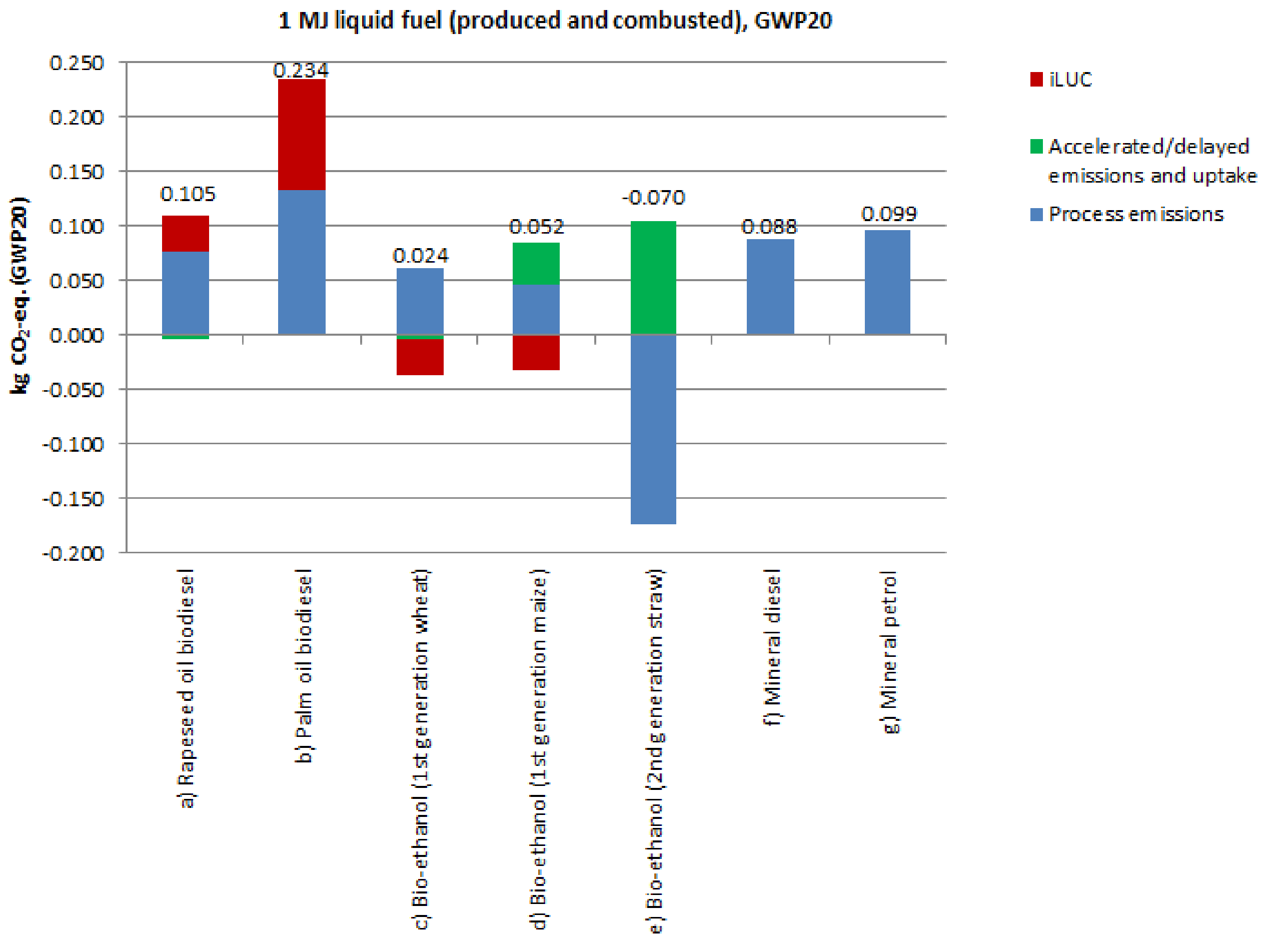

Figure 14.2, Comparison of all liquid fuels scenarios (**GWP20**). The functional unit is 1 MJ produced and combusted fuel.

General summary of important assumptions in the data affecting the results for the production and combustion of biofuel for transport:

- Biodiesel:
  - Biodiesel data are based on high qualitive and comprehensive inventory data from Schmidt (2007) and updates hereof (e.g. Dalgaard and Schmidt 2012).
  - By-products (the oil meal) are modelled as substituted feed energy and protein. The marginal source of feed energy is identified as Ukrainian barley and the marginal source of protein is identified as Brazilian soybean meal.
  - iLUC is modelled as the affected land is arable land. The effect is a combination of intensification and accelerated deforestation. Intensification is associated with significant uncertainties: N_2O from fertiliser production is overestimated because nitric acid today is produced with catalytic N_2O (this is not addressed in the used data from the ecoinvent database). Further, intensification is modelled as intensification of average barley in Canada. This may not be a good representative of where intensification is going to take place in reality. This issue will be further addressed in the next version of the iLUC model (Schmidt et al. 2012a,b).
- 1st generation bio-ethanol:

- Marginal source of wheat and maize for 1st generation bio-ethanol is modelled as Danish cultivation. Here it should be noticed that a change in cultivation of a certain crop in Denmark may displace another crop, i.e. the marginal crop; barley (Schmidt 2008). This is relevant when demanding a crop in an area/country with constrained production. Hence, a not included effect may be avoided Danish barley and a corresponding amount of induced marginal barley (identified as Ukrainian barley). The exclusion of this effect may underestimate the impact on GHG-emissions from Danish 1st generation bio-ethanol.
- By-products from 1st generation bio-ethanol (DDGS) are modelled as substituted feed energy and protein. The marginal source of feed energy is identified as Ukrainian barley and the marginal source of protein is identified as Brazilian soybean meal.
- Other biomass residues from the process are modelled as biogasification and substitution of district heating and electricity.
- iLUC is modelled as for biodiesel as described above.

- 2nd generation bio-ethanol:
    - The modelled technology is the Integrated Biomass Utilisation System (IBUS) concept developed by DONG Energy A/S (briefly described in Jensen et al. 2007). This represents a best-case for 2nd generation bio-ethanol.
    - The by-product, C5 molasses, is modelled as substituted feed energy and protein. The marginal source of feed energy is identified as Ukrainian barley and the marginal source of protein is identified as Brazilian soybean meal. It should be noticed that the content of feed and protein in C5 molasses is based on Jensen et al. (2007) and not official feed property data as for DDGS and the oil meals where the energy and protein contents are based on Møller et al. (2005). The data in Jensen et al. (2007) are not verified and it is recommended to use the data with caution.
    - Other biomass residues from the process are modelled as biogasification and substitution of district heating and electricity.
    - It has been assumed that straw is currently and in the future being left in the field unused, i.e. the residue resource is flexible – this may not be the case and it should be investigated further. If the straw would have been harvested anyway, the impact can be expected to be significant higher because the marginally affected technology would be something else.
    - No iLUC for the straw-removal, but avoided iLUC from the substitutions caused by the C5 molasses.

14.2 Liquid fuels, biodiesel

Biodiesel, rapeseed oil

The hotspots in the product system of rapeseed oil are iLUC and field emissions (N_2O). Notice that the rapeseed oil mill supplies the co-product rapeseed meal, which is associated with displacements of energy and protein feed. Energy feed is significant because the marginal source of feed energy is Ukraine, which is associated with a relatively low productivity (yields) and associated high iLUC.

The difference between the GWP100 and GWP20 results is mainly that the iLUC are higher for the GWP20 results (accelerated deforestation becomes more significant with a shorter time horizon).

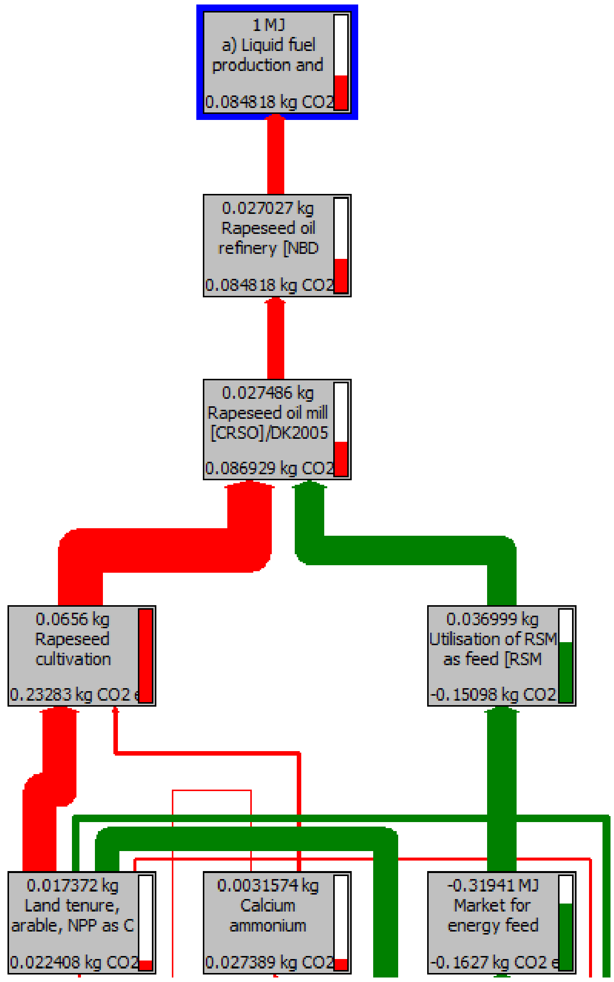

Figure 14.3, Process contribution to **GWP100** for rapeseed biodiesel. The functional unit is 1 MJ produced and combusted fuel.

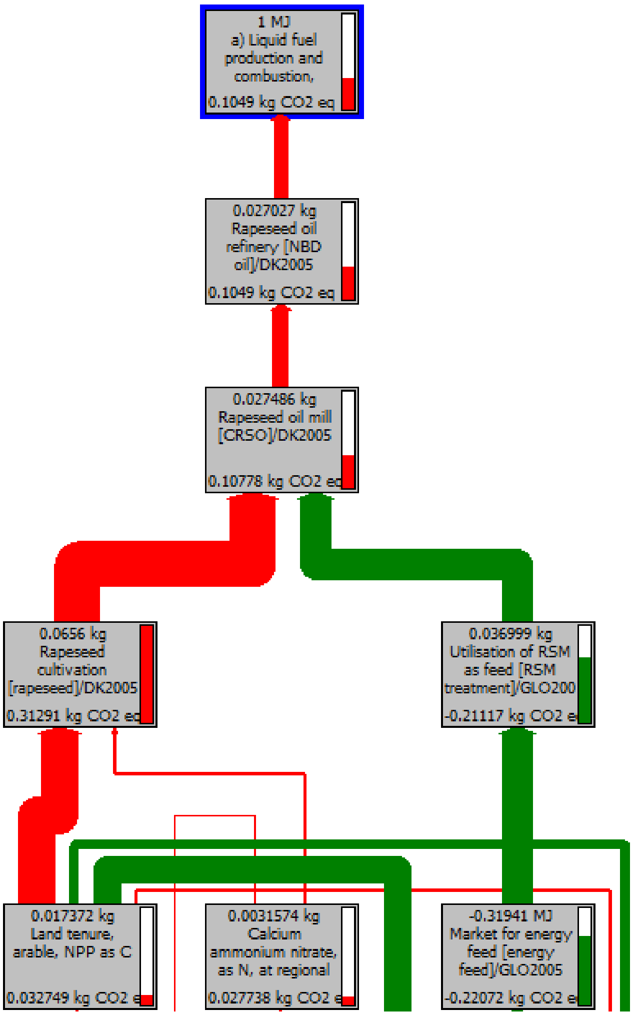

Figure 14.4, Process contribution to **GWP20** for rapeseed biodiesel. The functional unit is 1 MJ produced and combusted fuel.

Biodiesel, palm oil

The hotspots in the palm oil biodiesel product system are iLUC, CO2 and N2O from peat decay (draining of organic soils), palm oil mill effluent CH_4 (anaerobic digestion) and field emissions (N_2O).

The difference between the GWP100 and GWP20 results is mainly that the iLUC are higher for the GWP20 results (accelerated deforestation becomes more significant with a shorter time horizon) and that the GWP for CH_4 (anaerobic digestion) is higher.

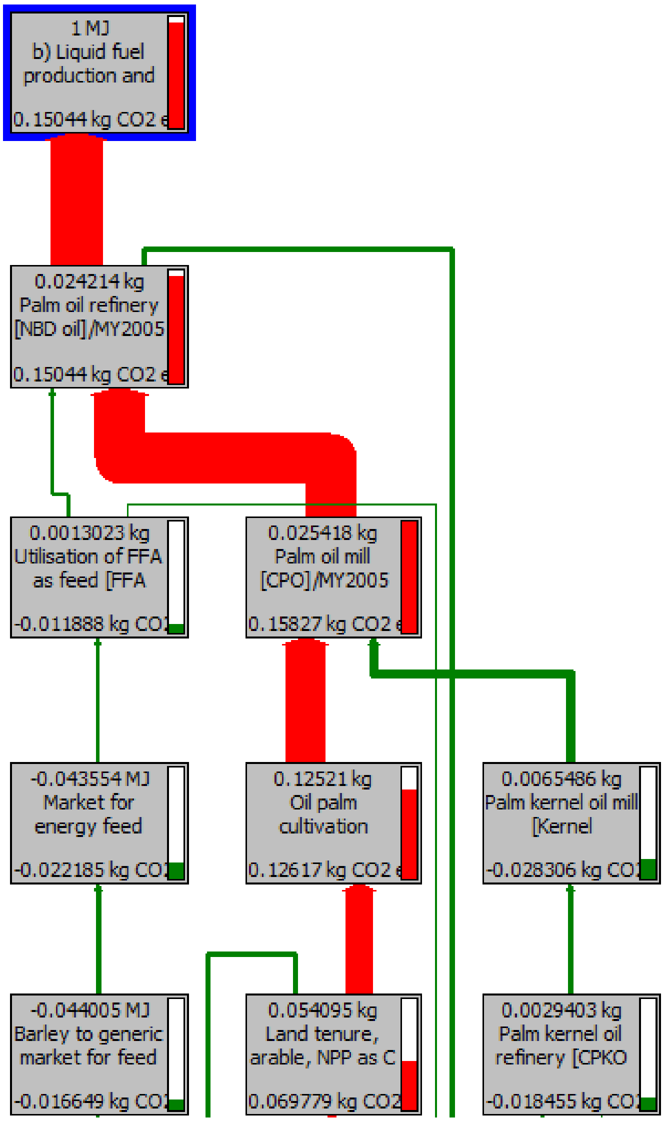

Figure 14.5, Process contribution to **GWP100** for palm oil biodiesel. The functional unit is 1 MJ produced and combusted fuel.

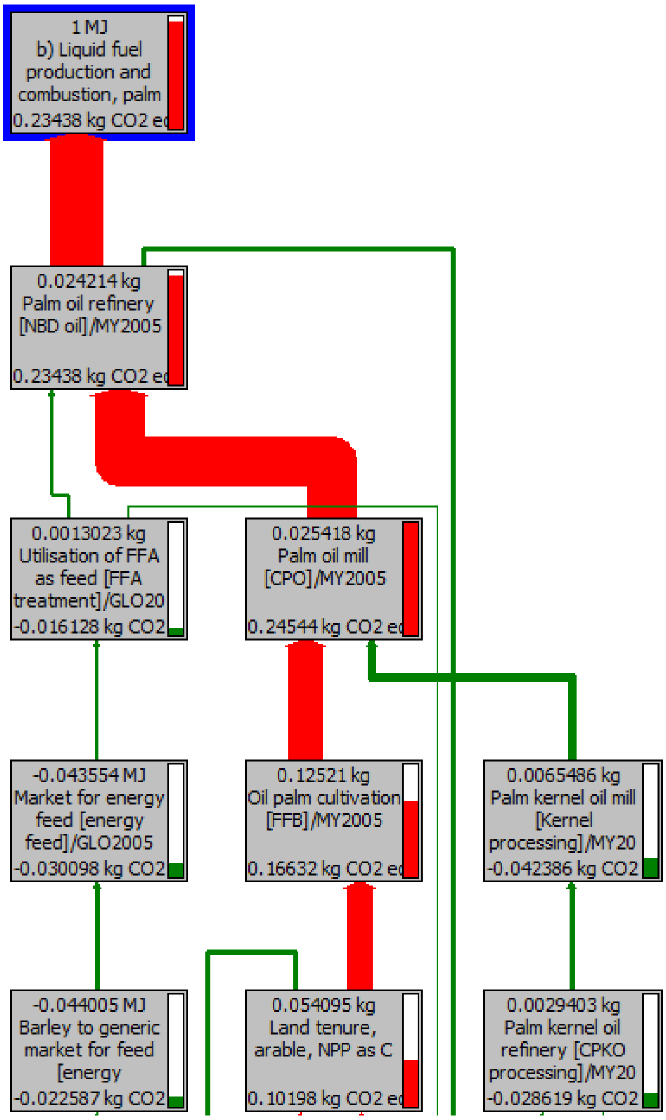

Figure 14.6, Process contribution to **GWP20** for palm oil biodiesel. The functional unit is 1 MJ produced and combusted fuel.

14.3 Liquid fuels, bio-ethanol

Bio-ethanol, wheat

The main hotspot in the product system of wheat based bio-ethanol is iLUC. Notice that the by-product DDGS is associated with significant displacement of energy feed. Energy feed is significant because the marginal source of feed energy is Ukraine, which is associated with a relatively low productivity (yields) and associated high iLUC. It should also be noticed that the cultivation of wheat in Denmark is associated with a significant substitution due to the utilization of straw for energy purposes. This is also the main reason for the difference between the wheat based and the maize based scenario for bio-ethanol. Maize is not associated with the same utilization of straw.

The difference between the GWP100 and GWP20 results is not significant.

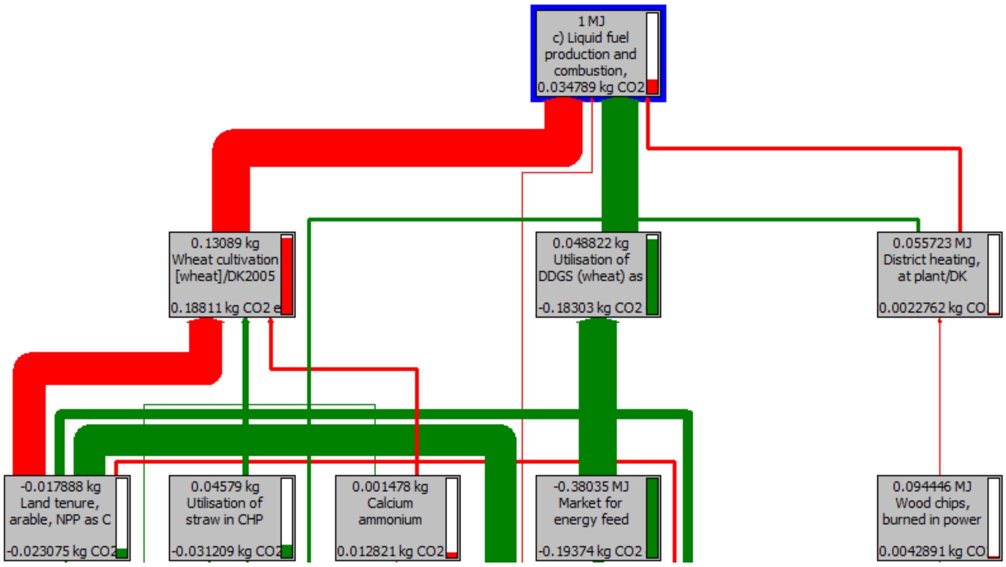

Figure 14.7, Process contribution to **GWP100** for bio-ethanol (wheat). The functional unit is 1 MJ produced and combusted fuel.

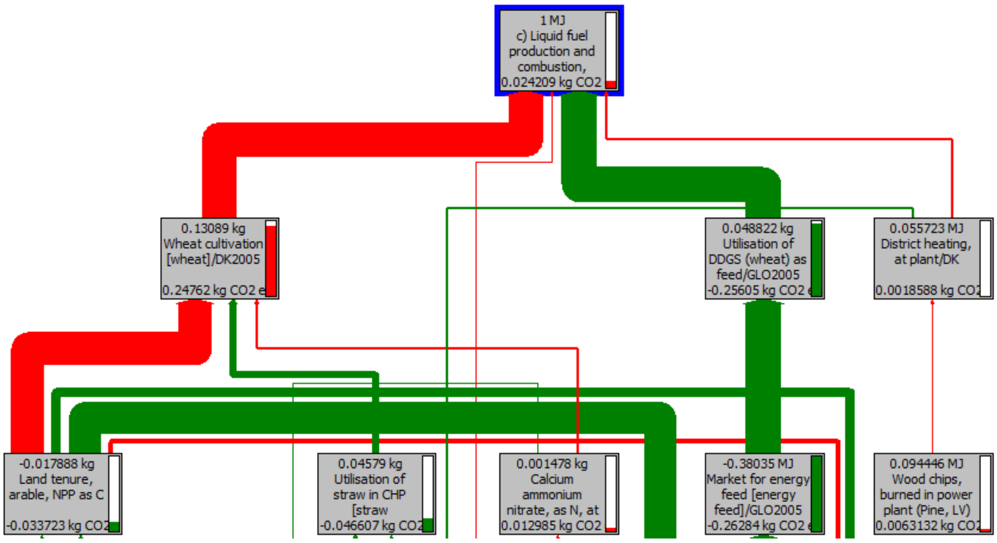

Figure 14.8, Process contribution to **GWP20** for bio-ethanol (wheat). The functional unit is 1 MJ produced and combusted fuel.

Bio-ethanol, maize

The hotspots are the same as for the wheat based bio-ethanol. Notice that maize is not associated with utilization of straw. Hence, the GHG-emissions related to the cultivation are higher compared to wheat. This explains the difference between bio-ethanol based on wheat and maize.

The difference between the GWP100 and GWP20 results is not significant.

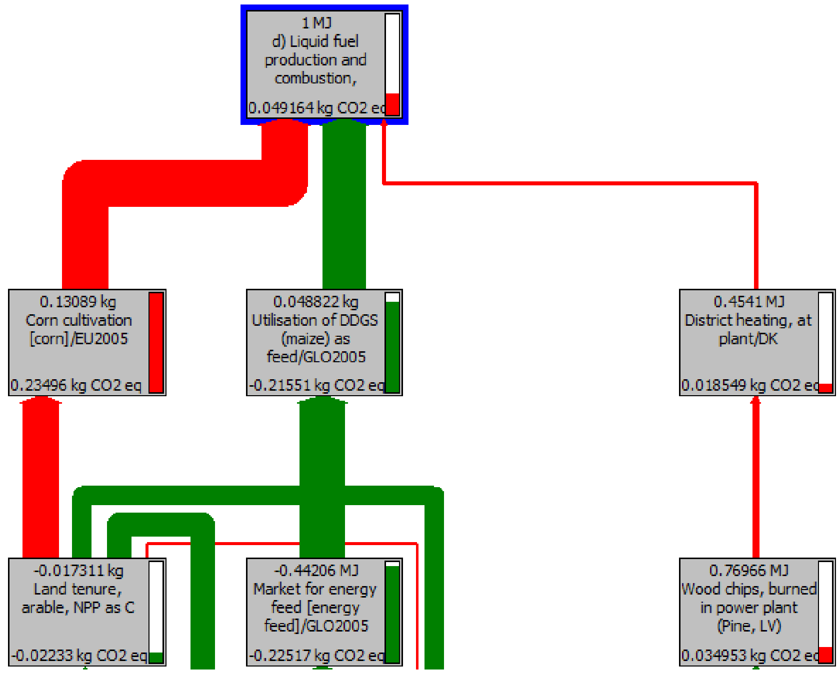

Figure 14.9, Process contribution to **GWP100** for bio-ethanol (maize). The functional unit is 1 MJ produced and combusted fuel.

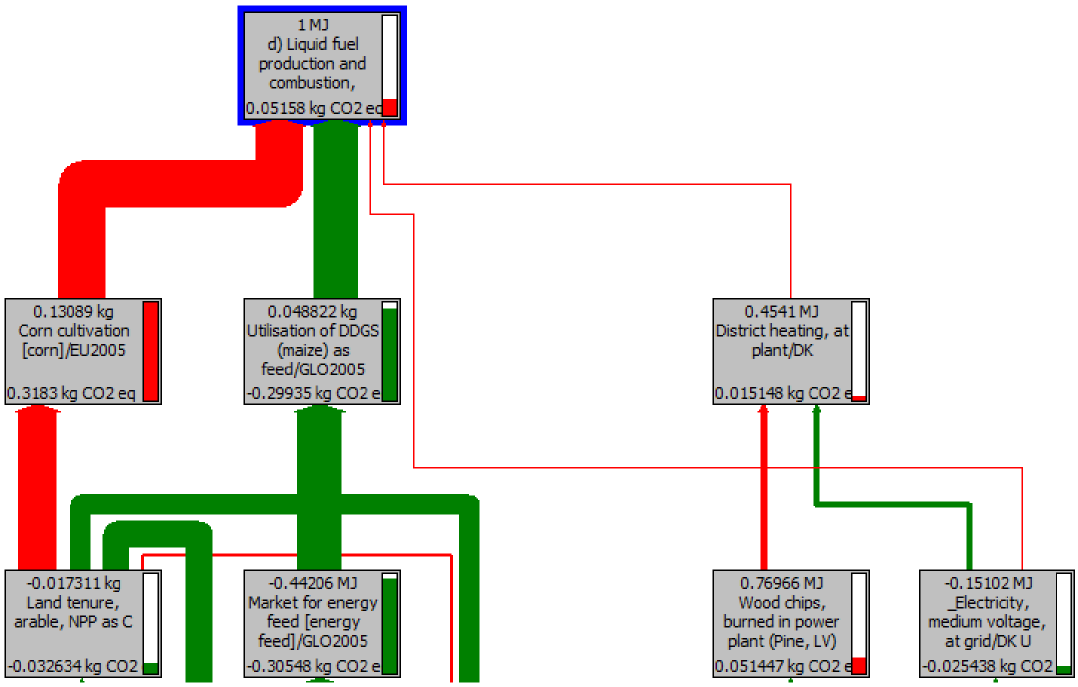

Figure 14.10, Process contribution to **GWP20** for bio-ethanol (maize). The functional unit is 1 MJ produced and combusted fuel.

Bio-ethanol, straw

The hotspots in bio-ethanol from straw are the heat used in the fermentation process and the avoided decay of straw (and immediate CO_2-emissions instead). The production of straw based bio-ethanol is associated with significant substitutions caused by the by-product C5 molasses which is used for feed purposes.

The difference between the GWP100 and GWP20 results is insignificant.

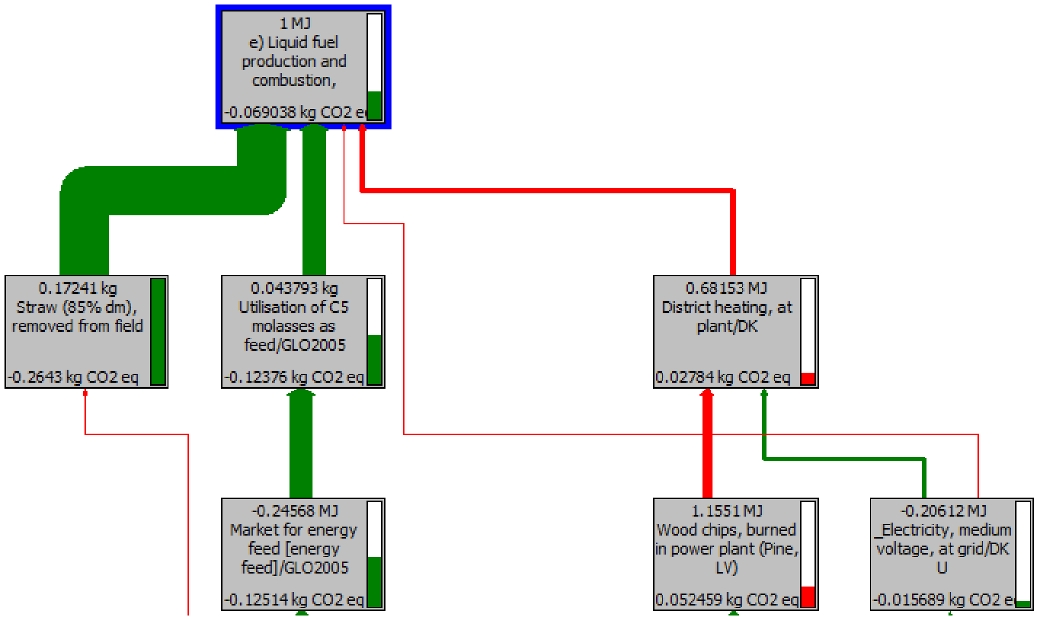

Figure 14.11, Process contribution to **GWP100** for bio-ethanol (straw). The functional unit is 1 MJ produced and combusted fuel.

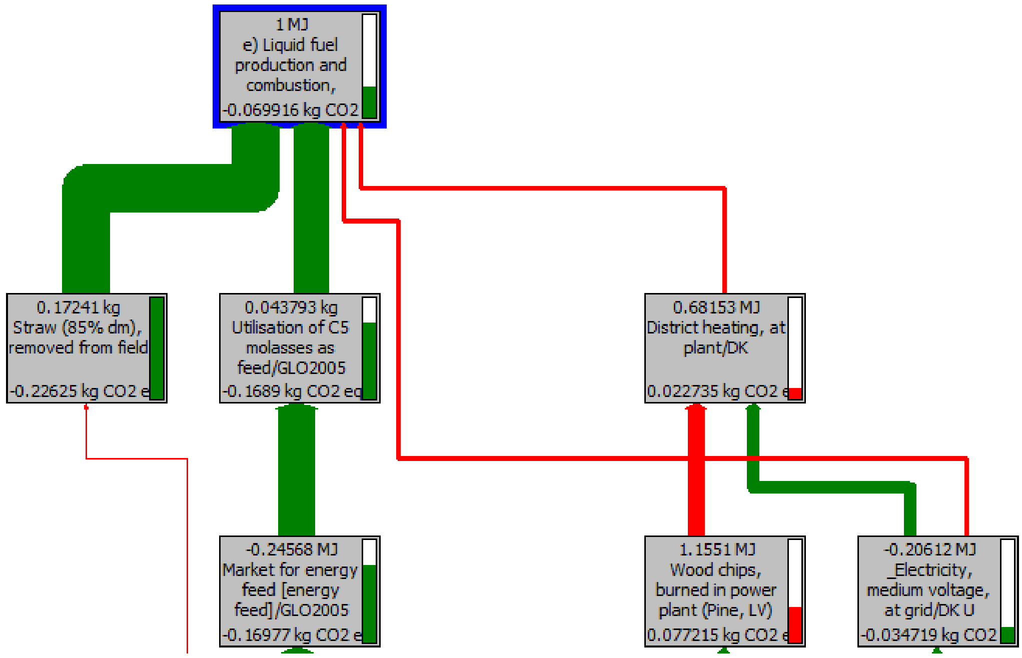

Figure 14.12, Process contribution to **GWP20** for bio-ethanol (straw). The functional unit is 1 MJ produced and combusted fuel.

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