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Life Cycle Assessment of Fossil and Biomass Power Generation Chains

An analysis carried out for ALSTOM Power Services

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Abbreviations

AU	Australia
BAT	Best Available Technology
CC	Combined Cycle
CH	Switzerland
CHP	Combined Heat and Power
CN	China
CO	Colombia
D	Germany
E, E	Egalitarian perspective, Egalitarian weighting
EIA	Environmental Impact Assessment
GHG	Greenhouse Gas
H, A	Hierarchist perspective, Average weighting
I, I	Individualist perspective, Individualist weighting
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LNG	Liquid Natural Gas
PL	Poland
RER	Europe
RU	Russia
SNG	Synthetic Natural Gas
ZA	South Africa

Acknowledgement

The author sincerely thanks Andreas Bögli, Director Strategy at Alstom power service, for the fruitful co-operation within this project and for the valuable data provided. Very much appreciated were also the continuous discussions during the whole project with Stefan Hirschberg, Head of the Laboratory of Energy Systems Analysis at the Paul Scherrer Institut.

Abstract

On behalf of Alstom Power Services the Paul Scherrer Institut carried out a comprehensive Life Cycle Assessment (LCA) of various fossil (hard coal, lignite and natural gas) and biomass (wood and Synthetic Natural gas (SNG) made from wood) energy chains for power generation. Pure fossil and biomass chains as well as co-combustion power plants are assessed. The general objective of this analysis is an evaluation of specific as well as overall environmental burdens resulting from these different options for electricity production. The results provide insights into the energy chains by quantifying the contributions of single steps of the chains to cumulative environmental burdens per kWh electricity.

The assessment covers fossil fuel production in various European regions as well as fuel imports to Europe from the most important export regions worldwide. In the case of biomass the scope is limited to average European forestry analyzing effects of fuel transport distance and mode of transport on the environmental performance of the systems. State-of-the-art power plant technologies, based on data partly provided by Alstom, are used for modelling of the fuel conversion steps. Background Life Cycle Inventories from the LCA database ecoinvent are used for performing the calculations of cumulative burdens.

The LCA results show that the so-called “upstream chain”, i.e. the part of the energy chain before the power plant operation (mainly fuel production and transport), can contribute significantly to cumulative environmental burdens per kWh electricity produced for all fuels included in this analysis. In case of the important air pollutants NO_x, SO_2 and particulates, these processes can even dominate overall results, if power plants are equipped with highly efficient pollution control systems as it is assumed in this analysis. Such an importance of the upstream processes can result in significant differences in terms of environmental performance between energy chains with fuels of different origin. The cleaner the power plants (i.e. the higher their thermal efficiencies and the more efficient their flue gas cleaning systems), the higher the relative contributions from the rest of the energy chains to cumulative emissions per kWh electricity – depending on the type of pollutant optimization of the upstream chain can result in much higher reduction of environmental impacts than power plant optimization. Therefore, not only LCI data for power plant operation, but also for the upstream processes are of high importance for the quality of an LCA assessments and have to be established and used on a country-specific basis to the extent possible.

Among the assessed hard coal chains, fuel supply from China leads to the worst environmental performance for all indicators (i.e. highest emissions to air, water and soil as well as resource consumption) due to inefficient and “dirty” power supply in the Chinese coal mining sector. Among the natural gas chains, electricity generation with fuel supply from Russia and from Nigeria (as LNG) produces the highest total environmental burdens due to significant leakage in the pipelines and high energy demand for LNG production and transport, respectively. Short fuel transport distances are in general beneficial for both fossil fuels, but whether the overall impact in terms of cumulative burdens per kWh electricity is important or not depends on the species of emission.

Compared to fossil fuels, the use of biomass (both wood and SNG) clearly reduces Greenhouse Gas (GHG) emissions. However, the overall environmental performance of wood chains strongly depends on the efficiencies of emission control technologies installed at the power plants: direct power plant emissions from wood combustion can be much higher than from coal plants, which may result – depending on the method for aggregating different impacts on human health and ecosystems – in

higher overall impacts on human health and ecosystems of wood chains. In this case co-combustion of wood together with coal in big units with higher efficiencies and state-of-the-art pollution control devices is beneficial. Also the use of SNG is not superior to natural gas in any case, since the contributions from forestry and SNG production to cumulative emissions can be significant and can lead to higher environmental burdens. Similarly to fossil chains, short distances for wood transport reduce impacts on human health and ecosystems. In case of most burdens, co-combustion chains perform better than pure hard coal and lignite chains, also with long-distance import of wood (1000 km). In general, co-firing of wood in large scale hard coal and lignite power plants reduces direct power plant emissions compared to small wood firing units, since thermal efficiencies as well as pollution control systems of these smaller power plants are worse.

Comparing the different fuel chains in terms of overall environmental performance only allows few clear conclusions. The use of coal for electricity production results in the highest GHG emissions followed by natural gas. GHG emissions of wood and SNG chains are about 85%-95% (compared to coal) and 70%-90% (compared to natural gas) lower. The results are diverse for other pollutants, depending on emission control at the power plants, origin of the fossil fuels, and transport mode and distance of the biomass. Except of GHG emissions, SNG chains for electricity generation produce less environmental burdens than direct wood combustion.

Aggregation of environmental burdens based on Life Cycle Impact Assessment methods, which aims at allowing evaluation of total environmental performance of different power generation chains, shows differing results, depending on the method, i.e. mainly on the weighting of different environmental impact categories (impacts on human health, ecosystems and consumption of resources) contributing to total LCIA scores. Assigning high importance to scarcity of fossil fuels (i.e. higher weighting of natural gas versus coal consumption) results in hard coal (with “clean” upstream chains) and lignite including co-firing with wood as best environmental performers in terms of overall impacts on the environment (including human beings). The reduction in air pollution and CO_2 emissions due to (natural and synthetic) gas instead of coal combustion is more than compensated by the high contribution of natural gas consumption (as a more scarce resource than coal) to total LCIA-cores per kWh. In case of SNG land use due to forestry increases (worsens) the LCIA score. Equal weighting of fossil resources and assignment of higher weights to impacts on human health results in the lowest (best) LCIA scores for (synthetic and natural) gas chains, mainly due to a significant reduction in the emission of air pollutants. Independently of the weighting scheme of the impact categories, pure wood chains with power plants with comparatively low efficiency and high emissions of air pollutants are among the systems with the highest (worst) LCIA scores.

1 Introduction

Almost 70% of electricity worldwide is produced with fossil power plants today. Coal is the dominating fuel (40% in 2004) and while the share of natural gas is continuously growing (20% in 2004), oil (7% in 2004) is expected to become less important for power generation (WEO 2006). Considering the quickly growing electricity demand of developing economies, coal and natural gas are expected to remain the dominating fuels for large-scale electricity production at affordable costs in the next decades.

Fossil fuel based electricity production is one of the major anthropogenic sources of CO_2 emissions today and responsible for the ongoing climate change to a great extent. The combustion of coal, natural gas and oil for electricity production contributes about 41% to total energy-related CO_2 emissions worldwide (WEO 2006). However, CO_2 emissions are not the only environmental burden: fossil and particularly coal power plants can be a major source of air pollution: NO_x. SO_2 and particulate emission lead to negative impacts on human health and ecosystem quality.

Additionally to direct power plants emissions, activities in the associated so-called “upstream” parts of complete energy chains – coal mining and extraction of natural gas and oil as well as transport of these fuels to the power plant sites – contribute to total environmental burdens of electricity production. Depending on the species of pollutant, these contributions per kWh power generation can be significant. Therefore, measures for reduction of these burdens cannot be limited to direct power plant emissions, but also reducing impacts due to fuel supply have to be taken into account. Such a comprehensive approach requires the application of Life Cycle Analysis (LCA), which includes all processes directly and indirectly associated with the production of electricity and therefore allows a consistent evaluation of complete energy chains. The LCA methodology applied allows fair comparison of different electricity generation technologies using various fuels – hard coal, lignite, natural gas, wood and Synthetic Natural Gas (SNG, made out of wood) are in focus of this particular analysis. Furthermore, application of Life Cycle Impact Assessment (LCIA) methods as well as the calculation of external costs associated with the production of electricity allows comparing complete environmental profiles (i.e. the full spectrum of environmental burdens per kWh of electricity) by weighting the different impacts on human health, ecosystems, etc. against each other.

2 Goal and scope

The main goals of this study, based on the analysis of entire energy chains by application of Life Cycle Analysis (LCA), are the following:

- The environmental assessment and comparison of different fuel chains for electricity production, particularly hard coal, lignite and natural gas as well as wood and Synthetic Natural Gas (SNG: CH_4 made of wood). Wood and SNG are both assessed as single fuels and co-combustion fuels (in combination with coal and natural gas, respectively). The different energy chains are compared in terms of cumulative environmental burdens per kWh electricity produced at the power plant. Not only specific burdens – Greenhouse gas (GHG) emissions, CO_2, NO_x, SO_2 and particulates (PM_{10}) – but also full environmental profiles are analysed, the latter based on several Life Cycle Impact Assessment (LCIA) methods as well as external costs.
- The identification of the most relevant steps (in terms of environmental burdens per kWh electricity production) in the complete energy chains for power generation.
- The analysis of region- or country-specific fuel supply and its effect on cumulative emissions per kWh electricity, in particular hard coal and natural gas supply from specific mining and production regions around the world. Also the effects of different transport modes and distances for wood (for direct (co-)combustion and SNG production) are analysed.

Figure 2.1 shows – as a representative example of the analysed energy chains – the various steps of the modelled hard coal chains together with the consumption of goods and services as inputs to the processes of the energy chain in order to illustrate the concept of cumulative environmental burdens per kWh of electricity using LCA. The so-called functional unit is 1 kWh of electricity produced at the busbar of the power plants (losses in distribution and transmission of electricity are not taken into account), i.e. all cumulative environmental burdens refer to this unit.

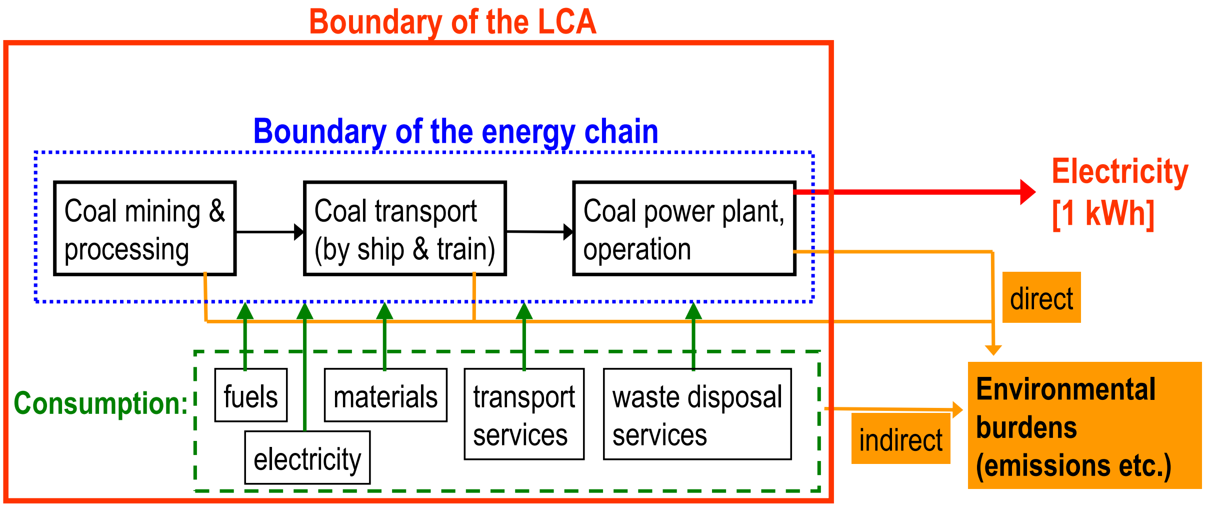

Figure 2.1 Simplified schematic overview of the modelled hard coal chains as an illustration of the LCA concept.

This study addresses electricity production only. Options for Combined Heat and Power generation (CHP) are not analysed.

State-of-the-art power plant technologies with characteristics based on data from Alstom[1] are used for modelling of the fuel conversion steps (i.e. for the electricity production at the power plants) of all

[1] As a result of iterated personal communication and email exchange with Andreas Bögli, Director Strategy, ALSTOM Power Service, between January and April 2008.

energy chains. These power plant characteristics provided by Alstom include net efficiencies, capacities, load factors and lifetimes of the power plants as well as emission data for key airborne pollutants. Modelling of the fuel chains are in general based on (Dones et al. 2004, 2007), while data from the ecoinvent LCA database (v1.3) are used as LCA background data (ecoinvent 2004), i.e. for the quantification of energy and material flows of all processes not directly being part of the energy chains in focus. The LCA calculations are performed using the LCA software SimaPro v7.1.5.

3 Characterization of power plant technologies and the associated energy chains

3.1 Power plant technologies: overview

The following power plant technologies with their associated fuel chains have been analysed in this LCA study:

- Hard coal power plant, supercritical, 800 MW_{el}
- Hard coal power plant, subcritical, 400 MW_{el}
- Lignite power plant, supercritical, 950 MW_{el}
- Natural gas power plant, Combined Cycle (CC), 400 MW_{el}
- SNG power plant, Combined Cycle (CC), 400 MW_{el}
- Natural gas/SNG co-firing power plant, Combined Cycle (CC), 400 MW_{el}
- Wood power plant, subcritical, 20 MW_{el}
- Hard coal/wood co-firing power plant, supercritical, 800 MW_{el}
- Hard coal/wood co-firing power plant, subcritical, 400 MW_{el}
- Lignite/wood co-firing power plant, subcritical, 400 MW_{el}

Table 3.1 provides an overview of the technology characteristics of these power plants. These technology characteristics are based on specifications of state-of-the-art power plants today provided by Alstom[2] and data from the NEEDS project on advanced fossil power technologies (Bauer et al. 2008a). While hard coal and lignite plants are assumed to be provide base-load electricity, natural gas and SNG (co-combustion) plants are operated in mid-load mode also in order to meet peaks in demand. The power plants are assumed to be operated in central Europe, i.e. Germany is used as the generic reference location. Since the LCIA methods used for the evaluation of the cumulative environmental burdens in general do not take into account site-specific health or environmental damages, this choice only plays a role for modelling of the fuel chains, i.e. for transport of the fuels burned in the power plants. Also the power plant net efficiencies would slightly differ at significantly higher or lower ambient temperatures. Contrary to commonly used LCIA methods, the evaluation of burdens on human health and the environment based on external costs could take into account site-specific factors like weather conditions and population density, but employment of this so-called Environmental Impact Assessment (EIA) was out of scope of this study. Average European damage factors have been used for external cost calculations.

[2] Personal communication and email exchange with Andreas Bögli, Director Strategy, ALSTOM Power Service, between January and April 2008.

Table 3.1 Technology characteristics of the power plants addressed in this study.

type of power plant		hard coal, supercritical	hard coal, subcritical	lignite, supercritical	natural gas, CC	SNG, CC
capacity (net)	MW	800	400	950	400	400
electric efficiency (net)	%	46	40	43.2	59	59
lifetime	a	40	40	40	30	30
full load hours per year	h/a	8200	8000	8400	4500	4500
fuel type		hard coal	hard coal	lignite	natural gas	synthetic natural gas (SNG)
fuel share (based on energy input - LHV)		100% hard coal	100% hard coal	100% lignite	100% nat gas	100% SNG
type of power plant		natural gas/SNG co-firing, CC	wood, subcritical	hard coal/wood co-firing, supercritical	hard coal/wood co-firing, subcritical	lignite/wood co-firing, supercritical
capacity (net)	MW	400	20	800	400	950
electric efficiency (net)	%	59	32	46	40	43.2
lifetime	a	30	40	40	40	40
full load hours per year	h/a	4500	7000	8200	8000	8400
fuel type		natural gas/SNG co-combustion	wood	hard coal/wood co-combustion	hard coal/wood co-combustion	lignite/wood co-combustion
fuel share (based on energy input - LHV)		90% nat gas 10% SNG	100% wood chips	90% coal 10% wood chips	90% coal 10% wood chips	90% lignite 10% wood chips

LHV = Low Heating Value.

3.2 Fuel chains

3.2.1 Hard coal

Hard coal based electricity production differentiates between various hard coal mining regions in the so-called upstream chain[3]: mining and processing of the coal is specifically modelled for Australia, Colombia, Germany, Poland, Russia, South Africa, the USA (Röder et al. 2004) and China (Röder et al. 2007). This worldwide produced hard coal for export is transported by train (and to a small extent by lorry) in the mining region to the next suitable harbour, shipped by big freight ships to a harbour in the vicinity of the consumption (in this study: Germany) and transported again by railway to the power plant. Usually the coal is stored in an interim storage in the harbour of the exporting region.

Figure 3.1 shows a schematic overview of the modelled hard coal chains with the different steps of the energy chain and the associated main environmental burdens from each step.

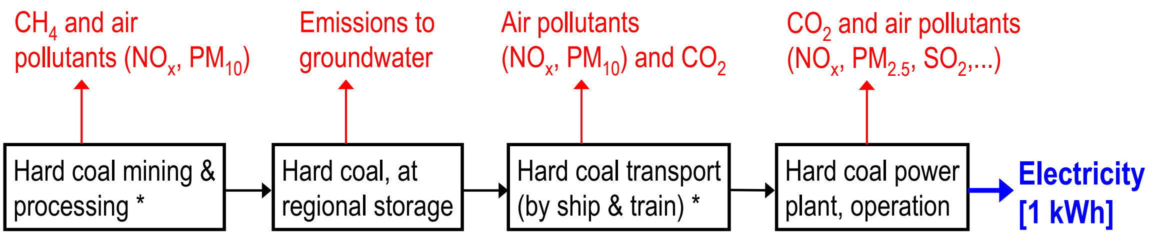

Figure 3.1 Schematic overview of the modelled hard coal chains for electricity production; * the so-called upstream chain (coal mining and transport to the power plant) is modelled specifically for the considered mining regions (Australia, China, Colombia, Germany, Poland, Russia, South Africa, USA).

[3] In case of electricity production based on fossil fuels the "upstream" part of the energy chains represents all steps of the energy chain before the operation of the power plant, i.e. production and processing of the fuel and its transport to the power plant, including intermediate storage (if applicable).

The characteristics of the hard coal used for electricity production depend on the origin of the fuel. Table 3.2 summarizes the main characteristics per mining region and the associated transport distances and transport modes.

Table 3.2 Characteristics of the hard coal used for modelling of the hard coal chains in this study.

origin of the fuel		Australia	China	Colombia	Germany	Poland	Russia	USA	South Afica
transport distance		train (within AU): 200 km ship: 23000 km train (within EU): 500 km	train (within CN): 650 km ship: 20000 km train (within EU): 500 km	train (within CO): 200 km ship: 8500 km train (within EU): 500 km	train (within D): 200 km train (within EU): 300 km	train (within PL): 500 km train (within EU): 500 km	train (within RU): 4000 km ship: 3000 km train (within EU): 500 km	train (within US): 800 km ship: 7400 km train (within EU): 500 km	train (within ZA): 600 km ship: 13500 km train (within EU): 500 km
means of transport		train & ship	train & ship	train & ship	train	train	train & ship	train & ship	train & ship
LHV									
hard coal	MJ/kg	25.1	20.1	20	25.7	23.7	22.3	24	23.7
Water content									
hard coal	%	9.1	10	8.7	8.5	7.2	12.2	14.6	10.4

3.2.2 Lignite

Figure 3.2 shows a schematic overview of the modelled lignite chain with the different steps of the energy chain and the associated main environmental burdens from each step. Lignite power plants are operated as “mine-mouth” plants, i.e. the lignite burned in the power plant is mined in its vicinity or vice versa, therefore no transport step is taken into account. LCI data for the lignite mining process are based on German lignite mining (Röder et al. 2007). The energy content of the lignite is 8.8 MJ/kg (LHV), its water content 58%.

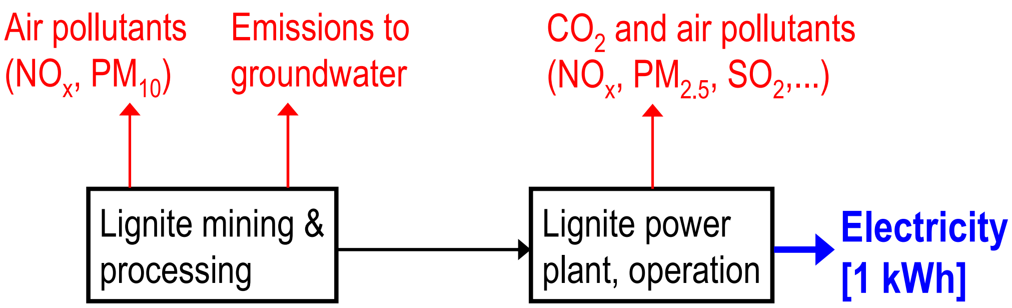

Figure 3.2 Schematic overview of the modelled lignite chain.

3.2.3 Wood

Figure 3.3 shows a schematic overview of the modelled wood chain with the different steps of the energy chain and the associated main environmental burdens from each step. Modelling of the production of wood chips – used either as input for direct combustion in wood power plants and for co-firing with hard coal and lignite or as feed stock for SNG production – is based on central European forestry (Werner et al. 2004, Bauer 2007), i.e. representative German conditions. This analysis covers sustainable management of natural forests: only the naturally growing amount of wood is harvested and used – not only as fuel, but also for furniture or as base material for construction of buildings, etc. Neither clear cutting of dedicated forest areas, nor fast rotation forestry (with quickly growing trees like poplar) is taken into account.

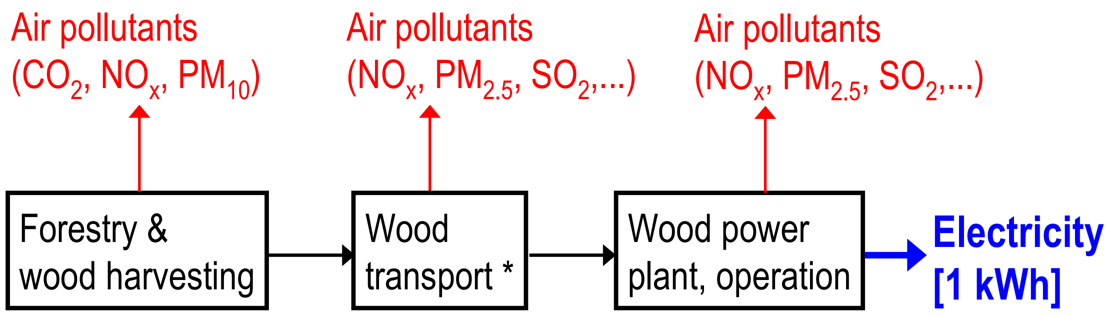

Figure 3.3 Schematic overview of the modelled wood energy chain. * Wood transport either by lorry (25 km), train, or barge (1000 km each).

Table 3.3 gives an overview about the key characteristics of the wood chips used in this analysis.

Table 3.3 Key characteristics of the wood fuel used in this study (wood chips, mixed[4], u=120%[5], at forest).

Lower heating value (LHV)	Density (wet)	Density (wet)	Water content
MJ/m^3	kg/MJ	kg/m^3	%
3298.5	0.1258	415	54.6

The wood chips usually produced within the forest or within short distance to the place where the trees are cut are directly transported to the point of use, i.e. the power plant for combustion or the SNG production plant for gasification and methanation. In order to evaluate the effects of different transport modes (lorry, ship, and railway) and distances (i.e. use of wood from the vicinity of the power plants vs. long-distance supply) on cumulative environmental burdens per kWh electricity, several wood chains are analysed, differing for “wood only” power plants and co-firing plants, respectively.

3.2.4 Co-combustion: hard coal/wood and lignite/wood

Figure 3.4 shows a schematic overview of the modelled wood/coal chains with the different steps of the energy chains and the associated main environmental burdens from each step. Either hard coal or lignite (both from Germany) are burned together with wood chips in co-combustion power plants. The assumed fuel share is 90% hard coal or lignite and 10% wood, based on the energy content (LHV). The different fuel chains are presented in chapters 3.2.1, 3.2.2, and 3.2.3.

The assessed combinations of different transport modes and distances with power plant technologies are shown in Table 3.4.

[4] “Mixed” represents a mixture of hardwood and softwood (72% vs. 28%), representative for Swiss conditions.

[5] The humidity or water content u of the wood is defined with respect to the dry matter content in terms of mass of the wood. I.e. a humidity u=100% means that 50% of the total mass of the wood (including water) is water and 50% dry matter (mostly cellulose, hemicelluloses, and lignin).

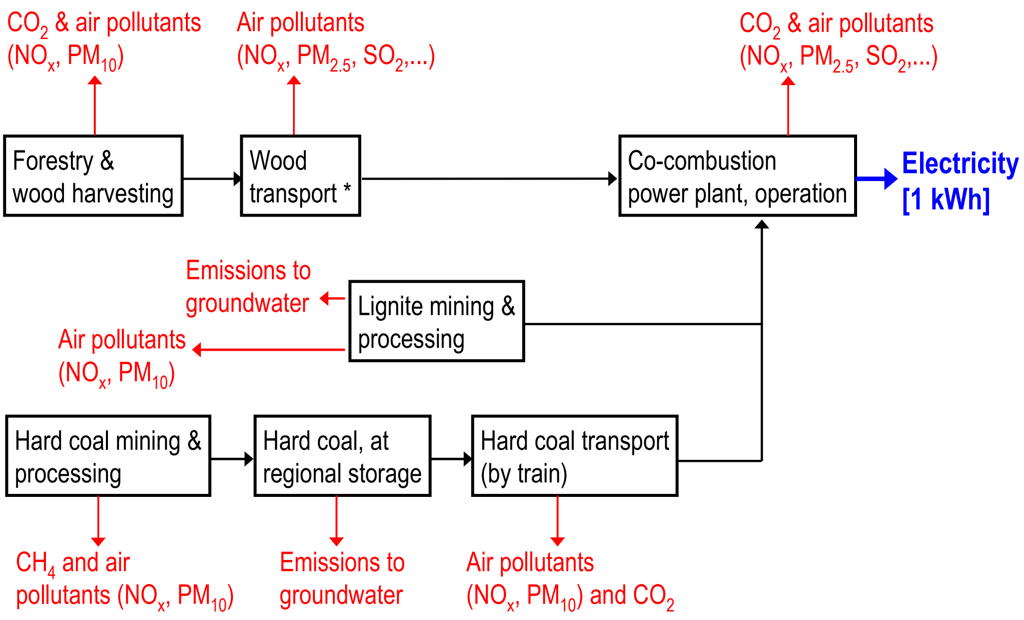

Figure 3.4 Schematic overview of the modelled co-combustion chains (hard coal/wood and lignite or wood). * Wood transport either by lorry (25 km), train, or barge (1000 km each).

Table 3.4 Overview of the modelled wood chains (wood and co-firing power plants).

power plant type	capacity (net) [MW]	fuel type	fuel share (based on energy input - LHV)	fuel source	transport distance	means of transport
wood, subcritical	20	wood	100% wood chips	wood: local (central European wood chain)	wood: 25 km	wood: lorry
wood, subcritical	20	wood	100% wood chips	wood: Europe (central European wood chain)	wood: 1000 km	wood: train
wood, subcritical	20	wood	100% wood chips	wood: Europe (central European wood chain)	wood: 1000 km	wood: barge
hard coal/wood co-firing, subcritical	400	hard coal/wood co-combustion	90% coal 10% wood chips	hard coal: Germany wood: local (central European wood chain)	hard coal: 500 km wood: 50 km	hard coal: train wood: lorry
hard coal/wood co-firing, subcritical	400	hard coal/wood co-combustion	90% coal 10% wood chips	hard coal: Germany wood: Europe (central European wood chain)	hard coal: 500 km wood: 1000 km	hard coal: train wood: train
hard coal/wood co-firing, subcritical	400	hard coal/wood co-combustion	90% coal 10% wood chips	hard coal: Germany wood: Europe (central European wood chain)	hard coal: 500 km wood: 1000 km	hard coal: train wood: barge
hard coal/wood co-firing, supercritical	800	hard coal/wood co-combustion	90% coal 10% wood chips	hard coal: Germany wood: Europe (central European wood chain)	hard coal: 500 km wood: 50 km	hard coal: train wood: lorry
hard coal/wood co-firing, supercritical	800	hard coal/wood co-combustion	90% coal 10% wood chips	hard coal: Germany wood: Europe (central European wood chain)	hard coal: 500 km wood: 1000 km	hard coal: train wood: train
hard coal/wood co-firing, supercritical	800	hard coal/wood co-combustion	90% coal 10% wood chips	hard coal: Germany wood: Europe (central European wood chain)	hard coal: 500 km wood: 1000 km	hard coal: train wood: barge
lignite/wood co-firing, supercritical	950	lignite/wood co-combustion	90% lignite 10% wood chips	lignite: Germany wood: Europe (central European wood chain)	lignite: no transport (mine-mouth) wood: 50 km	wood: lorry
lignite/wood co-firing, supercritical	950	lignite/wood co-combustion	90% lignite 10% wood chips	lignite: Germany wood: Europe (central European wood chain)	lignite: no transport (mine-mouth) wood: 1000 km	wood: train
lignite/wood co-firing, supercritical	950	lignite/wood co-combustion	90% lignite 10% wood chips	lignite: Germany wood: Europe (central European wood chain)	lignite: no transport (mine-mouth) wood: 1000 km	wood: barge

3.2.5 Natural gas

Figure 3.5 shows a schematic overview of the modelled natural gas chain with the different steps of the energy chain and the associated main environmental burdens from each step. Natural gas production is specifically modelled for seven regions (Algeria, Germany, Russia, Norway, Nigeria, Netherlands, UK) based on (Faist Emmenegger et al. 2004). Natural gas from Algeria, Germany, Russia, Norway, The Netherlands and UK is transported to the reference site (Germany) via pipeline. Additionally, transport as LNG from Algeria and Nigeria is modelled. Due to lack of data, gas exploration and production in Algeria is used for Nigerian conditions as well in first approximation. Table 3.5 shows the energy content and transport distances of the natural gas from the different regions included in this study. Further characteristics of the gas can be found in (Faist Emmenegger et al. 2004).

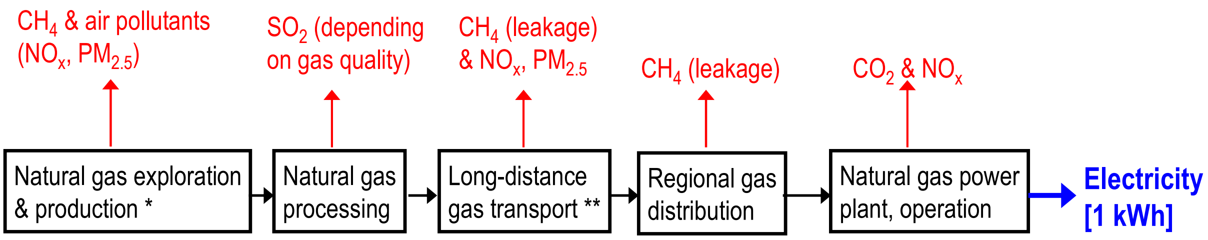

Figure 3.5 Schematic overview of the modelled natural gas chains. * specifically modelled for the considered production regions (Algeria, Germany, Russia, Norway, Nigeria, The Netherlands, UK); ** gas transport via pipeline and/or as LNG (Algeria, Nigeria).

Table 3.5 Transport distances and energy content of the natural gas delivered to the power plant at the reference site Germany.

origin of the fuel		Russia	Algeria	Algeria (LNG)	UK	Netherlands	Norway	Germany	Nigeria (LNG)
transport distance		6000 km	2100 km	LNG: 926 km (500 seamiles) pipeline: 300 km	500	700	1400	600	LNG: 7000 km pipeline: 300 km
means of transport		pipeline	pipeline	ship/pipeline	pipeline	pipeline	pipeline	pipeline	ship/pipeline
LHV									
natural gas/SNG	MJ/Nm3	36.4	38.5	38.5	37	34.9	40.8	35	38.5

3.2.6 Synthetic Natural Gas (SNG)

Figure 3.6 shows a schematic overview of the modelled Synthetic Natural Gas (SNG) chain with the different steps of the energy chain and the associated main environmental burdens from each step. LCI data for the SNG production are based on (Felder & Dones 2007). Three different scenarios for wood transport are modelled: over 25 km by lorry and over 1000 km by train or barge. More details about modelling of forestry can be found in chapter 3.2.3. The produced SNG is assumed to be fed into the natural gas network and burned in conventional natural gas CC power plants.

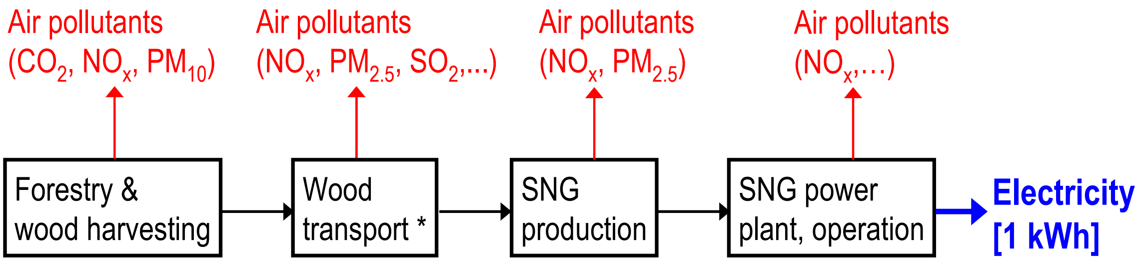

Figure 3.6 Schematic overview of the modelled SNG chain. * Wood transport either by lorry (25 km), train, or barge (1000 km each).

3.2.7 Co-combustion: natural gas/SNG

Figure 3.7 shows a schematic overview of the modelled co-combustion chains with the different steps of the energy chains and the associated main environmental burdens from each step. Natural gas and SNG are assumed to be mixed with shares of 90% and 10%, respectively. The SNG chain is described in chapter 3.2.6, the natural gas chains in chapter 3.2.5. The natural gas supply of the co-combustion plants is modelled with the European import mix in year 2000, import shares shown in Table 3.6. The SNG/natural gas mix is burned in conventional natural gas CC power plants.

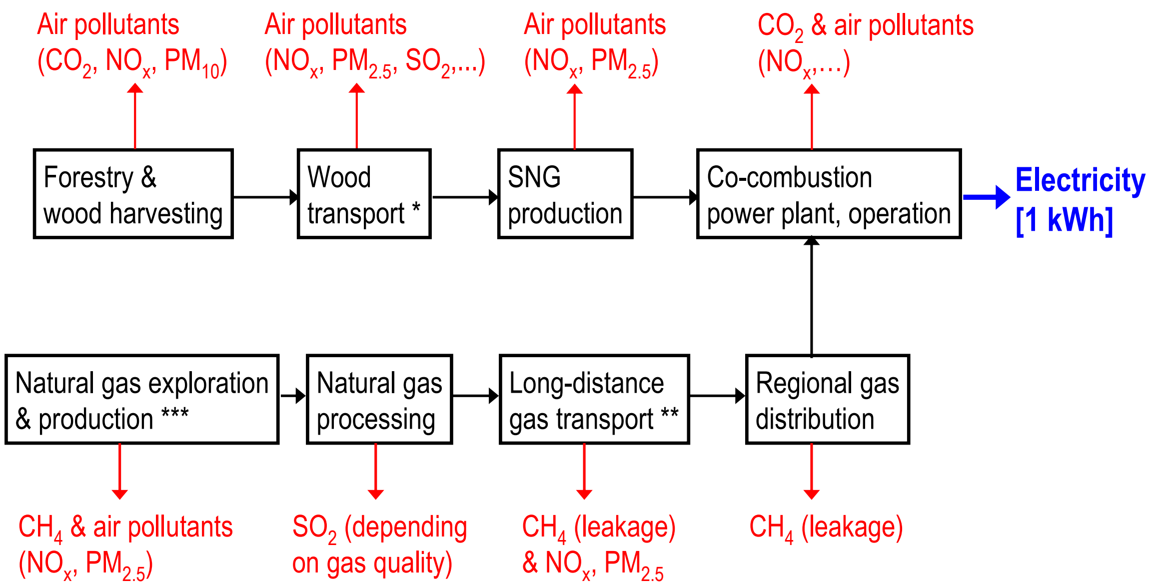

Figure 3.7 Schematic overview of the modelled natural gas/SNG chain. * Wood transport either by lorry (25 km), train, or barge (1000 km each); gas transport either via pipeline or as LNG (depending on the production region); * natural gas: EU import mix.**

Table 3.6 Natural gas import shares to EU-15 in year 2000 (Faist Emmenegger et al. 2004).

	Share of natural gas imports (year 2000)	
	Switzerland	Europe
Germany	0.10	0.05
Algeria	0.04	0.16
UK	0.05	0.04
Netherlands	0.28	0.24
Norway	0.17	0.17
Russia	0.36	0.34

3.3 Energy conversion (power plant operation)

The main characteristics and key operational data of the different power plant technologies employed in the modelling of the various energy chains are shown in Table 3.1.

Table 3.7 through Table 3.11 provide the complete LCI data for the operation of the different power plants with the associated fuel chains, i.e. emissions, waste flows and consumption of water, chemicals, etc. per MJ fuel burned, or kWh electricity produced. In order to convert data from MJ fuel burned to one kWh of electricity generation, the power plant efficiencies in Table 3.1 have to be used.

Emission data of hard coal as well as lignite power plants are based on (Röder et al. 2007, Bauer et al. 2008a, b). Due to the fact that natural gas and SNG are the same in terms of quality (energy content, composition, etc.) and power plant technology is the same, emission data of natural gas as well as SNG power plants are identical and based on (Faist Emmenegger et al. 2007). Two different cases (options) for wood power plants are modelled, differing in NO_x, $PM_{2.5}$ and SO_2 emissions. In case A emission data for these pollutants are based on information from Alstom[6], option B is based on emission data of the 6.4 MW_{el} wood-fuelled CHP plant in (Bauer 2007). All other emission parameters are identical for both options, taken from (Bauer 2007). In case of co-combustion of wood at hard coal and lignite power plants, the overall emissions are a combination of pure hard coal/lignite and wood chips combustion, calculated with the shares of fuel input of 90% and 10% (based on energy input), respectively. Due to the installation of highly efficient pollution control systems at the co-combustion plants, NO_x and particle emissions of the wood combustion are assumed to be reduced to the level of pure coal combustion. SO_2 emissions from wood combustion are already lower than from coal combustion (wood option B) and therefore not adjusted. Key emission parameters for all power plant technologies are cross-checked with Alstom.[7]

[6] Personal communication and email exchange with Andreas Bögli, Director Strategy, ALSTOM Power Service, between January and April 2008.

[7] Personal communication and email exchange with Andreas Bögli, Director Strategy, ALSTOM Power Service, between January and April 2008.

Table 3.7 LCI data of the hard coal power plant operation, supplied with coal from Australia (representative for all modelled hard coal chains, i.e. hard coal supply from the different mining regions; data are identical if not stated otherwise below the table).

	hard coal AU, burned in power plant 800 MW (BAT) *	MJ
Resources		
Water, cooling, nspecified natural origin/m3	3.50E-03	m3
Materials/fuels		
Chlorine, liquid, production mix, at plant/RER	1.00E-05	kg
construction, hard coal power plant 800 MW	1.06E-12	p
dismantling, hard coal power plant 800 MW	1.06E-12	p
NOx retained, in SCR/GLO	1.26E-04	kg
SOx retained, in hard coal flue gas desulphurisation/RER	6.14E-04	kg
Hard coal AU, at regional storage Germany **	3.98E-02	kg
Light fuel oil, at regional storage/RER	1.70E-05	kg
Transport, freight, rail/RER ***	1.19E-02	tkm
Water, completely softened, at plant/RER	6.00E-03	kg
Water, decarbonised, at plant/RER	1.50E-01	kg
Emissions to air		
Antimony	8.65E-11	kg
Arsenic	1.29E-09	kg
Barium	5.71E-09	kg
Benzene	2.17E-07	kg
Benzo(a)pyrene	2.00E-13	kg
Boron	1.23E-07	kg
Bromine	6.36E-08	kg
Butane	1.90E-08	kg
Cadmium	5.76E-11	kg
Carbon dioxide, fossil	9.22E-02	kg
Carbon monoxide, fossil	8.00E-06	kg
Chromium	6.56E-10	kg
Chromium VI	8.11E-11	kg
Cobalt	3.26E-10	kg
Copper	1.65E-09	kg
Dinitrogen monoxide	3.97E-06	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	7.00E-15	kg
Ethane	4.10E-08	kg
Formaldehyde	5.80E-08	kg
Heat, waste	5.47E-01	MJ
Hydrocarbons, aliphatic, alkanes, nspecified	2.19E-07	kg
Hydrocarbons, aliphatic, nsaturated	2.16E-07	kg
Hydrogen chloride	2.08E-06	kg
Hydrogen fluoride	1.30E-06	kg
Iodine	2.37E-08	kg
Lead	5.53E-09	kg
Lead-210	1.61E-06	kBq
Manganese	1.22E-09	kg
Mercury	4.10E-09	kg
Methane, fossil	1.00E-06	kg
Molybdenum	3.62E-10	kg
Nickel	2.49E-09	kg
Nitrogen oxides	5.61E-05	kg
PAH, polycyclic aromatic hydrocarbons	1.00E-09	kg
Particulates, < 2.5 µm	4.76E-06	kg
Particulates, > 10 µm	5.28E-06	kg
Particulates, > 2.5 µm, and < 10 µm	5.61E-07	kg
Pentane	1.47E-07	kg
Polonium-210	2.95E-06	kBq
Potassium-40	2.12E-06	kBq
Propane	3.50E-08	kg
Propene	1.60E-08	kg
Radium-226	4.16E-07	kBq
Radium-228	2.12E-07	kBq
Selenium	5.45E-09	kg
Strontium	7.14E-10	kg
Sulfur dioxide	4.38E-05	kg
Thorium-228	1.14E-07	kBq
Thorium-232	1.79E-07	kBq
Toluene	1.09E-07	kg
Uranium-238	3.47E-07	kBq
Vanadium	6.53E-10	kg
Xylene	9.22E-07	kg
Zinc	4.11E-09	kg
Waste to treatment		
Disposal, residue from cooling tower, 30% water, to sanitary landfill/CH	5.00E-06	kg

* "AU" indicates the origin of the fuel; the study contains specific datasets for power plant operation with hard coal supply from all addressed mining regions (not included in this report).

** Mass of coal input depends on the region-specific energy content of the coal.

*** Mass of coal to be transported depends on the region-specific energy content of the coal.

Table 3.8 LCI data of the lignite power plant operation.

	operation, lignite power plant 950 MW (BAT)	kWh
Resources		
Water, cooling, nspecified natural origin/m3	2.92E-02	m3
Materials/fuels		
Chlorine, liquid, production mix, at plant/RER	8.33E-05	kg
Water, completely softened, at plant/RER	5.00E-02	kg
Water, decarbonised, at plant/RER	1.25E+00	kg
SOx retained, in lignite flue gas desulphurisation/GLO	8.27E-03	kg
NOx retained, in SCR/GLO	1.68E-03	kg
Transport, freight, rail/RER	6.25E-05	tkm
Emissions to air		
Heat, waste	5.60E+00	MJ
Antimony	1.09E-10	kg
Arsenic	6.15E-09	kg
Barium	3.64E-08	kg
Benzene	1.81E-06	kg
Benzo(a)pyrene	1.67E-12	kg
Boron	1.72E-05	kg
Bromine	2.30E-07	kg
Butane	1.58E-07	kg
Cadmium	1.27E-10	kg
Carbon dioxide, fossil	9.02E-01	kg
Carbon monoxide, fossil	1.67E-04	kg
Chromium	1.62E-09	kg
Chromium VI	2.00E-10	kg
Cobalt	7.27E-10	kg
Copper	1.67E-09	kg
Dinitrogen monoxide	2.16E-05	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	5.83E-14	kg
Ethane	3.42E-07	kg
Formaldehyde	4.83E-07	kg
Hydrocarbons, aliphatic, alkanes, nspecified	1.83E-06	kg
Hydrocarbons, aliphatic, nsaturated	1.80E-06	kg
Hydrogen chloride	2.44E-05	kg
Hydrogen fluoride	6.81E-06	kg
Iodine	2.16E-07	kg
Lead	4.36E-09	kg
Lead-210	1.05E-05	kBq
Manganese	9.09E-09	kg
Mercury	1.92E-08	kg
Methane, fossil	8.33E-06	kg
Molybdenum	7.27E-10	kg
Nickel	3.60E-09	kg
Nitrogen oxides	6.97E-04	kg
PAH, polycyclic aromatic hydrocarbons	8.33E-09	kg
Particulates, < 2.5 µm	5.91E-05	kg
Particulates, > 10 µm	4.51E-05	kg
Particulates, > 2.5 µm, and < 10 µm	6.96E-06	kg
Pentane	1.22E-06	kg
Polonium-210	1.91E-05	kBq
Potassium-40	6.77E-06	kBq
Propane	2.92E-07	kg
Propene	1.33E-07	kg
Radium-226	2.70E-06	kBq
Radium-228	2.63E-06	kBq
Selenium	2.49E-08	kg
Strontium	3.82E-09	kg
Sulfur dioxide	1.22E-04	kg
Thorium-228	1.42E-06	kBq
Thorium-232	2.23E-06	kBq
Toluene	9.08E-07	kg
Uranium-238	2.25E-06	kBq
Vanadium	9.09E-10	kg
Xylene	7.68E-06	kg
Zinc	6.36E-09	kg
Waste to treatment		
Disposal, lignite ash, 0% water, to opencast refill/DE	5.94E-02	kg

Table 3.9 LCI data of the wood power plant operation, alternative A.

	wood chips, burned in wood power plant 20 MW (A) (wood transport: truck, 25km) *	MJ
Materials/fuels		
Ammonia, liquid, at regional storehouse/CH	8.20E-09	kg
Chlorine, liquid, production mix, at plant/RER	3.28E-07	kg
Sodium chloride, powder, at plant/RER	4.10E-06	kg
Chemicals organic, at plant/GLO	5.74E-06	kg
Lubricating oil, at plant/RER	3.28E-06	kg
Transport, lorry 3.5-20t, fleet average/CH **	3.15E-03	tkm
Water, decarbonised, at plant/RER	7.87E-04	kg
Wood chips, mixed, =120%, at forest/RER	3.03E-04	m3
Wood combustion power plant 20 MW	4.96E-11	p
Emissions to air		
Acetaldehyde	6.10E-08	kg
Ammonia	1.74E-06	kg
Arsenic	1.00E-09	kg
Benzene	9.10E-07	kg
Benzene, ethyl-	3.00E-08	kg
Benzene, hexachloro-	7.20E-15	kg
Benzo(a)pyrene	5.00E-10	kg
Bromine	6.00E-08	kg
Cadmium	7.00E-10	kg
Calcium	5.85E-06	kg
Carbon dioxide, biogenic	1.04E-01	kg
Carbon monoxide, biogenic	7.00E-06	kg
Chlorine	1.80E-07	kg
Chromium	3.96E-09	kg
Chromium VI	4.00E-11	kg
Copper	2.20E-08	kg
Dinitrogen monoxide	2.30E-06	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	3.10E-14	kg
Fluorine	5.00E-08	kg
Formaldehyde	1.30E-07	kg
Heat, waste	9.87E-01	MJ
Hydrocarbons, aliphatic, alkanes, unspecified	9.10E-07	kg
Hydrocarbons, aliphatic, unsaturated	3.10E-06	kg
Lead	2.49E-08	kg
Magnesium	3.61E-07	kg
Manganese	1.71E-07	kg
Mercury	3.00E-10	kg
Methane, biogenic	4.34E-07	kg
m-Xylene	1.20E-07	kg
Nickel	6.00E-09	kg
Nitrogen oxides ***	4.29E-04	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	6.10E-07	kg
PAH, polycyclic aromatic hydrocarbons	1.10E-08	kg
Particulates, < 2.5 µm ***	2.53E-05	kg
Phenol, pentachloro-	8.10E-12	kg
Phosphorus	3.00E-07	kg
Potassium	2.34E-05	kg
Sodium	1.30E-06	kg
Sulfur dioxide	2.02E-04	kg
Toluene	3.00E-07	kg
Zinc	3.00E-07	kg
Waste to treatment		
Disposal, sed mineral oil, 10% water, to hazardous waste incineration/CH	3.28E-06	kg
Treatment, sewage, to wastewater treatment, class 2/CH	7.87E-07	m3
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH	3.28E-06	kg
Disposal, wood ash mixture, pure, 0% water, to landfarming/CH	1.36E-04	kg
Disposal, wood ash mixture, pure, 0% water, to municipal incineration/CH	1.36E-04	kg
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH	2.72E-04	kg

* (A) indicated emission data for NO_x, $PM_{2.5}$ and SO_2 from Alstom; three different cases for wood transport are modelled: 25 km by truck, 1000 km by barge and train.

** Datasets used for wood transport by train and barge: “Transport, freight, rail/RER” and “Transport, barge/RER”.

*** Specific emission data from Alstom.

Table 3.10 LCI data of the wood power plant operation, alternative B.

	wood chips, burned in wood power plant 20 MW (B) (wood transport: truck, 25km) *	MJ
Materials/fuels		
Ammonia, liquid, at regional storehouse/CH	8.20E-09	kg
Chlorine, liquid, production mix, at plant/RER	3.28E-07	kg
Sodium chloride, powder, at plant/RER	4.10E-06	kg
Chemicals organic, at plant/GLO	5.74E-06	kg
Lubricating oil, at plant/RER	3.28E-06	kg
Transport, lorry 3.5-20t, fleet average/CH **	3.15E-03	tkm
Water, decarbonised, at plant/RER	7.87E-04	kg
Wood chips, mixed, =120%, at forest/RER	3.03E-04	m3
Wood combustion power plant 20 MW	4.96E-11	p
Emissions to air		
Acetaldehyde	6.10E-08	kg
Ammonia	1.74E-06	kg
Arsenic	1.00E-09	kg
Benzene	9.10E-07	kg
Benzene, ethyl-	3.00E-08	kg
Benzene, hexachloro-	7.20E-15	kg
Benzo(a)pyrene	5.00E-10	kg
Bromine	6.00E-08	kg
Cadmium	7.00E-10	kg
Calcium	5.85E-06	kg
Carbon dioxide, biogenic	1.04E-01	kg
Carbon monoxide, biogenic	7.00E-06	kg
Chlorine	1.80E-07	kg
Chromium	3.96E-09	kg
Chromium VI	4.00E-11	kg
Copper	2.20E-08	kg
Dinitrogen monoxide	2.30E-06	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	3.10E-14	kg
Fluorine	5.00E-08	kg
Formaldehyde	1.30E-07	kg
Heat, waste	9.87E-01	MJ
Hydrocarbons, aliphatic, alkanes, unspecified	9.10E-07	kg
Hydrocarbons, aliphatic, unsaturated	3.10E-06	kg
Lead	2.49E-08	kg
Magnesium	3.61E-07	kg
Manganese	1.71E-07	kg
Mercury	3.00E-10	kg
Methane, biogenic	4.34E-07	kg
m-Xylene	1.20E-07	kg
Nickel	6.00E-09	kg
Nitrogen oxides ***	8.80E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	6.10E-07	kg
PAH, polycyclic aromatic hydrocarbons	1.10E-08	kg
Particulates, < 2.5 µm ***	4.49E-05	kg
Phenol, pentachloro-	8.10E-12	kg
Phosphorus	3.00E-07	kg
Potassium	2.34E-05	kg
Sodium	1.30E-06	kg
Sulfur dioxide ***	2.49E-06	kg
Toluene	3.00E-07	kg
Zinc	3.00E-07	kg
Waste to treatment		
Disposal, sed mineral oil, 10% water, to hazardous waste incineration/CH	3.28E-06	kg
Treatment, sewage, to wastewater treatment, class 2/CH	7.87E-07	m3
Disposal, municipal solid waste, 22.9% water, to municipal incineration/CH	3.28E-06	kg
Disposal, wood ash mixture, pure, 0% water, to landfarming/CH	1.36E-04	kg
Disposal, wood ash mixture, pure, 0% water, to municipal incineration/CH	1.36E-04	kg
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH	2.72E-04	kg

* (B) indicated emission data for NO_x, $PM_{2.5}$ and SO_2 after (Bauer 2007); three different cases for wood transport are modelled: 25 km by truck, 1000 km by barge and train.

** Datasets used for wood transport by train and barge: "Transport, freight, rail/RER" and "Transport, barge/RER".

*** Emission data after (Bauer 2007).

Table 3.11 LCI data of the natural gas and SNG power plant operation.

	Natural gas from Germany*, burned in combined cycle plant, BAT	MJ
Materials/fuels		
Hydrochloric acid, 30% in H2O, at plant/RER	2.50E-06	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER	2.00E-06	kg
Natural gas from Germany, high pressure, at consumer **	1.00E+00	MJ
Water, decarbonised, at plant/RER	5.00E-01	kg
Gas combined cycle power plant, 400MWe/RER/I	5.14E-12	p
Emissions to air		
Acenaphthene	7.93E-13	kg
Acetaldehyde	8.00E-10	kg
Acetic acid	1.21E-07	kg
Benzene	9.26E-10	kg
Benzo(a)pyrene	5.29E-13	kg
Butane	9.26E-07	kg
Carbon dioxide, fossil	5.60E-02	kg
Carbon monoxide, fossil	2.20E-06	kg
Dinitrogen monoxide	1.00E-06	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	2.90E-17	kg
Ethane	1.37E-06	kg
Formaldehyde	3.31E-08	kg
Heat, waste	5.25E-01	MJ
Hexane	7.93E-07	kg
Mercury	3.00E-11	kg
Methane, fossil	1.00E-06	kg
Nitrogen oxides	2.55E-05	kg
PAH, polycyclic aromatic hydrocarbons	8.00E-09	kg
Particulates, < 2.5 µm	5.00E-07	kg
Pentane	1.15E-06	kg
Propane	7.05E-07	kg
Propionic acid	1.60E-08	kg
Sulfur dioxide	5.00E-07	kg
Toluene	1.50E-09	kg
Waste to treatment		
Disposal, residue from cooling tower, 30% water, to sanitary landfill/CH	1.00E-06	kg

* Modelled for natural gas supply from Germany, The Netherlands, UK, Norway, Russia, Algeria, and Nigeria with identical emission data.

** Specifically modelled for the considered production regions for natural gas Germany, The Netherlands, UK, Norway, Russia, Algeria, and Nigeria taking into account pipeline and LNG gas transport; alternatively modelled with SNG supply.

3.3.1 Infrastructure

Material and energy consumption for the construction as well as disposal of the power plant infrastructure are modelled in a simplified way and can be regarded as approximate accounting of material and energy demand based on existing sources (Bauer et al. 2008a, Dones et al. 2004, 2007). The available data are either directly used (if applicable), or used for extrapolations reflecting the actual power plant technologies in focus of this assessment. This approximate modelling is justified by the small contributions of infrastructure to cumulative environmental burdens per kWh electricity (see chapter 4).

Table 3.12 through Table 3.20 show selected datasets of the power plant infrastructure as modelled in this study.

Table 3.12 LCI data for the construction of the 400 MW_{el} hard coal power plant, based on (Bauer et al. 2008a)[8].

	construction, hard coal power plant 400 MW	
Resources		
Transformation, fromnknown	4.00E+04	m2
Transformation, to industrial area	2.81E+04	m2
Transformation, to traffic area, road network	1.20E+04	m2
Occupation, industrial area	9.82E+05	m2a
Occupation, construction site	1.61E+05	m2a
Occupation, traffic area, road network	4.21E+05	m2a
Materials/fuels		
Concrete, normal, at plant/CH	9.49E+04	m3
Reinforcing steel, at plant/RER	7.13E+06	kg
Reinforcing steel, at plant/RER	2.87E+06	kg
Steel, low-alloyed, at plant/RER	6.04E+06	kg
Chromium steel 18/8, at plant/RER	1.64E+07	kg
Steel, electric,n- and low-alloyed, at plant/RER	2.42E+05	kg
Building, multi-storey/RER/I	1.73E+04	m3
Aluminium, primary, at plant/RER	8.89E+05	kg
Aluminium, secondary, from new scrap, at plant/RER	1.05E+05	kg
Aluminium, secondary, from old scrap, at plant/RER	5.24E+04	kg
Copper, at regional storage/RER	3.08E+05	kg
Brass, at plant/CH	1.08E+05	kg
Zinc, primary, at regional storage/RER	4.62E+04	kg
Lead, at regional storage/RER	3.08E+04	kg
Bitumen, at refinery/RER	1.47E+05	kg
Rock wool, at plant/CH	1.73E+06	kg
Polyvinylchloride, at regional storage/RER	5.65E+05	kg
Polyvinylchloride, at regional storage/RER	2.42E+05	kg
Glass fibre, at plant/RER	2.42E+05	kg
Polyethylene, HDPE, granulate, at plant/RER	6.93E+04	kg
Polypropylene, granulate, at plant/RER	3.47E+04	kg
Styrene-acrylonitrile copolymer, SAN, at plant/RER	1.16E+04	kg
Flat glass,ncoated, at plant/RER	1.17E+04	kg
Glued laminated timber, outdoorse, at plant/RER	3.37E+00	m3
Cast iron, at plant/RER	4.35E+05	kg
Epoxy resin, liquid, at plant/RER	9.17E+04	kg
Lubricating oil, at plant/RER	3.84E+05	kg
Ceramic tiles, at regional storage/CH	1.74E+05	kg
Synthetic rubber, at plant/RER	5.26E+04	kg
Electricity, medium voltage, productionCTE, at grid/UCTE	1.31E+07	kWh
Electricity, medium voltage, production CENTREL, at grid/CENTREL	1.78E+06	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER	2.26E+08	MJ
Transport, lorry >16t, fleet average/RER	4.38E+06	tkm
Transport, freight, rail/RER	1.18E+07	tkm
Emissions to air		
Heat, waste	5.35E+07	MJ

[8] The original dataset of a state-of-the-art hard coal power plant with a capacity of 350 MW_{el} in (Bauer et al. 2008) is scaled up with a factor of 1.1.

Table 3.13 LCI data for the construction of the 800 MW_{el} hard coal power plant after (Bauer et al. 2008a).

	construction, hard coal power plant 800 MW	
Resources		
Transformation, fromnknown	8.33E+04	m2
Transformation, to industrial area	5.83E+04	m2
Transformation, to traffic area, road network	2.50E+04	m2
Occupation, industrial area	2.04E+06	m2a
Occupation, construction site	3.33E+05	m2a
Occupation, traffic area, road network	8.75E+05	m2a
Materials/fuels		
Concrete, normal, at plant/CH	1.59E+05	m3
Reinforcing steel, at plant/RER	1.29E+07	kg
Reinforcing steel, at plant/RER	5.18E+06	kg
Steel, low-alloyed, at plant/RER	1.09E+07	kg
Chromium steel 18/8, at plant/RER	2.97E+07	kg
Steel, electric,n- and low-alloyed, at plant/RER	4.37E+05	kg
Building, multi-storey/RER/I	3.12E+04	m3
Aluminium, primary, at plant/RER	1.61E+06	kg
Aluminium, secondary, from new scrap, at plant/RER	1.89E+05	kg
Aluminium, secondary, from old scrap, at plant/RER	9.45E+04	kg
Copper, at regional storage/RER	5.56E+05	kg
Brass, at plant/CH	1.94E+05	kg
Zinc, primary, at regional storage/RER	8.33E+04	kg
Lead, at regional storage/RER	5.56E+04	kg
Bitumen, at refinery/RER	2.67E+05	kg
Rock wool, at plant/CH	3.13E+06	kg
Polyvinylchloride, at regional storage/RER	1.02E+06	kg
Polyvinylchloride, at regional storage/RER	4.38E+05	kg
Glass fibre, at plant/RER	4.38E+05	kg
Polyethylene, HDPE, granulate, at plant/RER	1.25E+05	kg
Polypropylene, granulate, at plant/RER	6.26E+04	kg
Styrene-acrylonitrile copolymer, SAN, at plant/RER	2.09E+04	kg
Flat glass,ncoated, at plant/RER	2.11E+04	kg
Glued laminated timber, outdoorse, at plant/RER	6.08E+00	m3
Cast iron, at plant/RER	7.85E+05	kg
Epoxy resin, liquid, at plant/RER	1.66E+05	kg
Lubricating oil, at plant/RER	6.94E+05	kg
Ceramic tiles, at regional storage/CH	3.13E+05	kg
Synthetic rubber, at plant/RER	9.49E+04	kg
Electricity, medium voltage, productionCTE, at grid/UCTE	2.36E+07	kWh
Electricity, medium voltage, production CENTREL, at grid/CENTREL	3.22E+06	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER	4.06E+08	MJ
Transport, lorry >16t, fleet average/RER	7.90E+06	tkm
Transport, freight, rail/RER	2.12E+07	tkm
Emissions to air		
Heat, waste	9.66E+07	MJ

Table 3.14 LCI data for the dismantling of the 400 MW_{el} hard coal power plant, based on (Bauer et al. 2008a)[9].

	dismantling, hard coal power plant 400 MW	
Disposal, building, concrete, not reinforced, to sorting plant/CH	2.26E+08	kg
Disposal, building, reinforcement steel, to sorting plant/CH	7.13E+06	kg
Disposal, building, bitumen sheet, to final disposal/CH	1.47E+05	kg
Disposal, building, mineral wool, to sorting plant/CH	1.73E+06	kg
Disposal, building, polyvinylchloride products, to final disposal/CH	5.65E+05	kg
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH	2.42E+05	kg
Disposal, building, mineral wool, to sorting plant/CH	2.42E+05	kg
Disposal, building, polyethylene/polypropylene products, to final disposal/CH	1.16E+05	kg
Disposal, building, glass sheet, to sorting plant/CH	1.17E+04	kg
Disposal, building, waste wood, ntreated, to final disposal/CH	3.37E+00	kg
Disposal, building, emulsion paint remains, to final disposal/CH	9.17E+04	kg
Disposal, sed mineral oil, 10% water, to hazardous waste incineration/CH	3.84E+05	kg
Disposal, inert waste, 5% water, to inert material landfill/CH	1.74E+05	kg
Disposal, rubber, nspecified, 0% water, to municipal incineration/CH	5.26E+04	kg

Table 3.15 LCI data for the dismantling of the 800 MW_{el} hard coal power plant after (Bauer et al. 2008a).

	dismantling, hard coal power plant 800 MW	
Disposal, building, concrete, not reinforced, to sorting plant/CH	3.79E+08	kg
Disposal, building, reinforcement steel, to sorting plant/CH	1.29E+07	kg
Disposal, building, bitumen sheet, to final disposal/CH	2.67E+05	kg
Disposal, building, mineral wool, to sorting plant/CH	3.13E+06	kg
Disposal, building, polyvinylchloride products, to final disposal/CH	1.02E+06	kg
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH	4.38E+05	kg
Disposal, building, mineral wool, to sorting plant/CH	4.38E+05	kg
Disposal, building, polyethylene/polypropylene products, to final disposal/CH	2.09E+05	kg
Disposal, building, glass sheet, to sorting plant/CH	2.11E+04	kg
Disposal, building, waste wood,ntreated, to final disposal/CH	6.08E+00	kg
Disposal, building, emulsion paint remains, to final disposal/CH	1.66E+05	kg
Disposal,sed mineral oil, 10% water, to hazardous waste incineration/CH	6.94E+05	kg
Disposal, inert waste, 5% water, to inert material landfill/CH	3.13E+05	kg
Disposal, rubber,nspecified, 0% water, to municipal incineration/CH	9.49E+04	kg

Table 3.16 LCI data for the construction and dismantling[10] of the 400 MW_{el} natural gas/SNG power plant (Faist Emmenegger et al. 2004).

	gas combined cycle power plant, 400MW	
Transformation, from unknown	4.00E+04	m2
Transformation, to industrial area	4.00E+04	m2
Occupation, industrial area	1.44E+06	m2a
Materials/fuels		
Aluminium, production mix, at plant/RER	4.40E+05	kg
Concrete, normal, at plant/CH	6.00E+03	m3
Copper, at regional storage/RER	4.40E+05	kg
Rock wool, packed, at plant/CH	6.60E+05	kg
Polyethylene, LDPE, granulate, at plant/RER	1.30E+06	kg
Chromium steel 18/8, at plant/RER	1.80E+06	kg
Reinforcing steel, at plant/RER	8.80E+06	kg
Nickel, 99.5%, at plant/GLO	6.30E+03	kg
Chromium, at regional storage/RER	9.76E+02	kg
Cobalt, at plant/GLO	7.20E+02	kg
Ceramic tiles, at regional storage/CH	4.20E+03	kg
Diesel, burned in building machine/GLO	1.48E+08	MJ
Heavy fuel oil, burned in industrial furnace 1MW, non-modulating/RER	1.48E+08	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE	3.02E+06	kWh
Emissions to air		
Heat, waste	1.09E+07	MJ

[9] The original dataset of a state-of-the-art hard coal power plant with a capacity of 350 MW_{el} in (Bauer et al. 2008) is scaled up with a factor of 1.1.

[10] In this case dismantling of the power plant is not modelled with a specific dataset, but the energy demand for dismantling is included in the general infrastructure dataset. Natural gas and SNG are burned in the same power plant, both as single fuels and as co-combustion fuels.

Table 3.17 LCI data for the construction of the 950 MW$_{el}$ lignite power plant after (Bauer et al. 2008a).

	construction, lignite power plant 950 MW	
Resources		
Transformation, fromnknown	1.34E+05	m2
Transformation, to industrial area	9.38E+04	m2
Transformation, to traffic area, road network	4.02E+04	m2
Occupation, industrial area	3.28E+06	m2a
Occupation, traffic area, road network	1.41E+06	m2a
Materials/fuels		
Concrete, normal, at plant/CH	1.83E+05	m3
Cast iron, at plant/RER	1.34E+06	kg
Steel, low-alloyed, at plant/RER	7.00E+07	kg
Reinforcing steel, at plant/RER	5.91E+07	kg
Chromium steel 18/8, at plant/RER	7.78E+06	kg
Aluminium, production mix, at plant/RER	3.34E+06	kg
Brass, at plant/CH	3.43E+05	kg
Copper, at regional storage/RER	9.81E+05	kg
Lead, at regional storage/RER	9.81E+04	kg
Zinc, primary, at regional storage/RER	1.19E+05	kg
Polyethylene, HDPE, granulate, at plant/RER	2.20E+06	kg
Rock wool, at plant/CH	1.70E+06	kg
Lubricating oil, at plant/RER	8.96E+05	kg
Flat glass,ncoated, at plant/RER	2.30E+04	kg
Brick, at plant/RER	1.61E+07	kg
Gravel,nspecified, at mine/CH	1.90E+07	kg
Sand, at mine/CH	1.62E+08	kg
Bitumen, at refinery/RER	6.59E+05	kg
Sanitary ceramics, at regional storage/CH	3.00E+04	kg
Plywood, outdoorse, at plant/RER	5.75E+03	m3
Electricity, medium voltage, productionCTE, at grid/UCTE	3.96E+07	kWh
Electricity, medium voltage, production CENTREL, at grid/CENTREL	5.40E+06	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER	2.53E+08	MJ
Transport, lorry >16t, fleet average/RER	4.75E+07	tkm
Transport, freight, rail/RER	3.18E+07	tkm
Emissions to air		
Heat, waste	1.62E+08	MJ

Table 3.18 LCI data for the dismantling of the 950 MW$_{el}$ lignite power plant after (Bauer et al. 2008a).

	dismantling, lignite power plant 950 MW	
Disposal, building, concrete, not reinforced, to sorting plant/CH	4.56E+08	kg
Disposal, building, reinforcement steel, to sorting plant/CH	1.16E+08	kg
Disposal, building, polyethylene/polypropylene products, to final disposal/CH	2.20E+06	kg
Disposal, building, mineral wool, to sorting plant/CH	1.70E+06	kg
Disposal,sed mineral oil, 10% water, to hazardous waste incineration/CH	8.96E+05	kg
Disposal, building, glass sheet, to sorting plant/CH	2.30E+04	kg
Disposal, building, brick, to sorting plant/CH	1.61E+07	kg
Disposal, building, bitumen sheet, to final disposal/CH	6.59E+05	kg
Disposal, building, waste wood,ntreated, to final disposal/CH	4.48E+06	kg

Table 3.19 LCI data for the construction of the 400 MW_{el} hard coal/wood co-firing power plant after (Bauer et al. 2008a)[11].

	construction, hard coal/wood co-firing power plant 400 MW	
Resources		
Transformation, from unknown	6.25E+04	m2
Transformation, to industrial area	4.37E+04	m2
Transformation, to traffic area, road network	1.87E+04	m2
Occupation, industrial area	1.53E+06	m2a
Occupation, construction site	2.50E+05	m2a
Occupation, traffic area, road network	6.56E+05	m2a
Materials/fuels		
Concrete, normal, at plant/CH	1.29E+05	m3
Reinforcing steel, at plant/RER	9.65E+06	kg
Reinforcing steel, at plant/RER	3.88E+06	kg
Steel, low-alloyed, at plant/RER	8.18E+06	kg
Chromium steel 18/8, at plant/RER	2.23E+07	kg
Steel, electric,n- and low-alloyed, at plant/RER	3.28E+05	kg
Building, multi-storey/RER/I	2.34E+04	m3
Aluminium, primary, at plant/RER	1.20E+06	kg
Aluminium, secondary, from new scrap, at plant/RER	1.42E+05	kg
Aluminium, secondary, from old scrap, at plant/RER	7.08E+04	kg
Copper, at regional storage/RER	4.17E+05	kg
Brass, at plant/CH	1.46E+05	kg
Zinc, primary, at regional storage/RER	6.25E+04	kg
Lead, at regional storage/RER	4.17E+04	kg
Bitumen, at refinery/RER	2.00E+05	kg
Rock wool, at plant/CH	2.34E+06	kg
Polyvinylchloride, at regional storage/RER	7.66E+05	kg
Polyvinylchloride, at regional storage/RER	3.28E+05	kg
Glass fibre, at plant/RER	3.28E+05	kg
Polyethylene, HDPE, granulate, at plant/RER	9.38E+04	kg
Polypropylene, granulate, at plant/RER	4.69E+04	kg
Styrene-acrylonitrile copolymer, SAN, at plant/RER	1.56E+04	kg
Flat glass,ncoated, at plant/RER	1.58E+04	kg
Glued laminated timber, outdoorse, at plant/RER	4.56E+00	m3
Cast iron, at plant/RER	5.88E+05	kg
Epoxy resin, liquid, at plant/RER	1.24E+05	kg
Lubricating oil, at plant/RER	5.21E+05	kg
Ceramic tiles, at regional storage/CH	2.35E+05	kg
Synthetic rubber, at plant/RER	7.11E+04	kg
Electricity, medium voltage, production UCTE, at grid/UCTE	1.77E+07	kWh
Electricity, medium voltage, production CENTREL, at grid/CENTREL	2.41E+06	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER	3.05E+08	MJ
Transport, lorry >16t, fleet average/RER	5.93E+06	tkm
Transport, freight, rail/RER	1.59E+07	tkm
Emissions to air		
Heat, waste	7.24E+07	MJ

Table 3.20 LCI data for the dismantling of the 400 MW_{el} hard coal/wood co-firing power plant after (Bauer et al. 2008a)[12].

	dismantling, hard coal/wood co-firing power plant 400 MW	
Disposal, building, concrete, not reinforced, to sorting plant/CH	3.06E+08	kg
Disposal, building, reinforcement steel, to sorting plant/CH	9.65E+06	kg
Disposal, building, bitumen sheet, to final disposal/CH	2.00E+05	kg
Disposal, building, mineral wool, to sorting plant/CH	2.34E+06	kg
Disposal, building, polyvinylchloride products, to final disposal/CH	7.66E+05	kg
Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH	3.28E+05	kg
Disposal, building, mineral wool, to sorting plant/CH	3.28E+05	kg
Disposal, building, polyethylene/polypropylene products, to final disposal/CH	1.56E+05	kg
Disposal, building, glass sheet, to sorting plant/CH	1.58E+04	kg
Disposal, building, waste wood,ntreated, to final disposal/CH	4.56E+00	kg
Disposal, building, emulsion paint remains, to final disposal/CH	1.24E+05	kg
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH	5.21E+05	kg
Disposal, inert waste, 5% water, to inert material landfill/CH	2.35E+05	kg
Disposal, rubber,nspecified, 0% water, to municipal incineration/CH	7.11E+04	kg

[11] LCI data for construction of a 600 MW_{el} hard coal power plant have been used as first approximation, reflecting the somewhat more complex infrastructure of a co-firing unit.

[12] LCI data for dismantling of a 600 MW_{el} hard coal power plant have been used as first approximation, reflecting the somewhat more complex infrastructure of a co-firing unit.

The construction and dismantling datasets of the 400 MW hard coal/wood co-firing plant are scaled up with a factor of 1.8 for the modelling of the 800 MW co-firing plant. Construction and dismantling of the 950 MW lignite/wood co-firing plant are modelled by scaling up the 950 MW lignite power plant by a factor of 1.2 taking somehow into account the more complex infrastructure for handling two different fuels. The modelling of construction and dismantling of the 20 MW wood-fired power plant is based in LCI data in (Bauer 2007): the datasets of the 6.4 MW wood-fired combined heat and power plant are scaled up with a factor of 3.

4 LCA results and conclusions

This chapter presents cumulative LCA and LCIA results of the various energy chains analyzed for electricity production, allowing comparison of the environmental performances of these options for power generation. Chapters 4.1 through 4.4 provide the most important findings from this analysis. All results are shown per one kWh of electricity produced at the busbar of the power plant, i.e. transmission and distribution of electricity are not included.

The author is aware of the fact that the given interpretation of results might not answer all questions from the reader. Therefore, all readers are encouraged to contact the author directly in case of open questions.

The evaluation focuses on few selected environmental flows, i.e. the main air pollutants representing the highest burden to human health and the environment:

- Total Greenhouse Gas (GHG) emissions in terms of CO_2-equivalents
- CO_2
- NO_x
- SO_2
- Particulates ($PM_{2.5}$)

Additionally to these specific emissions, Life Cycle Impact Assessment (LCIA) methods as well as calculation of external costs due to air pollution are used to evaluate the environmental performance of the systems analyzed in a more comprehensive way. Among the numerous LCIA methods available, Eco-Indicator 99 (Goedkoop & Spriensma 2000) with its three different weighting schemes ("H, A" – Hierarchist, "E, E" – Egalitarian, "I, I" – Individualist) as the most commonly used in the LCA community has been chosen for this analysis. Due to the aggregation of the impacts of all relevant environmental flows (i.e. emission of pollutants to air, water and soil as well as consumption of energy, non energy and land resources – characterized in so-called impact categories) into one number, LCIA in general allows a comprehensive evaluation of the environmental performance of human activities, in this case electricity production, and user-friendly comparison of different options. However, all available LCIA methods are somehow based on value judgement and the results therefore require careful interpretation. External costs, representing the monetized impacts of air pollution on human health, are calculated based on average European damage factors (Dones et al. 2005), which are shown in Table 4.1.

In general, this assessment shows the importance of fuel supply for the overall evaluation of environmental burdens from electricity production with fossil and biomass fuels. Therefore, not only LCI data for power plant operation, but also for the upstream processes are of high importance for the quality of LCA results and have to be established and used on a country-specific basis to the extent possible.

4.1 Hard coal

Figure 4.1 through Figure 4.5 show the selected environmental burdens from different hard coal chains: the 800 MW reference power plant is supplied with hard coal from various mining regions, which can have a significant effect on cumulative emissions per kWh electricity produced, especially for burdens mainly originating from the upstream chain (i.e. from coal mining and transport). Contributions from the infrastructure of the power plant (i.e. its construction and decommissioning) are negligible for the burdens shown here.

With the exception of the case of coal supply from china, GHG and CO_2 are mainly emitted at the power plant. Mining in China is relatively CO_2 intensive (Figure 4.2) due to uncontrolled coal fires and power supply with small and inefficient coal power plants, also responsible for (relatively) high

SO_2 and particle emissions (Figure 4.4 and Figure 4.5). Additionally, relatively much CH_4 is emitted at Chinese underground coal mines (Figure 4.1). Overseas shipping of coal is primarily responsible for high NO_x emissions and to a smaller extent for SO_2 emissions.

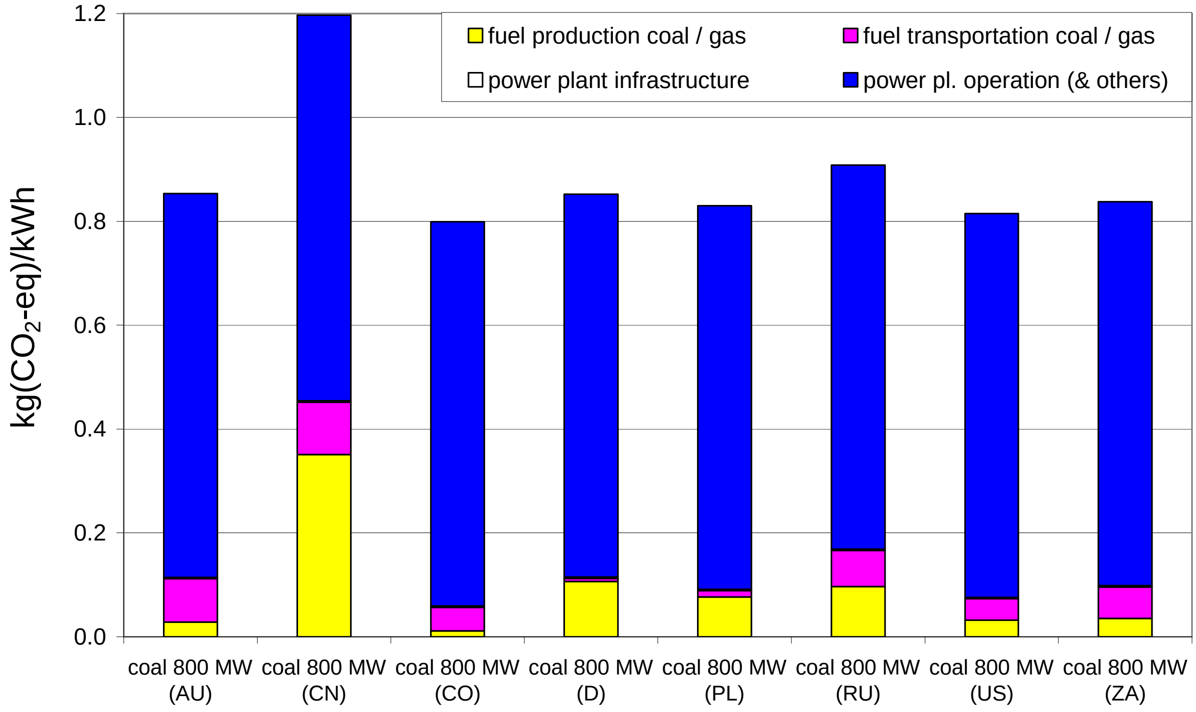

Figure 4.1 Breakdown of GHG emissions from hard coal chains (i.e. hard coal supply from different mining regions).

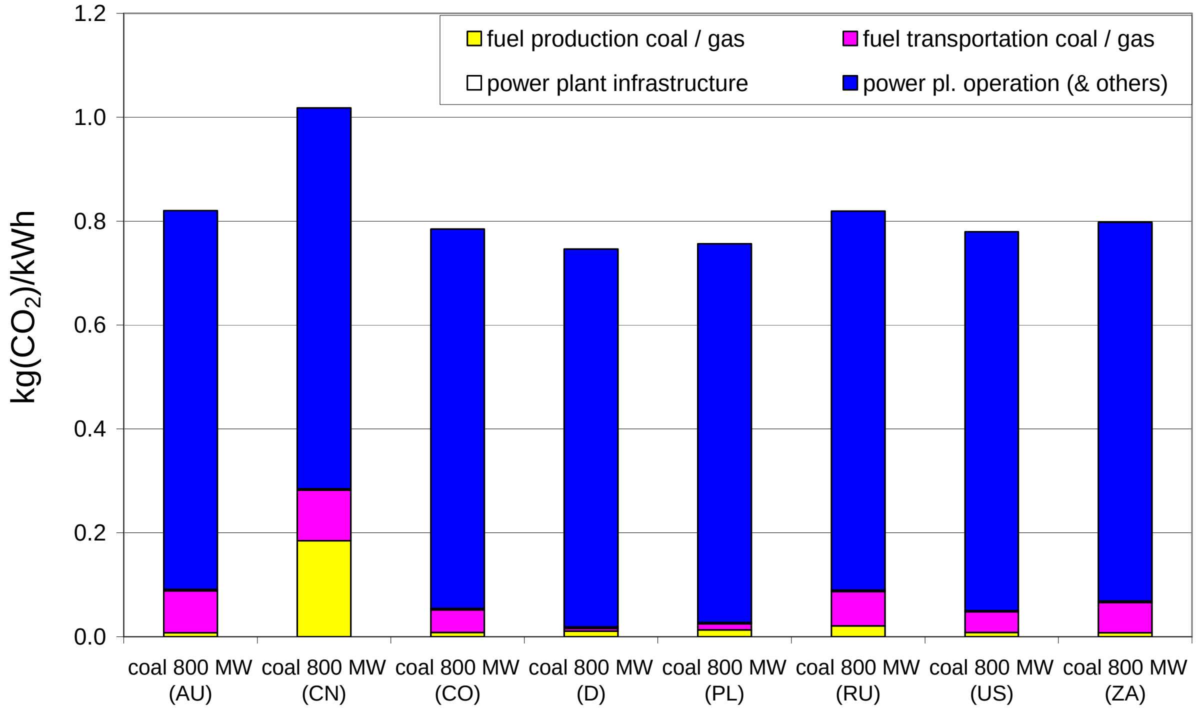

Figure 4.2 Breakdown of CO_2 emissions from hard coal chains (i.e. hard coal supply from different mining regions).

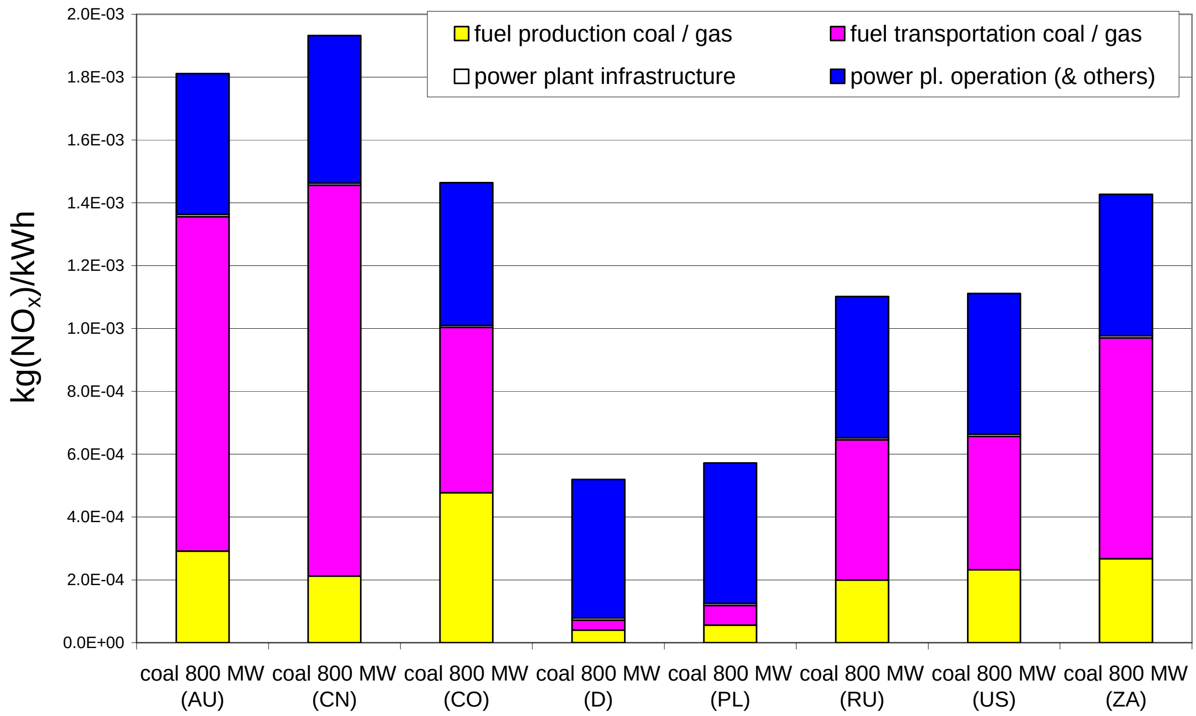

Figure 4.3 Breakdown of NO_x emissions from hard coal chains (i.e. hard coal supply from different mining regions).

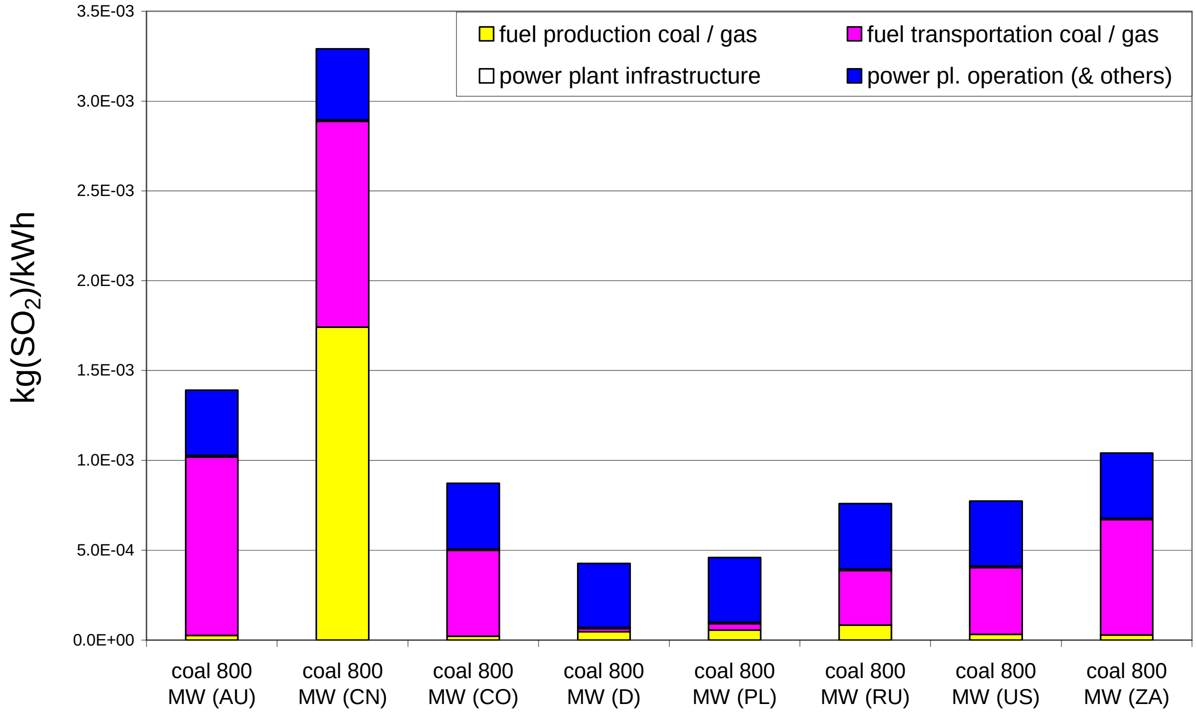

Figure 4.4 Breakdown of SO_2 emissions from hard coal chains (i.e. hard coal supply from different mining regions).

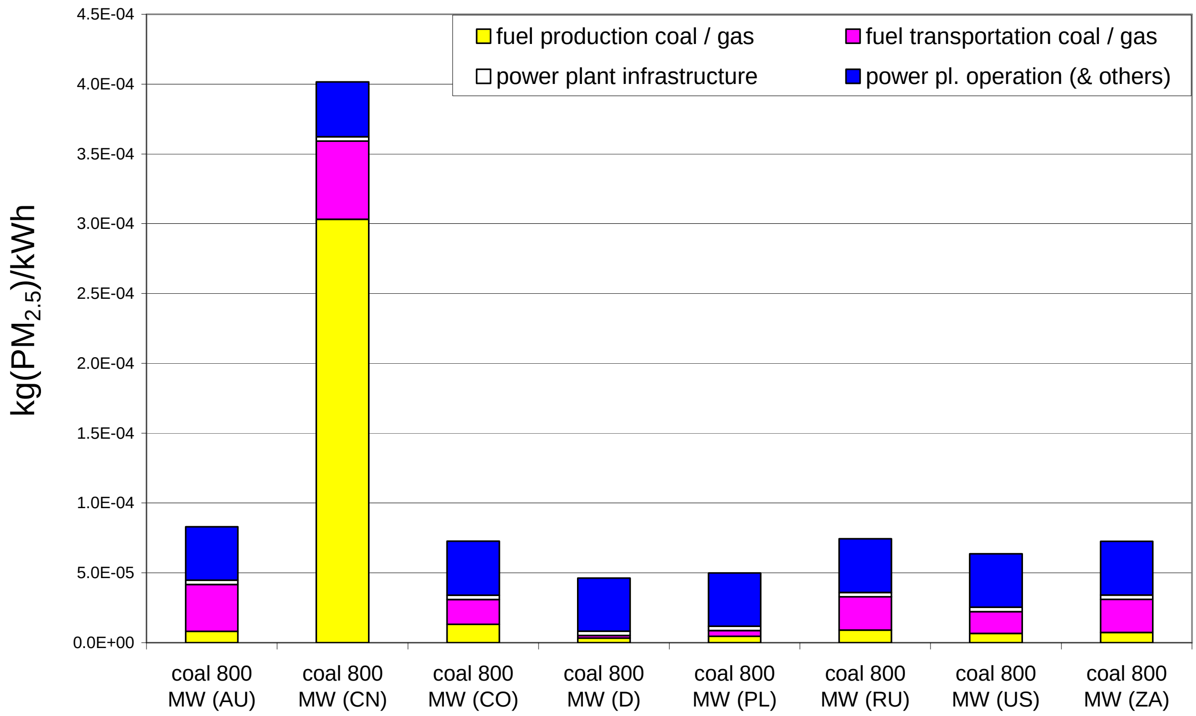

Figure 4.5 Breakdown of $PM_{2.5}$ emissions from hard coal chains (i.e. hard coal supply from different mining regions).

The fact that direct emissions from the power plant are smaller than contributions from the rest of the energy chain for selected environmental burdens allows the conclusion that optimizing the fuel supply chain can be more beneficial for the environment than optimization of the power plants.

The general pattern of the LCIA results is similar for all three Eco-Indicator 99 perspectives (Figure 4.6 through Figure 4.8): electricity production with hard coal import from China causes the highest environmental burdens, mainly due to air pollution with SO_2 and particulates (Figure 4.4 and Figure 4.5). However, contributions of different impact categories to the total scores are different: while the Individualist perspective does not consider the consumption of fossil resources (i.e. mainly coal in this case) as an environmental burden, this impact category is an important factor for the other two categories.

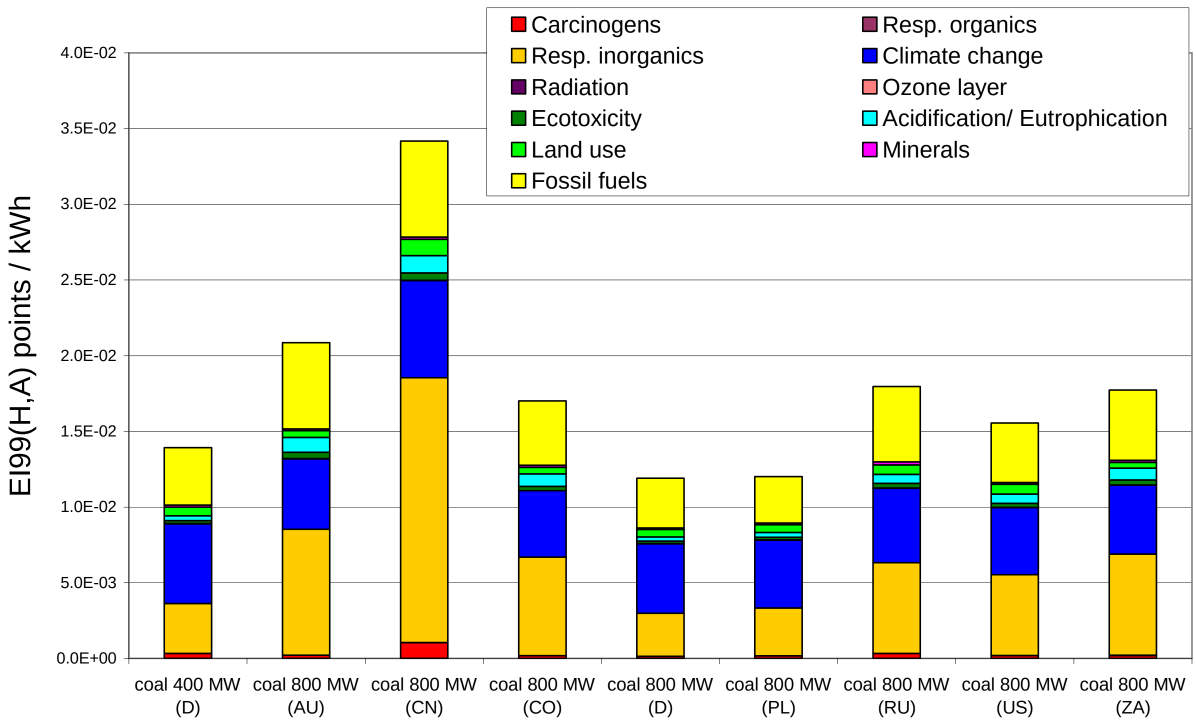

Figure 4.6 Comparison of different hard coal chains (i.e. hard coal supply from different mining regions) based on Eco-Indicator'99 (H, A).

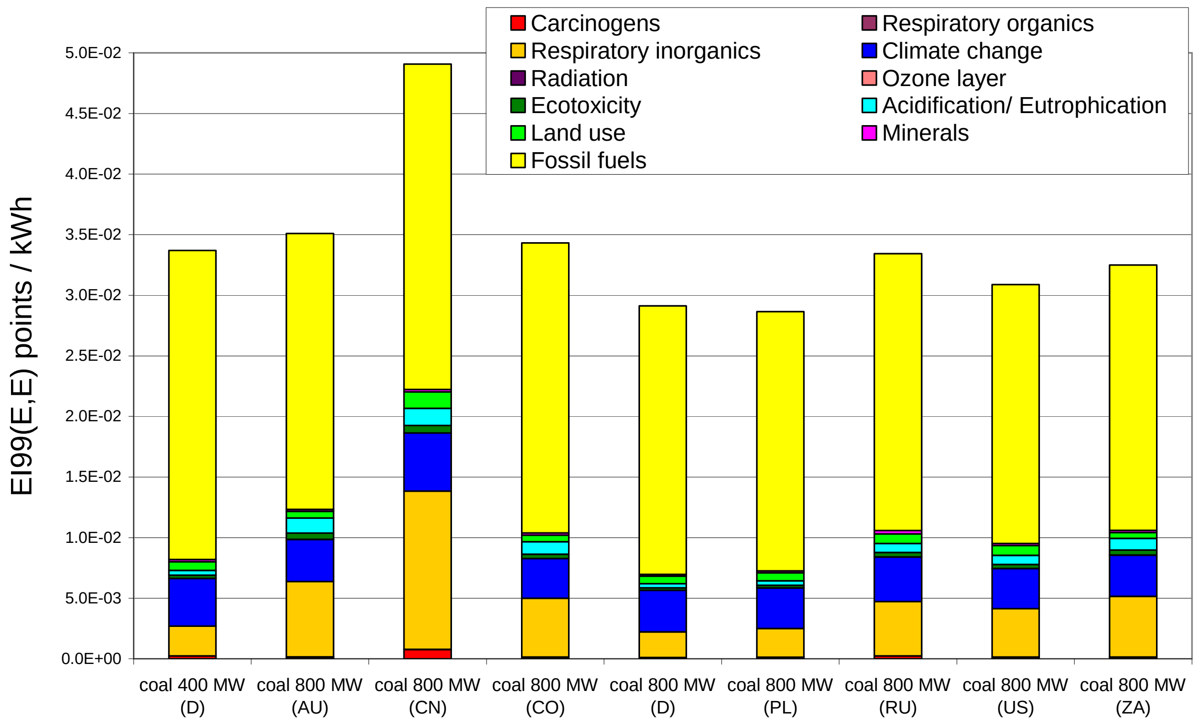

Figure 4.7 Comparison of different hard coal chains (i.e. hard coal supply from different mining regions) based on Eco-Indicator'99 (E, E).

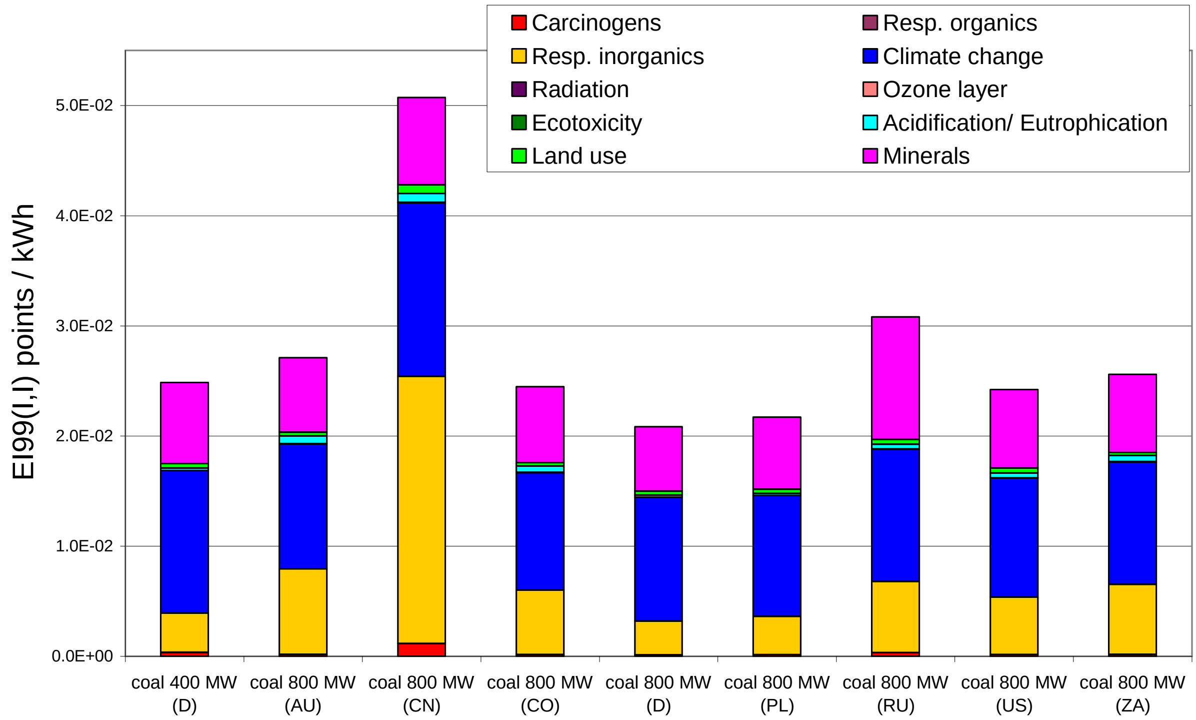

Figure 4.8 Comparison of different hard coal chains (i.e. hard coal supply from different mining regions) based on Eco-Indicator'99 (I, I).

Due to the comparably high emissions of air pollutants at Chinese coal mines, electricity production with hard coal import from China also causes the highest external costs (Figure 4.9). Otherwise, GHG emissions (corresponding to "IPCC GWP 100a") dominate the total external costs. However, it must be noted that a broad range of damage factors for GHG emissions between –3 \$/t(CO_2-eq.) and +95 \$/t(CO_2-eq.) is available in current literature (Klein et al. 2007) and therefore the results are in general afflicted with relatively high uncertainties.

Table 4.1 Monetized damage factors for air pollutants (Dones et al. 2005).

Species	**Damage factor**
	$€_{2000}$ / tonne
Greenhouse Gases (CO_2-eq.)	19
SO_2	2'939
NO_x	2'908
$PM_{2.5}$	19'539
Arsenic	80'000
Cadmium	39'000
Chromium-VI	240'000
Lead	1'600'000
Nickel	3'800
Formaldehyde	120
NMVOC	1'124
Radioactive Emissions	50'000 [$€_{2000}$ / DALY]

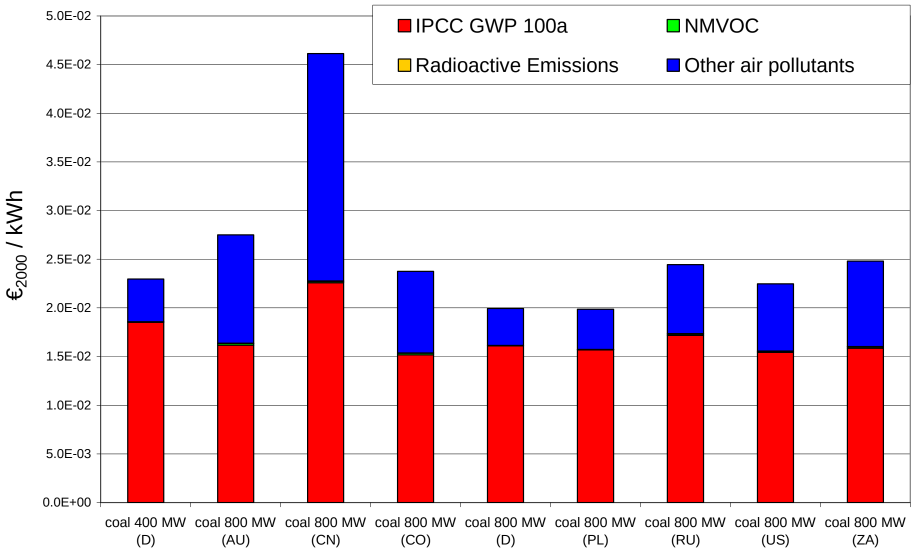

Figure 4.9 Comparison of different hard coal chains (i.e. hard coal supply from different mining regions) based on external costs.

4.2 Wood and co-combustion hard coal/lignite/wood

Figure 4.10 through Figure 4.14 show the selected environmental burdens from different wood, wood/hard coal and wood/lignite co-combustion chains as well as hard coal and lignite chains for comparison. The reference power plants – 20 MW in case of wood, 400 MW and 800 MW in case of hard coal and hard coal/wood co-combustion, and 950 MW in case of lignite and lignite/wood co-combustion (both co-combustion cases with 90%/10% fuel input based on energy input) – are assumed to be supplied with wood chips from central European forestry, hard coal, or lignite, both from German coal mining. Furthermore, three different transport modes and distances for the wood supply of the power plants are differentiated.

While the use of wood as fuel significantly reduces net GHG and CO_2 emissions (during the growth of trees, wood absorbs about the same amount of CO_2 from the atmosphere, which is emitted during its combustion) per kWh electricity production, it can cause higher air pollution compared to coal and lignite chains with sophisticated pollution control at the power plant. The environmental performance of the wood chains highly depends on direct emissions of air pollutants at the power plant, which can vary within relatively wide ranges, depending on power plant and installed pollution control technologies, characteristics of the wood burned, etc.[13] Usually co-combustion in combination with hard coal or lignite in state-of-the-art power plants with high capacities has advantages in terms of efficiency and pollution control compared to smaller wood power plants. Short-distance transport of wood is beneficial in terms of GHG emissions as well as air pollution, but the three different assumed cases for wood supply are for most burdens not decisive in terms of environmental performance of the entire wood (and co-combustion) chains. Compared to pure coal chains, co-firing of wood together with hard coal or lignite results in a slightly better environmental performance of the co-combustion systems assessed in this study, not significantly depending on the transport distance of the wood. Contributions from the infrastructure of the power plant (i.e. its construction and decommissioning) are negligible for the burdens shown here.

[13] In order to take these ranges somehow into account, two sets of data for direct power plant emissions have been used for the 20 MW wood power plant: emission data provided by Alstom – identified as option (A) – and emission data after (Bauer 2007) – identified as option (B).

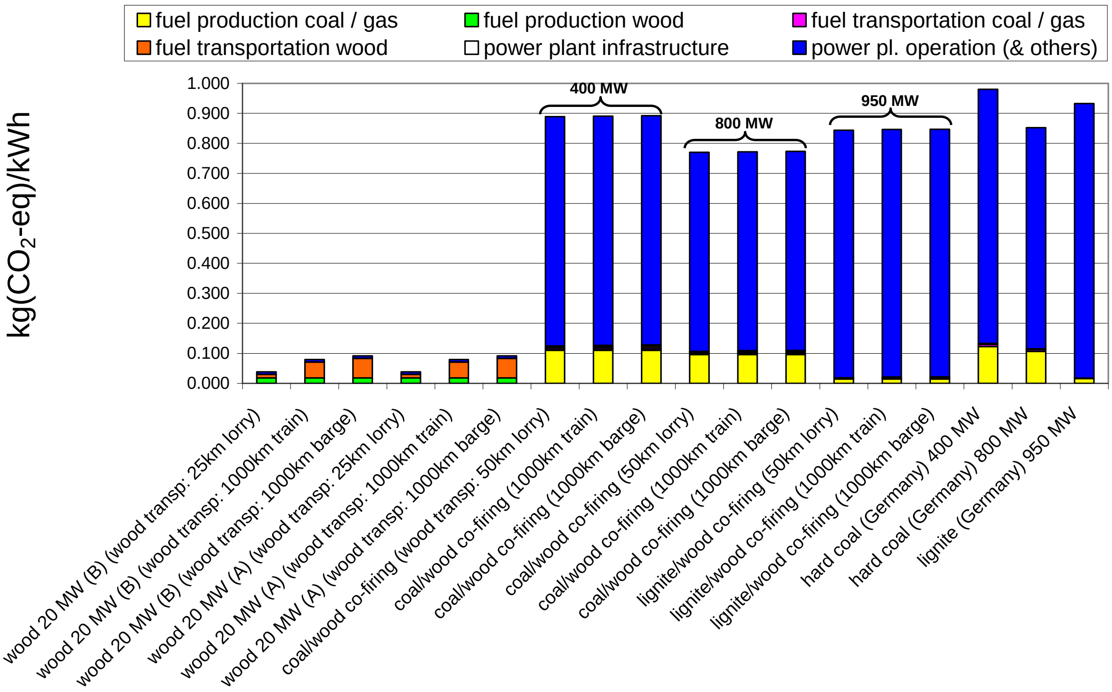

Figure 4.10 **Breakdown of GHG emissions from wood, hard coal, lignite and hard coal/lignite/wood co-combustion chains; (A) refers to emission data from Alstom[14], (B) refers to power plant emission data after (Bauer 2007).**

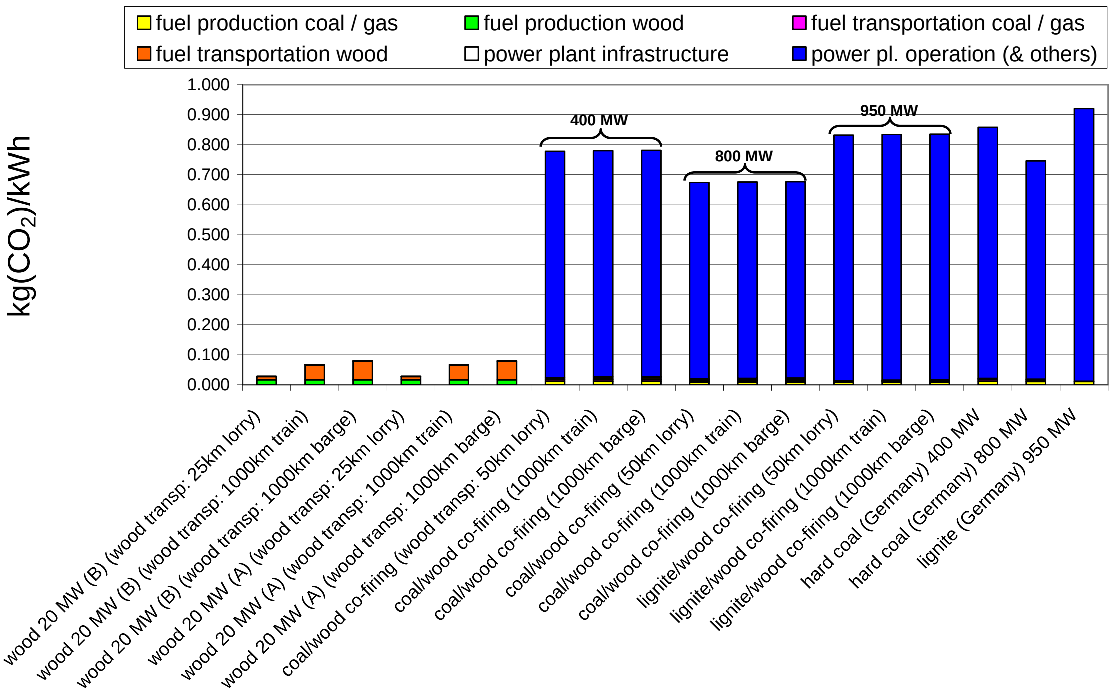

Figure 4.11 **Breakdown of CO_2 emissions from wood, hard coal, lignite and hard coal/lignite/wood co-combustion chains; (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).**

[14] As a result of iterated personal communication and email exchange with Andreas Bögli, Director Strategy, ALSTOM Power Service, between January and April 2008.

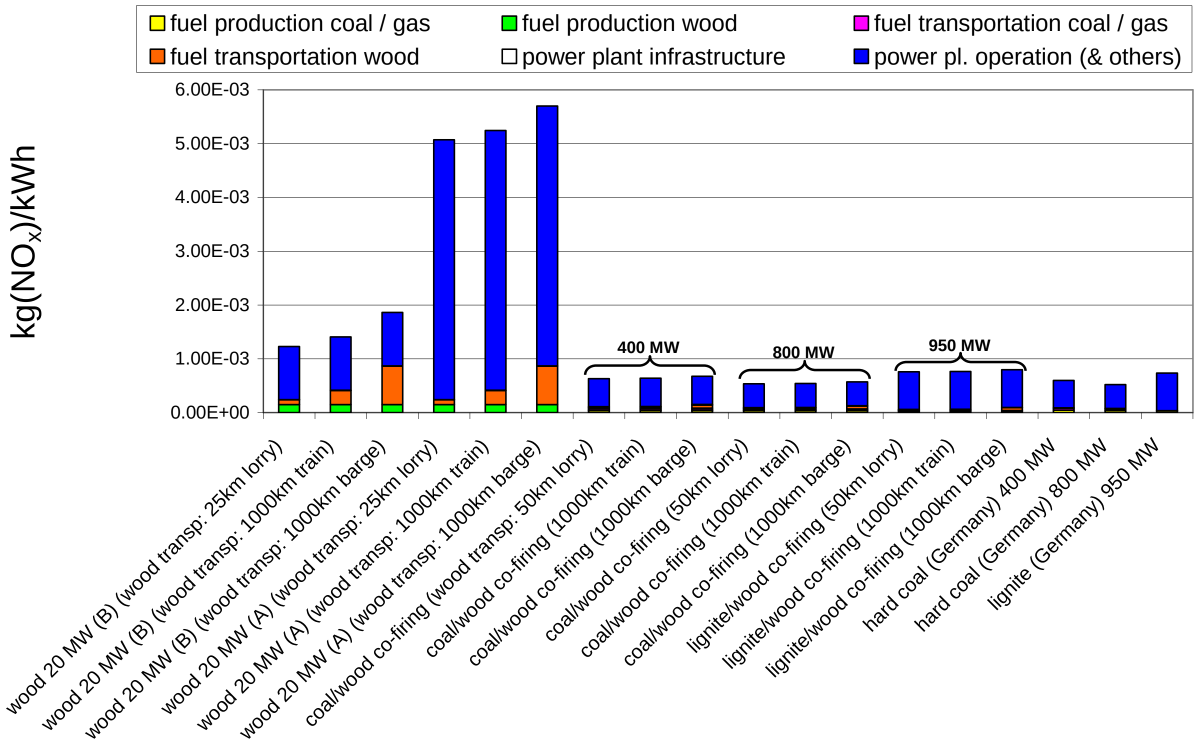

Figure 4.12 Breakdown of NO_x emissions from wood, hard coal, lignite and hard coal/lignite/wood co-combustion chains; (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).

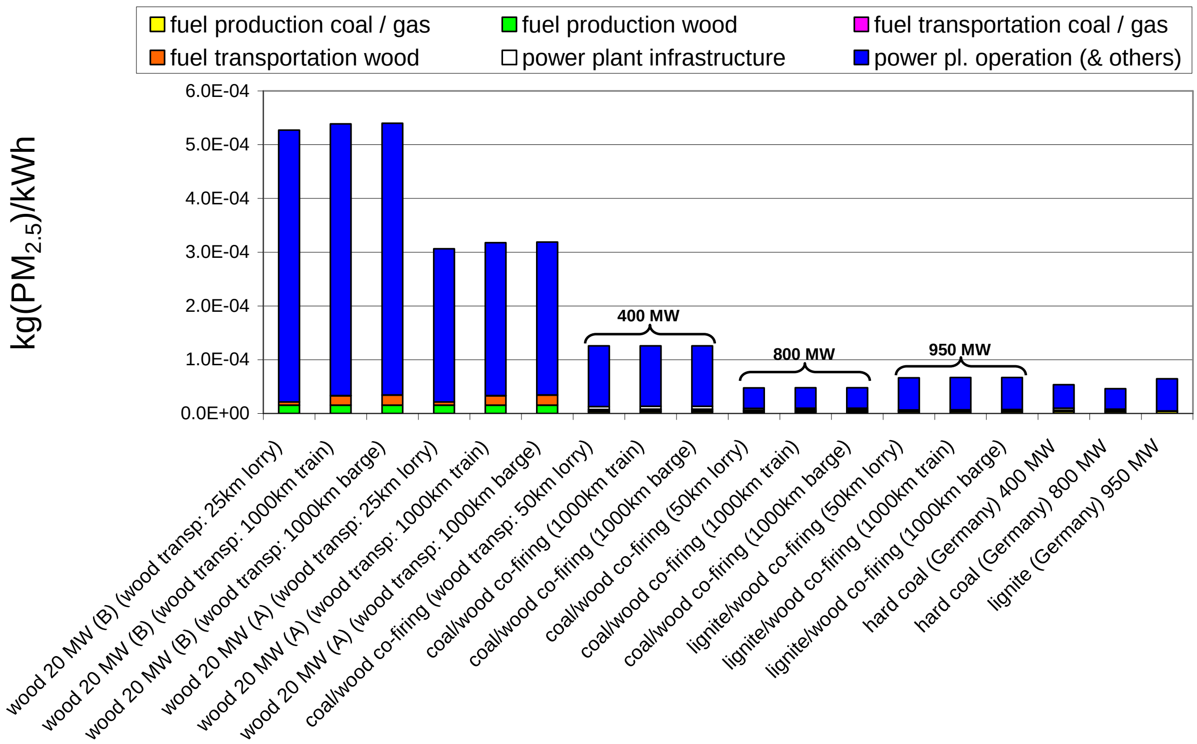

Figure 4.13 Breakdown of $PM_{2.5}$ emissions from wood, hard coal, lignite and hard coal/lignite/wood co-combustion chains; (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).

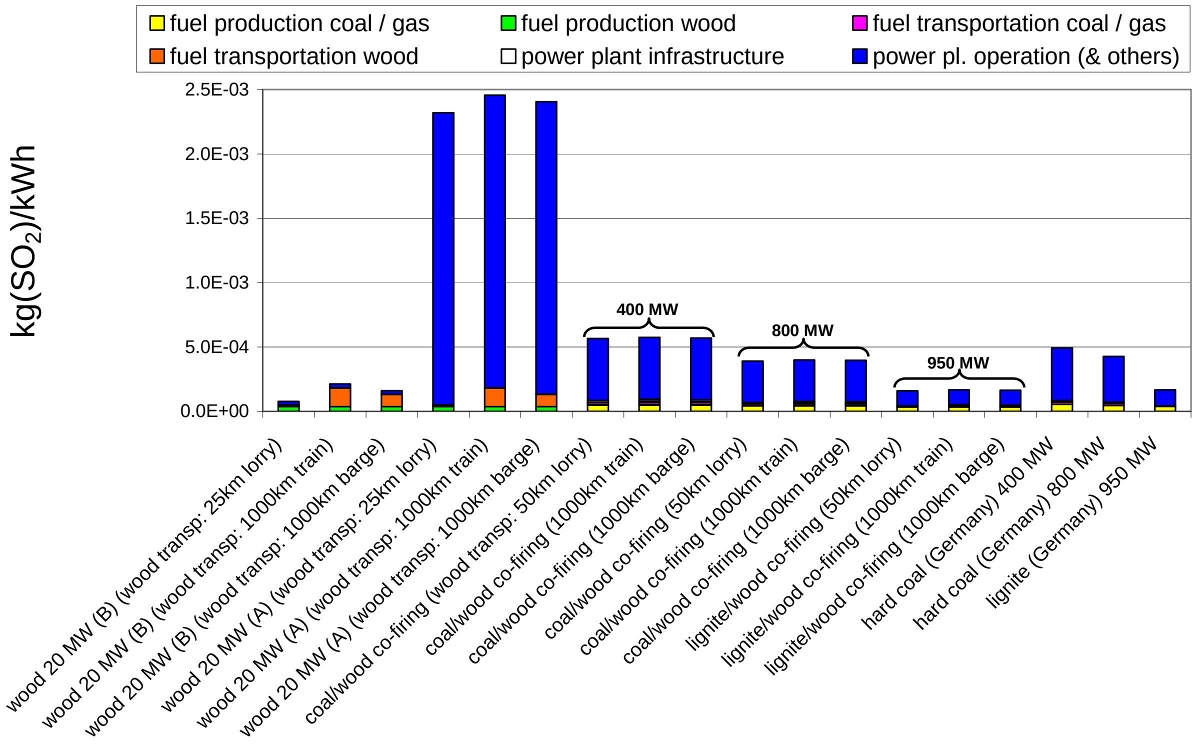

Figure 4.14 Breakdown of SO_2 emissions from wood, hard coal, lignite and hard coal/lignite/wood co-combustion chains; (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).

Figure 4.15 through Figure 4.17 show the LCIA results for the wood, hard coal, lignite, and co-combustion chains – depending on the perspective, the ranking of technologies can change. While aggregation with the (H, A) perspective with its relatively low weighting of hard coal and lignite consumption shows a clear advantage of coal and coal/wood co-combustion compared to wood chains due to their comparably higher emissions of air pollutants (characterized as “Respiratory inorganics”), the consumption of coal compensates the advantages of the fossil chains in terms of lower air pollution using the (E, E) perspective. Application of the (I, I) perspective leads to relatively small differences in the overall environmental performance of wood vs. fossil chains: air pollutants (characterized as “Respiratory inorganics”) dominate the results of wood chains and GHG emissions (characterized as “Climate change”) the results of fossil and co-combustion chains.

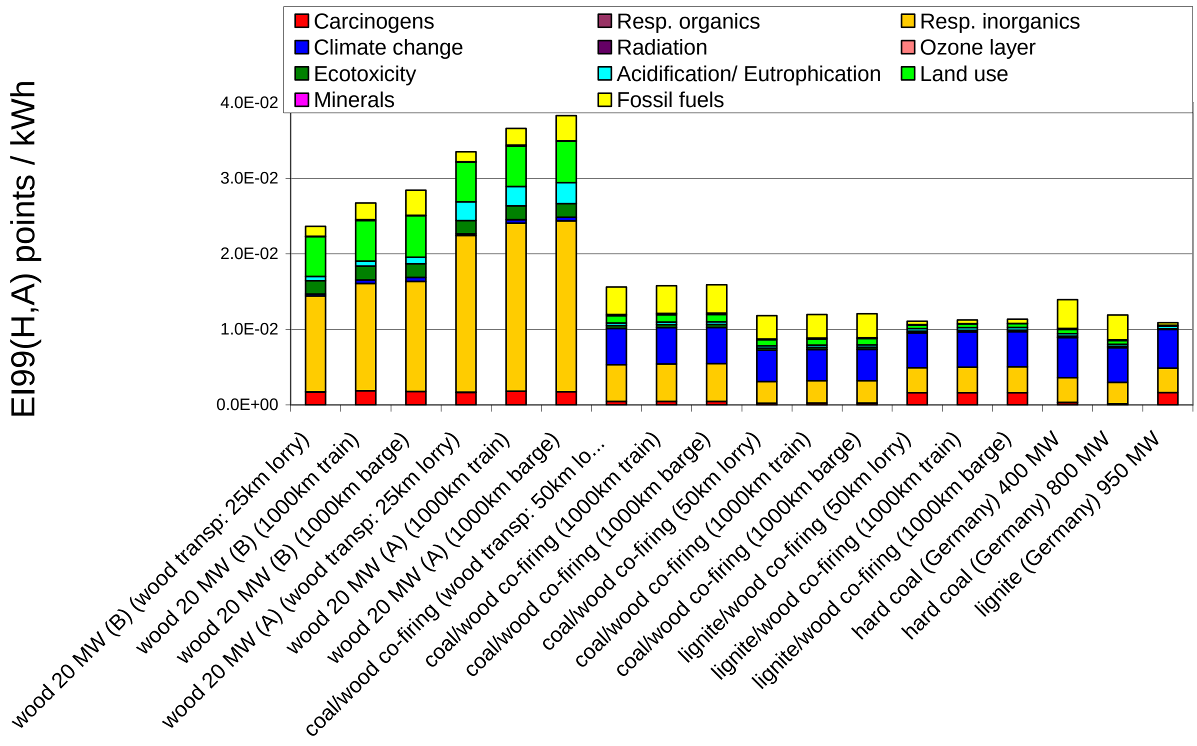

Figure 4.15 **Comparison of wood, hard coal, lignite, hard coal/lignite/wood co-combustion chains based on Eco-Indicator'99 (H, A); (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).**

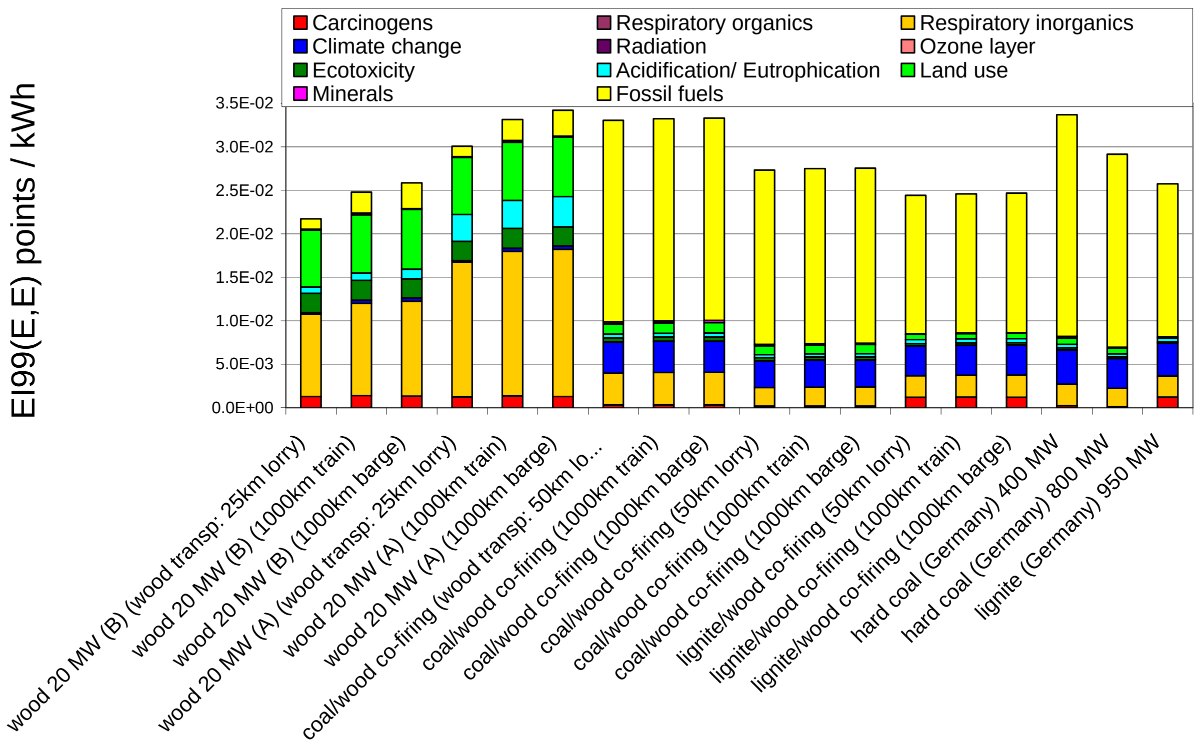

Figure 4.16 **Comparison of wood, hard coal, lignite, hard coal/lignite/wood co-combustion chains based on Eco-Indicator'99 (E, E); (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).**

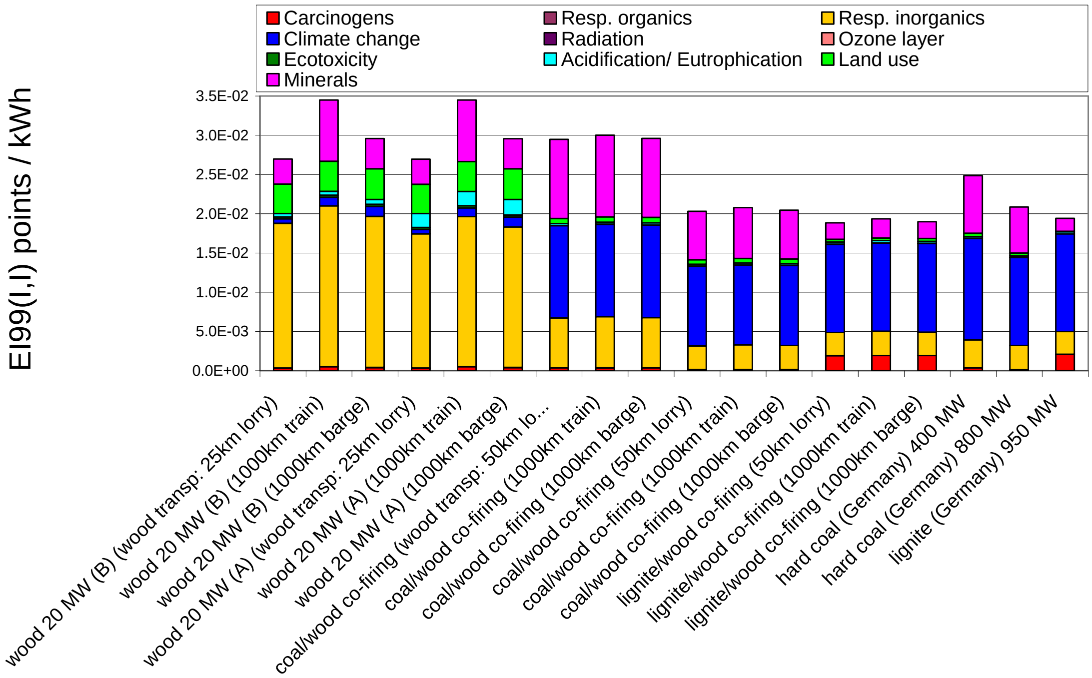

Figure 4.17 Comparison of wood, hard coal, lignite, hard coal/lignite/wood co-combustion chains based on Eco-Indicator'99 (I, I); (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).

Depending on the environmental performance of the wood power plant (i.e. direct emission of air pollutants), external costs of wood chains can be lower than those of fossil and co-combustion chains (Figure 4.18). In general, air pollution dominates the external costs of wood chains, while GHG emissions (i.e. "IPCC GWP") dominate the external costs of fossil and co-combustion chains.

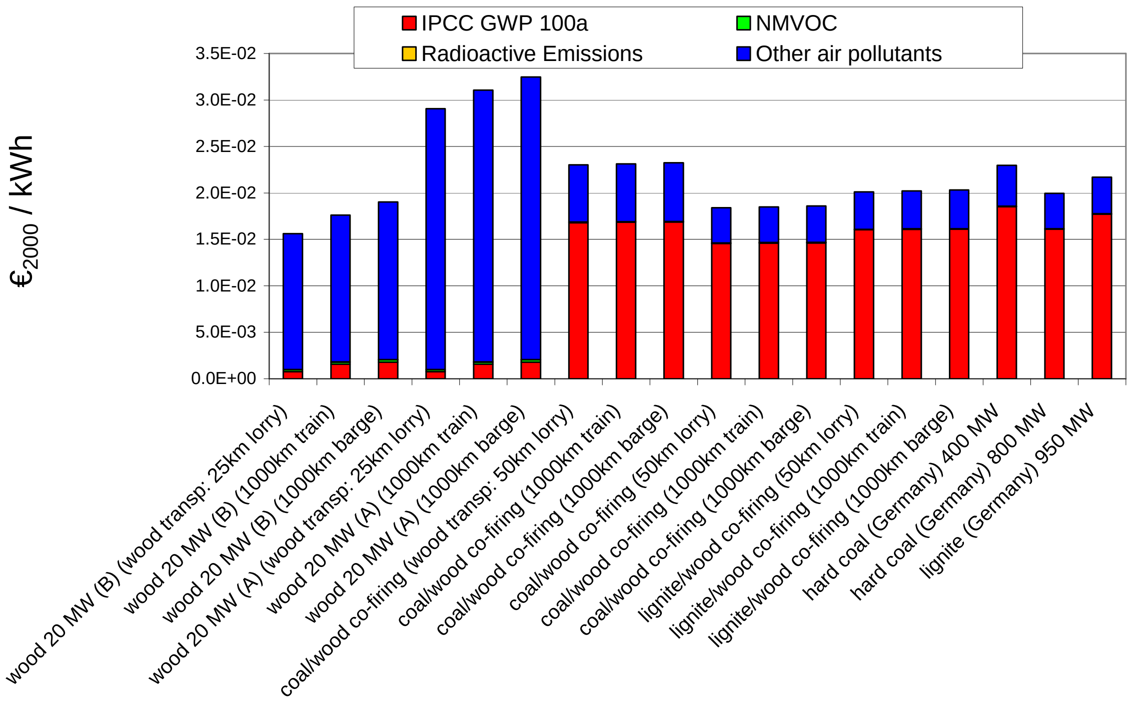

Figure 4.18 Comparison of wood, hard coal, lignite, hard coal/lignite/wood co-combustion chains based on external costs; (A) refers to emission data from Alstom, (B) refers to power plant emission data after (Bauer 2007).

4.3 Natural gas

Figure 4.19 through Figure 4.23 show the selected environmental burdens from different natural gas chains: the 400 MW Combined Cycle (CC) reference power plant is supplied with natural gas from various production regions, which can have a significant effect on cumulative emissions per kWh electricity produced, especially for burdens originating from the upstream chain (i.e. from gas production, processing and transport). Contributions from the infrastructure of the power plant (i.e. its construction and decommissioning) are negligible for the burdens shown here. Total GHG as well as CO_2 emissions are highest with natural gas supply from Russia and Nigeria (shipped as LNG) due to the relatively high leakage rates in the pipelines from Russia and the relatively high energy consumption (mostly supplied by natural gas combustion) for the long distance LNG transport from Nigeria. Gas transport as LNG in general causes higher environmental burdens than gas transport in pipelines, if the leakage rates do not exceed certain limits. Emissions of SO_2 primarily depend on the quality of the natural gas resources and the necessary processing after extraction.

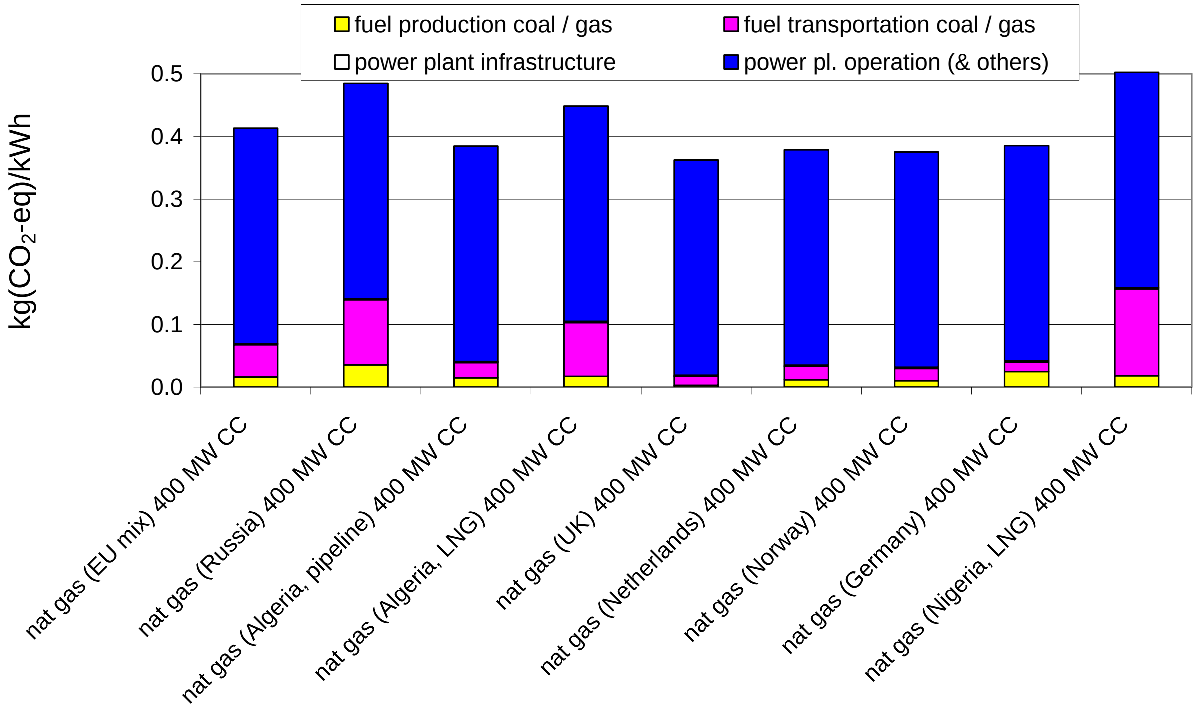

Figure 4.19 Breakdown of GHG emissions from natural gas chains (i.e. gas supply from different production regions).

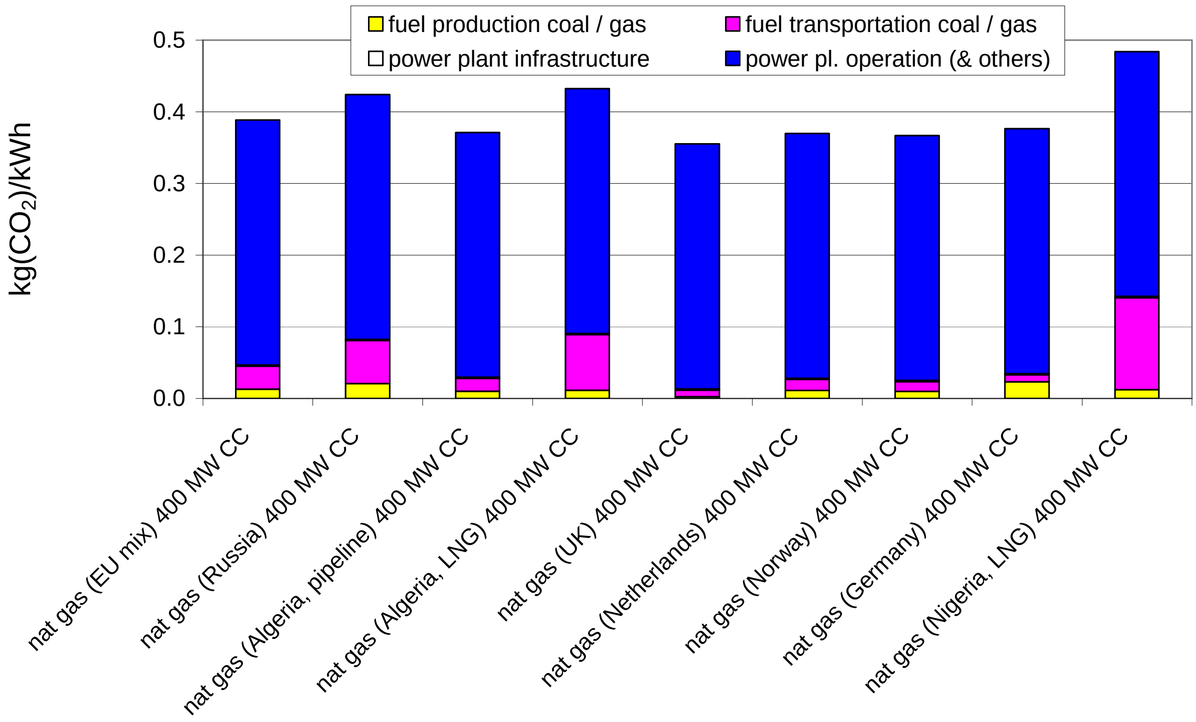

Figure 4.20 Breakdown of CO_2 emissions from natural gas chains (i.e. gas supply from different production regions).

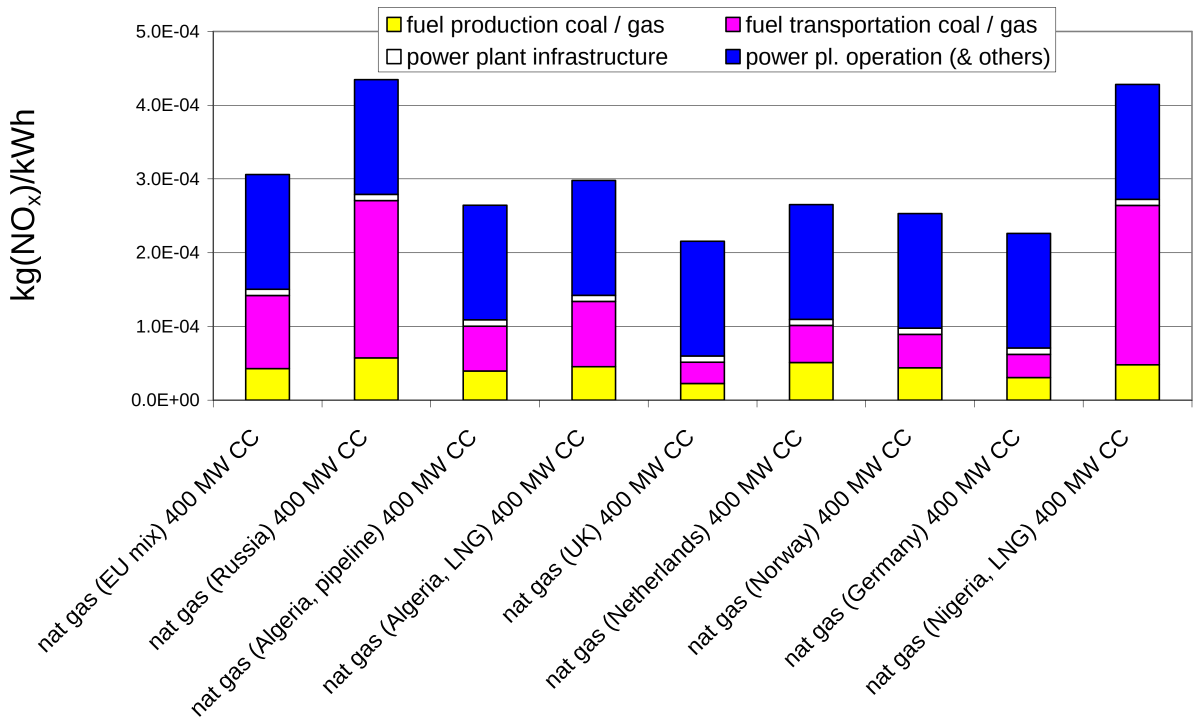

Figure 4.21 Breakdown of NO_x emissions from natural gas chains (i.e. gas supply from different production regions).

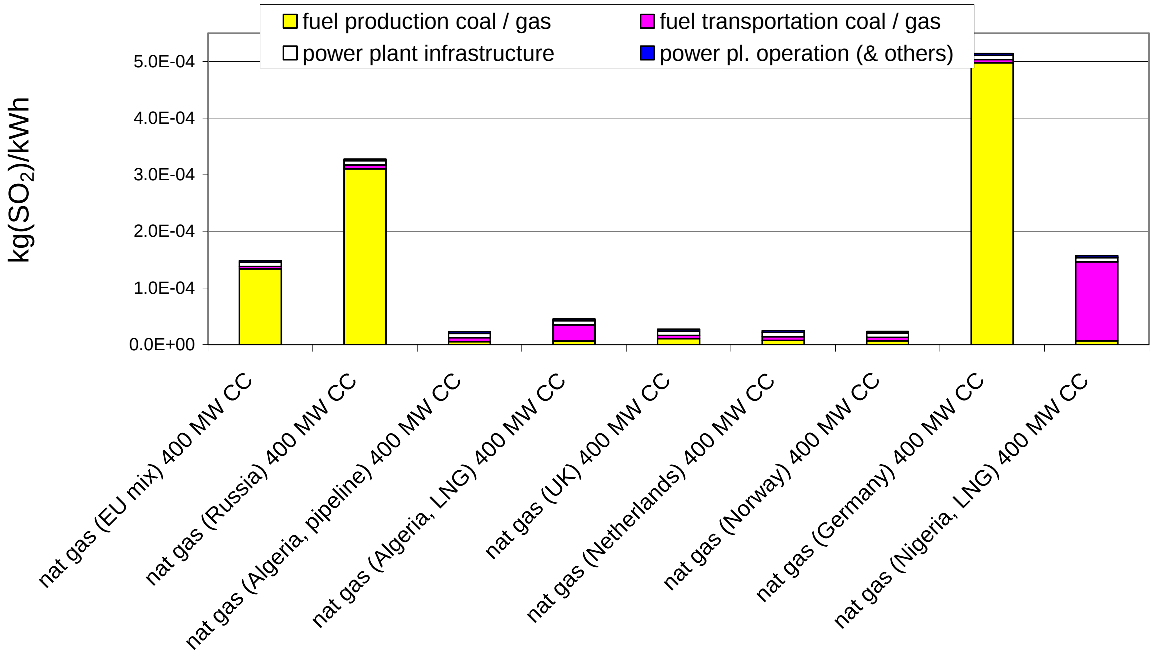

Figure 4.22 Breakdown of SO_2 emissions from natural gas chains (i.e. gas supply from different production regions).

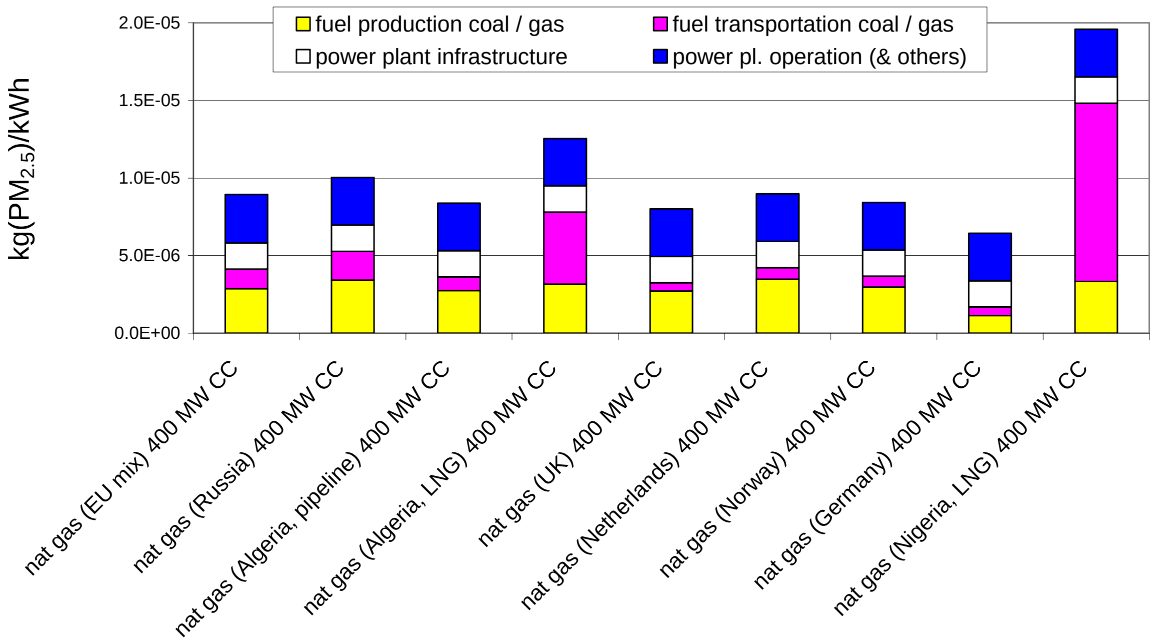

Figure 4.23 Breakdown of $PM_{2.5}$ emissions from natural gas chains (i.e. gas supply from different production regions).

Figure 4.24 through Figure 4.26 show the LCIA results of the different natural gas chains. Fossil fuel (i.e. primarily gas) consumption dominates the results for the two perspectives Hierarchist and Egalitarian, which means that the least efficient chain (LNG from Nigeria) scores worst. The Individualist perspective is dominated by climate change and therefore the results are similar to GHG emissions.

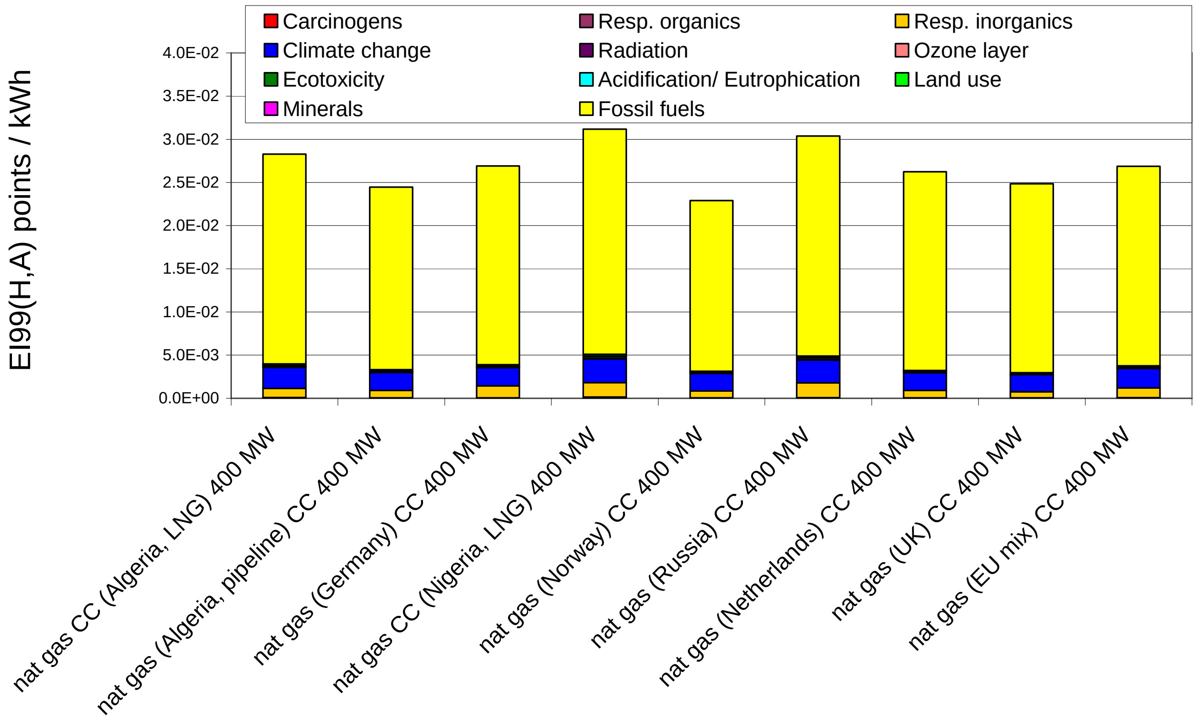

Figure 4.24 Comparison of different natural gas chains (i.e. gas supply from different production regions) based on Eco-Indicator'99 (H, A).

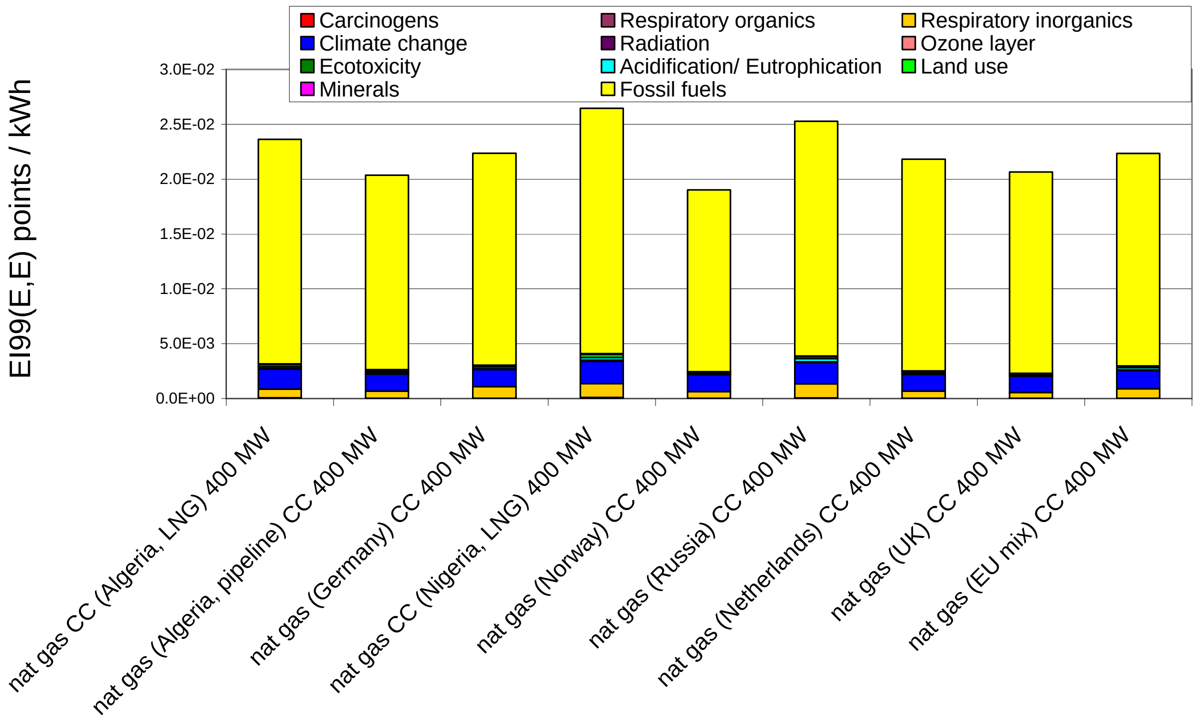

Figure 4.25 Comparison of different natural gas chains (i.e. gas supply from different production regions) based on Eco-Indicator'99 (E, E).

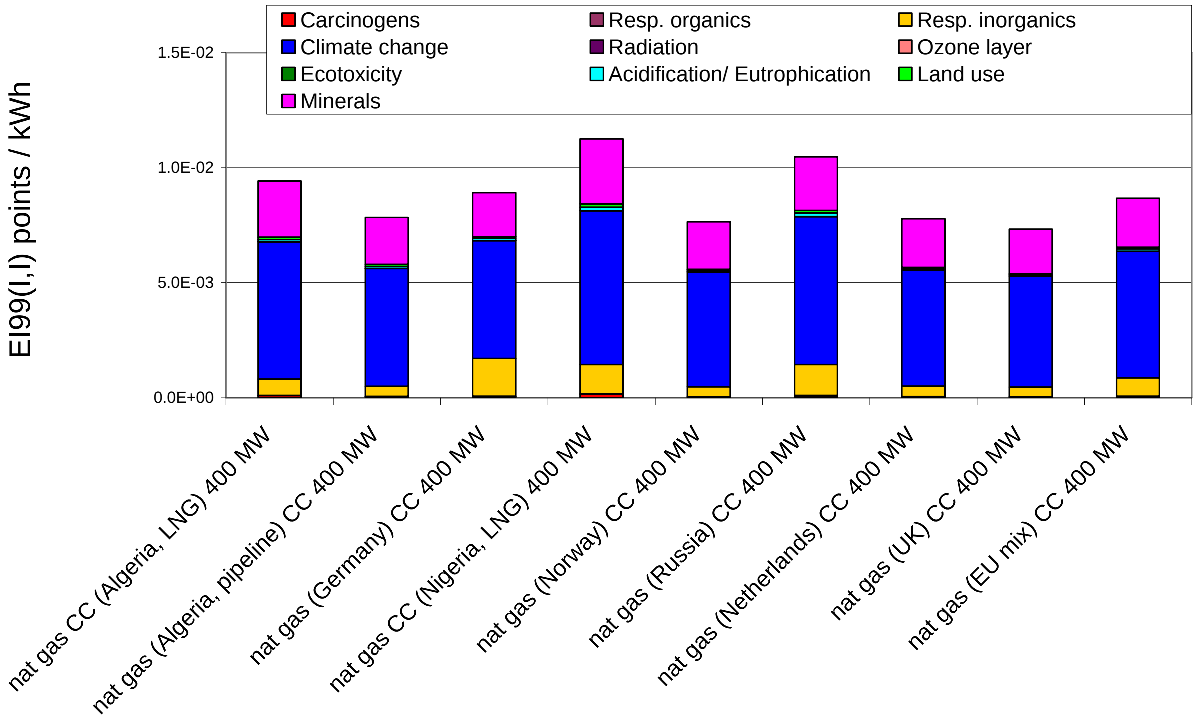

Figure 4.26 Comparison of different natural gas chains (i.e. gas supply from different production regions) based on Eco-Indicator'99 (I, I).

In general, GHG emissions (corresponding to "IPCC GWP 100a") dominate the total external costs (Figure 4.27) and therefore natural gas supply from Russia and Nigeria is associated with the highest external costs.

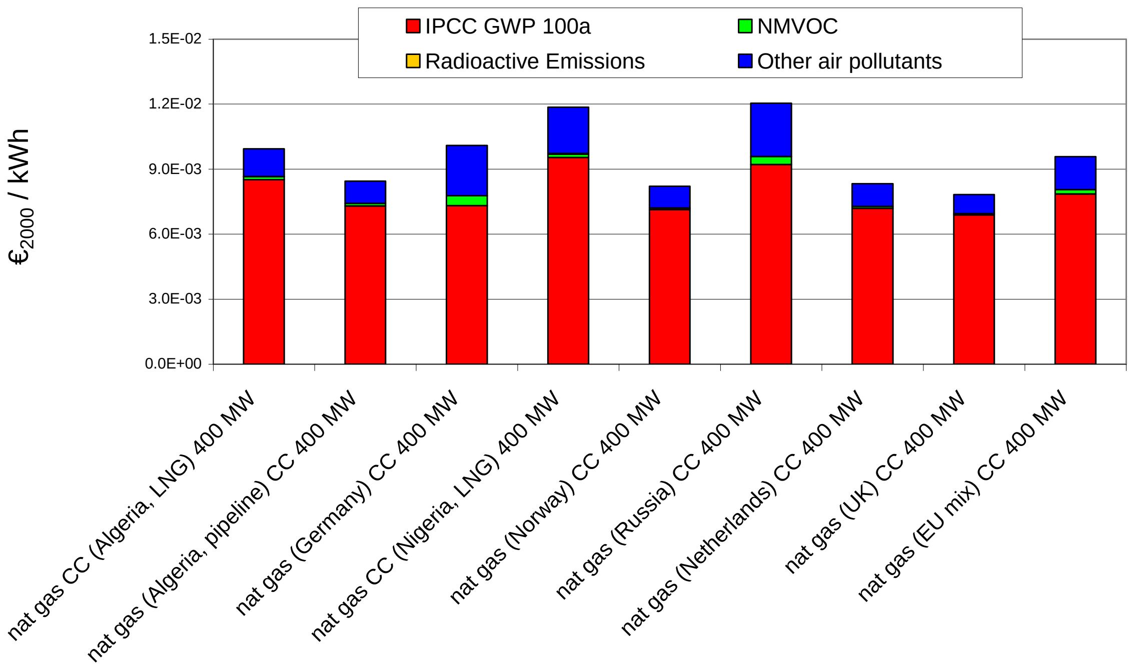

Figure 4.27 Comparison of different natural gas chains (i.e. gas supply from different production regions) based on external costs.

4.4 Synthetic natural gas (SNG) and co-combustion natural gas/SNG

Figure 4.28 through Figure 4.32 show the selected environmental burdens from different SNG and natural gas/SNG co-combustion as well as purely natural gas (for comparison) chains: the 400 MW Combined Cycle (CC) reference power plant is supplied with either the Swiss or the European natural gas mix (Table 3.6), 100% SNG through the natural gas network, or a mixture of natural gas and SNG (90%/10%, based on energy content). Furthermore, three different transport modes and distances for the wood supply of the SNG production facility are differentiated.

While for GHG and CO_2 emissions the combustion of natural gas dominates the results per kWh electricity production and therefore the pure SNG chain is clearly performing better, the other air pollutants show very differing sources within the fuel chains: wood transport, forestry ("fuel production wood") and SNG production partly show high emissions and therefore, the pure SNG chain (partly) performs worse than natural gas and co-combustion chains. Contributions from the infrastructure of the 400 MW CC power plants (i.e. construction and decommissioning) are negligible for the burdens shown here. Short distance wood transport is clearly beneficial from the environmental point of view and for selected burdens the effects of a change in the wood supply (i.e. in terms of distance and mode of transport) are decisive, since the direct emissions from the gas power plants are smaller compared to other fossil fuels.

LCIA results (Figure 4.33 through Figure 4.35) show a diverse pattern, depending on the perspective chosen: while pure SNG chains perform better based on Eco-Indicator'99 (H, A) and (E, E) due to the high weighting of fossil fuel consumption (i.e. mostly natural gas in this case), these SNG chains perform worse in the Individualist (I, I) perspective, which does not give any weight to fossil fuel consumption, but depletion of mineral reserves. An important contribution in all three perspectives comes from land use due to forestry.

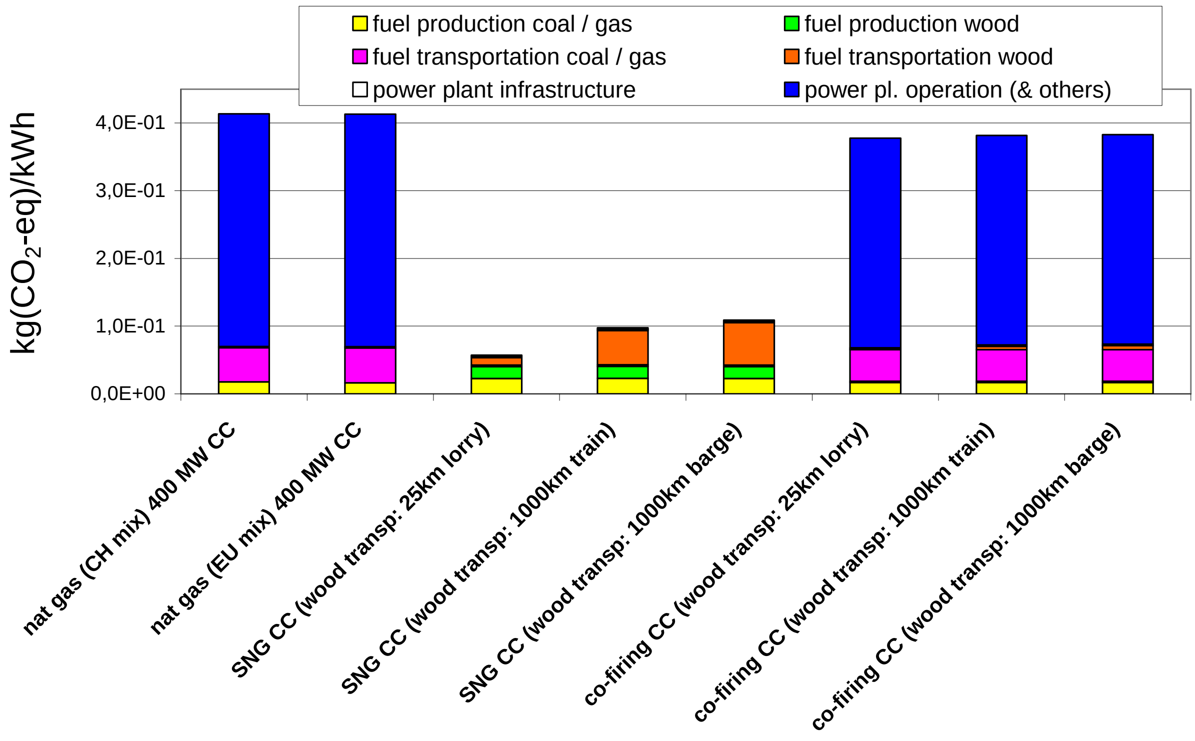

Figure 4.28 Breakdown of GHG emissions from natural gas, SNG and natural gas/SNG co-combustion chains; reference power plant: 400 MW CC for all chains.

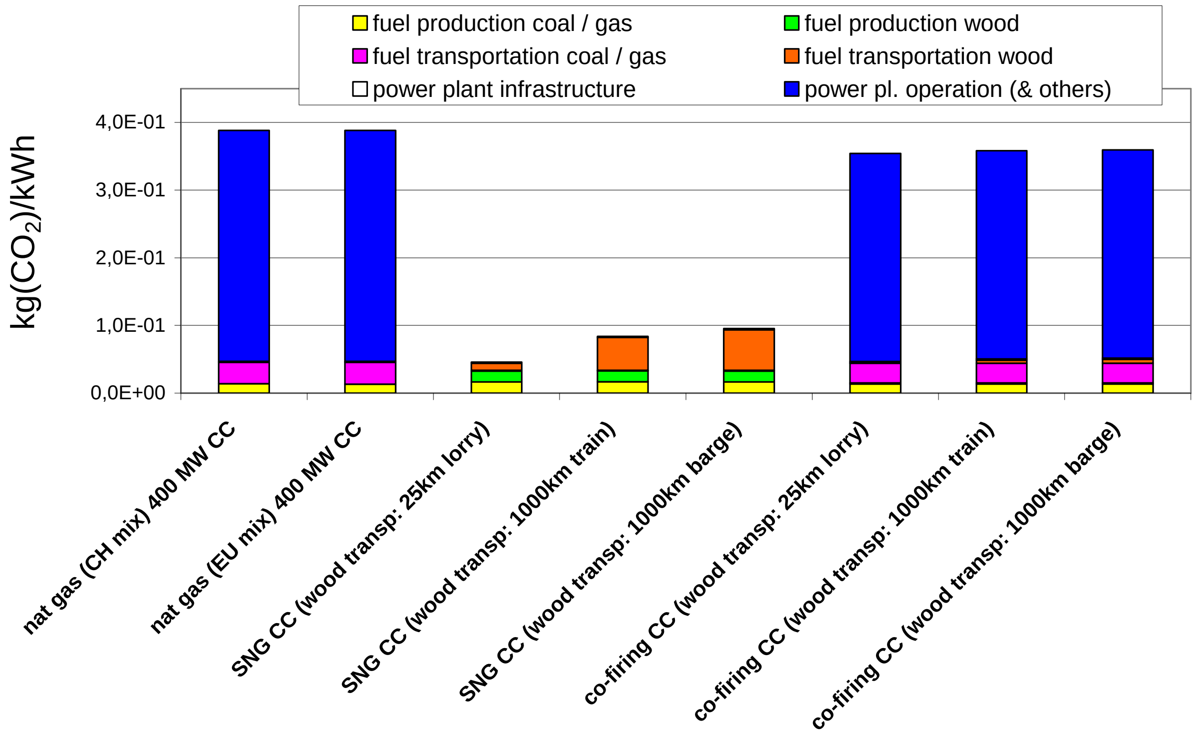

Figure 4.29 Breakdown of CO_2 emissions from natural gas, SNG and natural gas/SNG co-combustion chains; reference power plant: 400 MW CC for all chains.

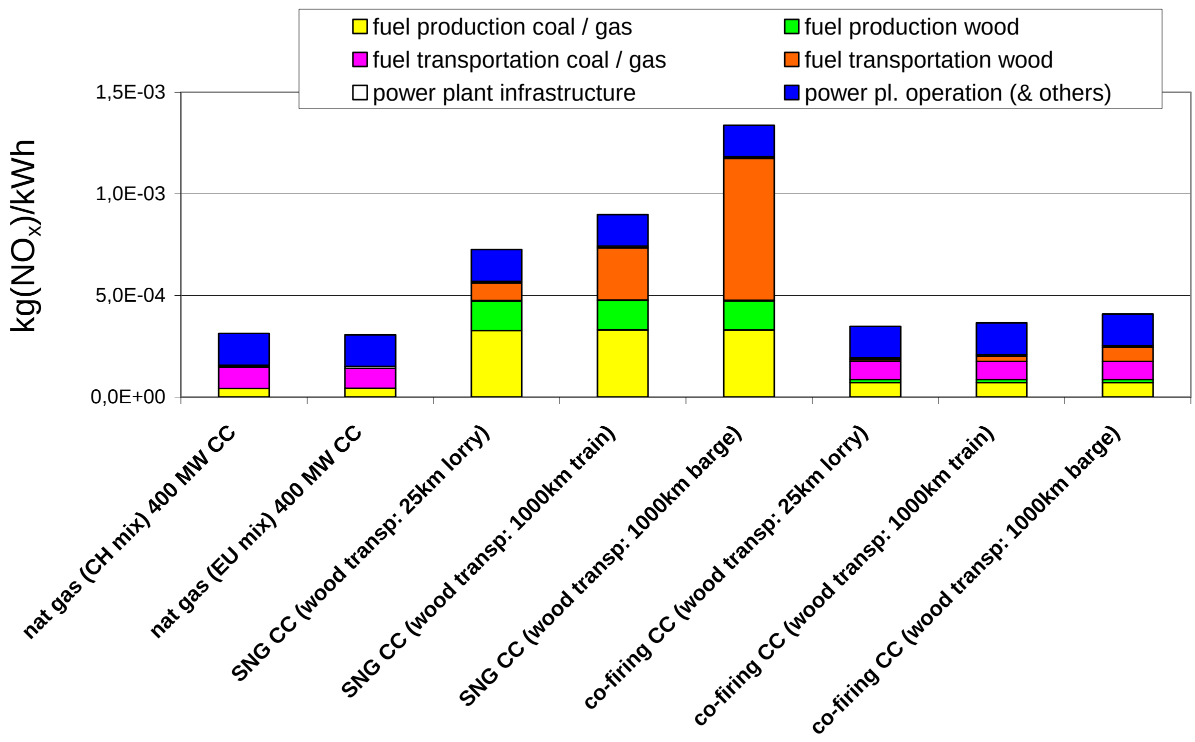

Figure 4.30 Breakdown of NO_x emissions from natural gas, SNG and natural gas/SNG co-combustion chains; reference power plant: 400 MW CC for all chains.

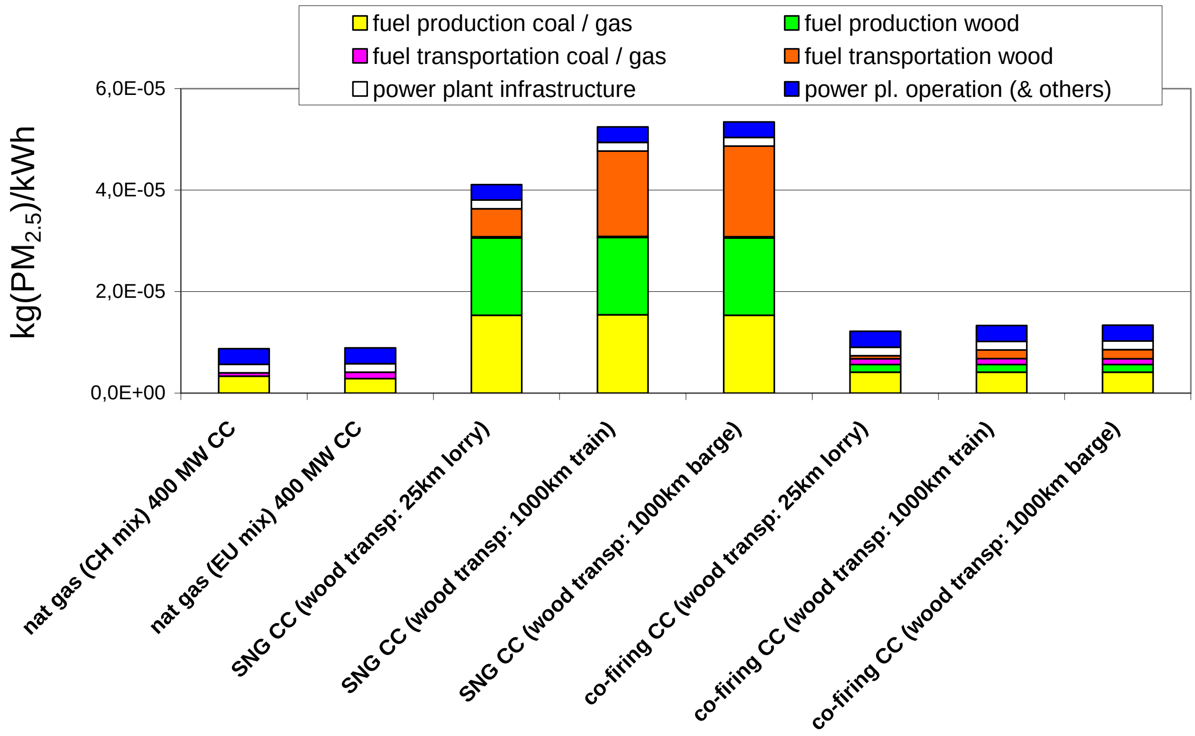

Figure 4.31 Breakdown of $PM_{2.5}$ emissions from natural gas, SNG and natural gas/SNG co-combustion chains; reference power plant: 400 MW CC for all chains.

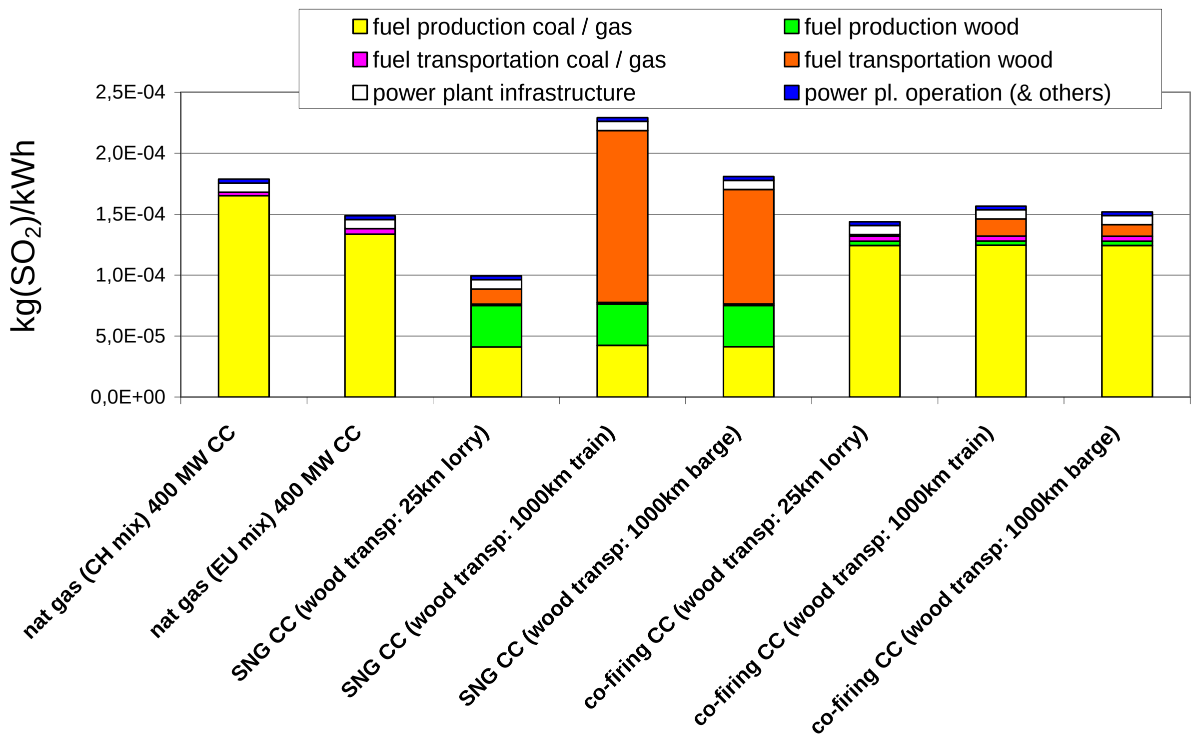

Figure 4.32 Breakdown of SO_2 emissions from natural gas, SNG and natural gas/SNG co-combustion chains; reference power plant: 400 MW CC for all chains.

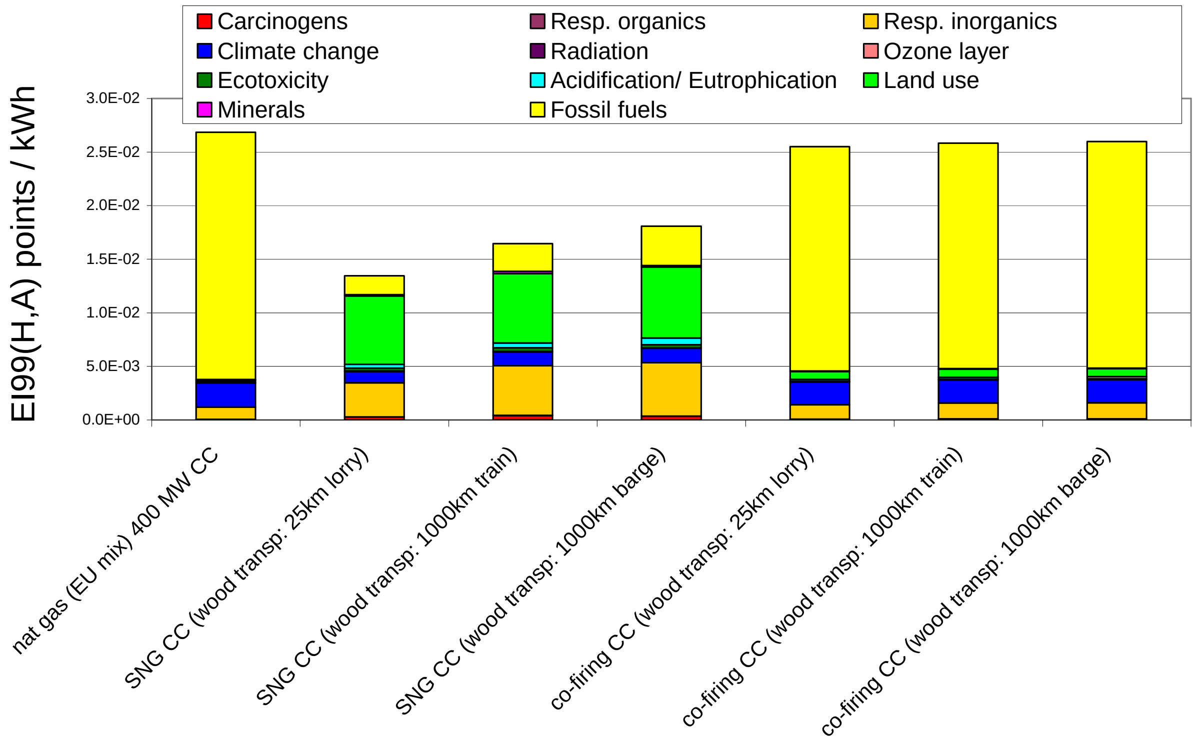

Figure 4.33 **Comparison of natural gas, SNG and natural gas/SNG co-combustion chains based on Eco-Indicator'99 (H, A); reference power plant: 400 MW CC for all chains.**

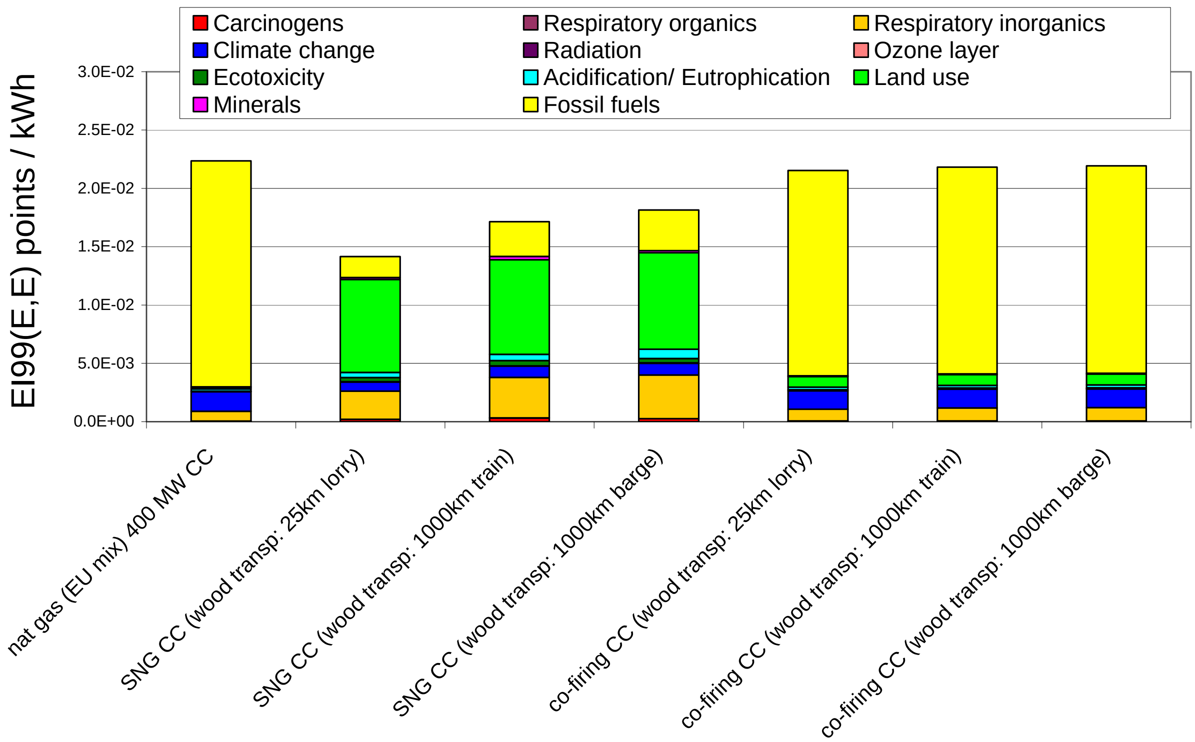

Figure 4.34 **Comparison of natural gas, SNG and natural gas/SNG co-combustion chains based on Eco-Indicator'99 (E, E); reference power plant: 400 MW CC for all chains.**

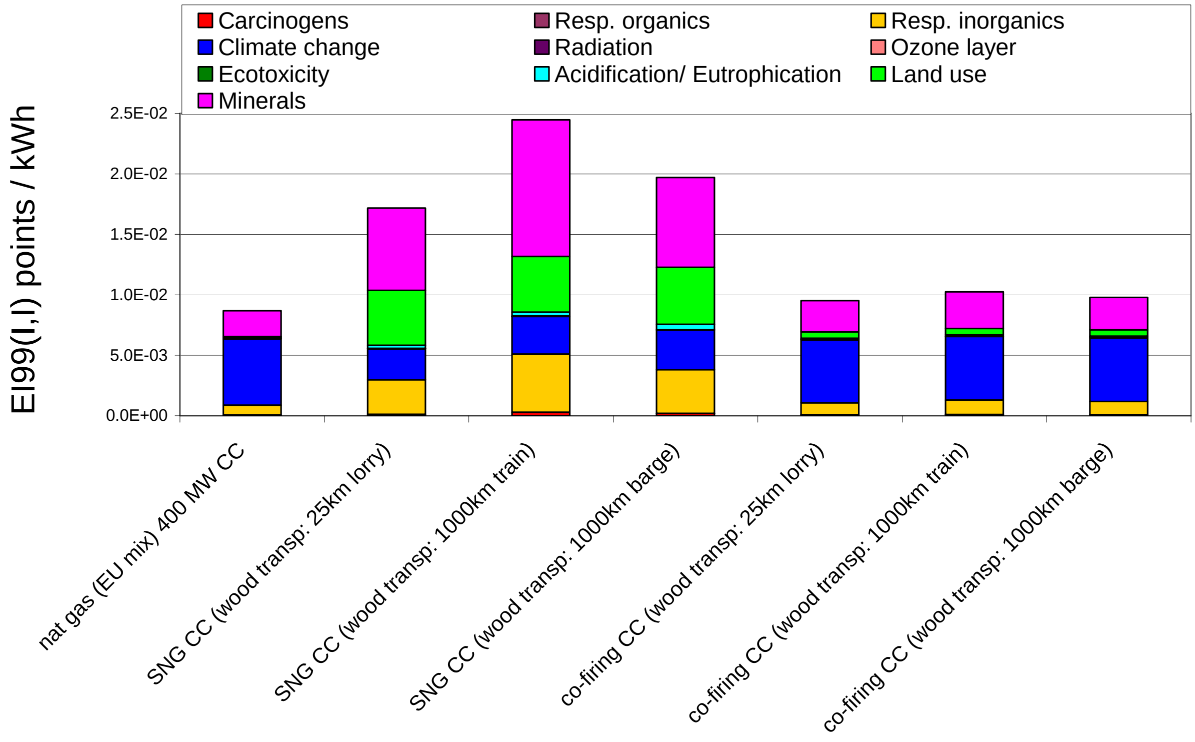

Figure 4.35 Comparison of natural gas, SNG and natural gas/SNG co-combustion chains based on Eco-Indicator'99 (I, I); reference power plant: 400 MW CC for all chains.

The evaluation based on external costs shows that the benefit of reduced GHG emissions (= IPCC GWP) can be outweighed by the increase in air pollution in case of pre SNG chains due to long-distance wood transport for SNG production (Figure 4.36).

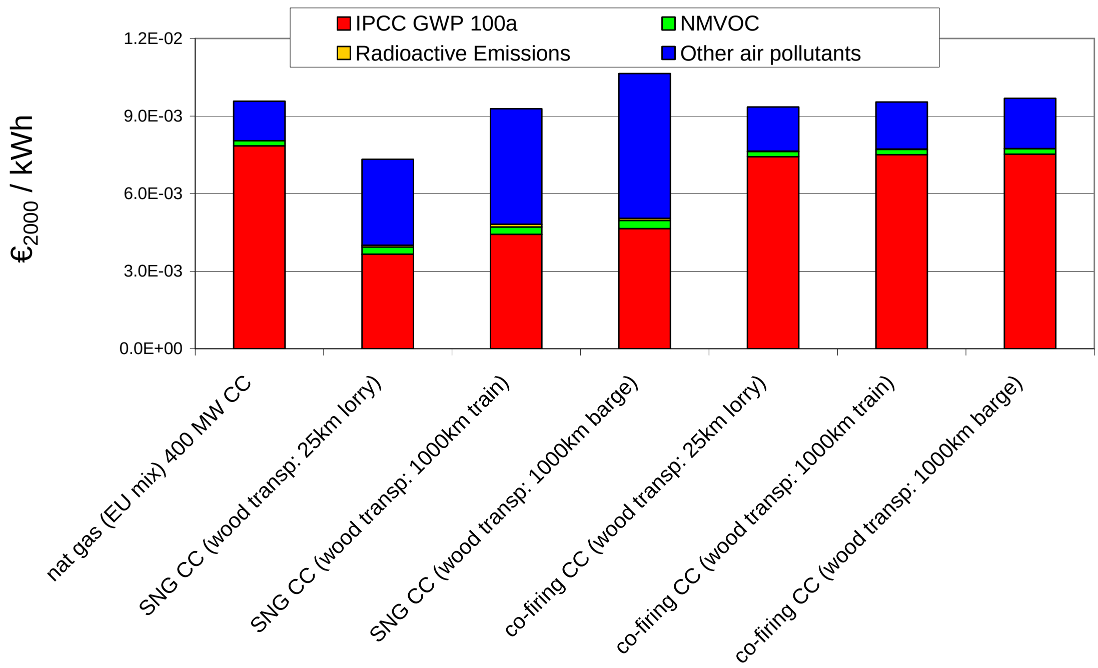

Figure 4.36 Comparison of natural gas, SNG and natural gas/SNG co-combustion chains based on external costs; reference power plant: 400 MW CC for all chains.

4.5 Overall comparison and conclusions

Figure 4.37 through Figure 4.45 show the environmental burdens, LCIA results and external costs of a selection of the analyzed power generation chains across the different fuel classes (i.e. biomass, natural gas, hard coal and lignite) in order to allow a comparison of the environmental performance of the different fuels.

Biomass fuel chains (i.e. wood and SNG) show clear advantages concerning CO_2 and GHG emissions. Depending on the contributions from the upstream processes, GHG emissions of wood and SNG chains per kWh electricity are in a range of about 40-100 g(CO_2-eq.)/kWh, while natural gas chains reach levels of about 380-500 g(CO_2-eq.)/kWh and coal about 800-1200 g(CO_2-eq.)/kWh. Concerning NO_x emissions, natural gas shows the best performance of all chains. Since NO_x emissions can be significant in some upstream processes of the biomass chains and also directly at the wood power plant, biomass performs worse. State-of-the-art coal power plants (as included in this assessment) have relatively low direct NO_x emissions, but depending on the origin of the coal, its transport can significantly worsen the overall emissions of the chain per kWh electricity. $PM_{2.5}$ emissions show a similar pattern with wood chains as the systems with highest emissions and natural gas with the lowest. SO_2 emissions of hard coal and natural gas chains mainly depend on contributions from upstream processes – coal chains perform worst, natural gas chains best. The differences between lignite and “clean” (i.e without oversea shipping) hard coal chains in terms of environmental impacts are in general small. However, contributions from hard coal mining and transport can significantly increase cumulative emissions per kWh electricity.

Aggregated LCIA results significantly depend on the weighting of the single damage categories: in case of high weighting of natural gas as energy resource (Eco-Indicator 99 H, A), “clean” hard coal and lignite chains (i.e. with state-of-the-art power plant technology as well as upstream chains with low environmental impacts) show the best overall performance. This evaluation demonstrates the importance of the consideration of the whole life cycle of power generation: while the total score for the hard coal chain with fuel supply from Poland is among the best systems, hard coal supply from China leads to the worst result of all energy chains compared. In such cases, optimizing the fuel supply allows clearly higher reduction of environmental burdens than optimizing the power plant. In case of equally high weighting of fossil energy resources (Eco-Indicator 99 E, E), natural gas slightly performs better than coal (except of Chinese coal supply with its high environmental burdens). Scores of wood chains are in the same range and SNG performs best. If no weight is attributed to fossil energy resources, but higher weights to human health impacts (Eco-Indicator 99 I, I), natural gas chains show the best results. The higher the weighting of damages to human health and the lower weighting of fossil resources, the better the performance of pure “clean” hard coal and lignite chains compared to small-scale biomass chains (Eco-Indicator 99 H, A and I, I). Only in case of high weighting of coal resources (Eco-Indicator 99 E, E) results for small-scale biomass chains are in the same range as those of co-combustion chains. Otherwise, co-combustion systems produce less environmental burdens due to their lower direct power plant emissions. Natural gas as well as SNG chains are also associated with the lowest external costs due low emissions of air pollutants and (compared to coal) relatively low GHG emissions.

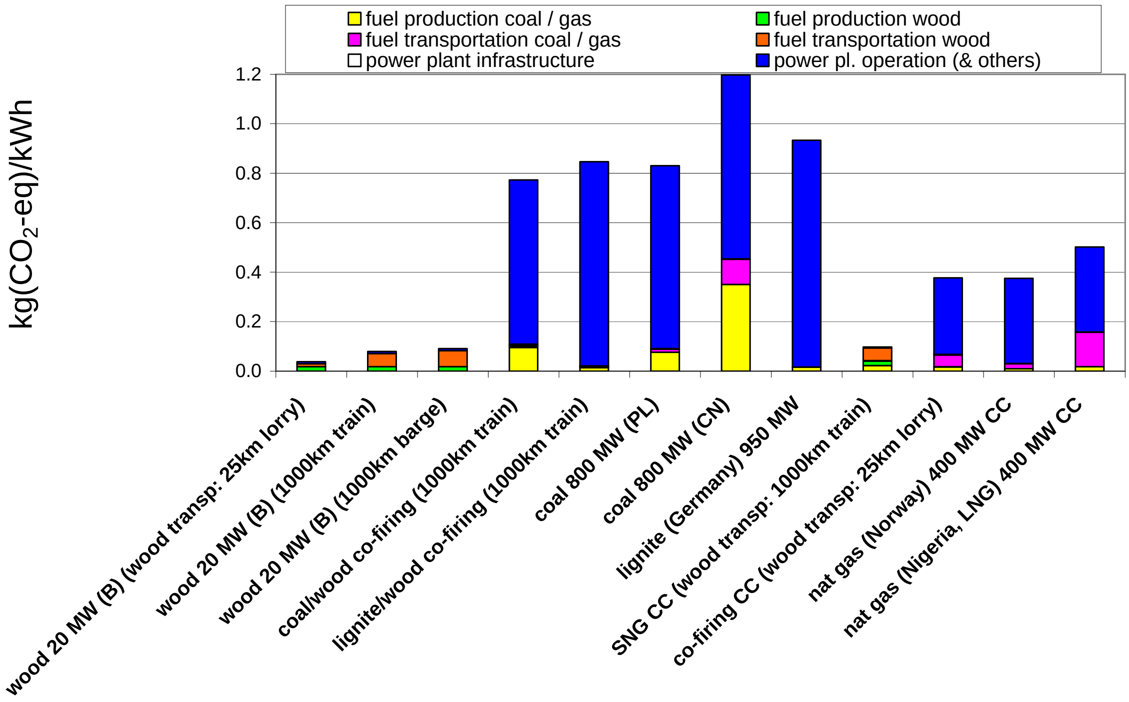

Figure 4.37 Breakdown of GHG emissions from selected energy chains.

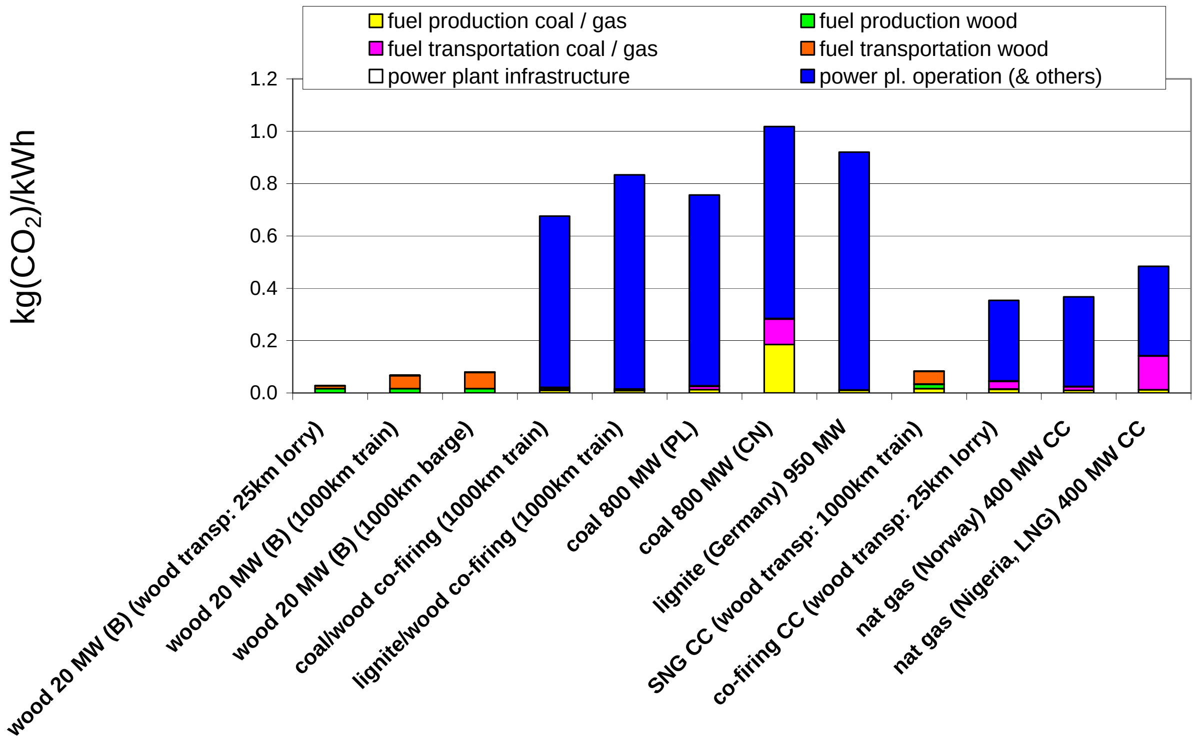

Figure 4.38 Breakdown of CO_2 emissions from selected energy chains.

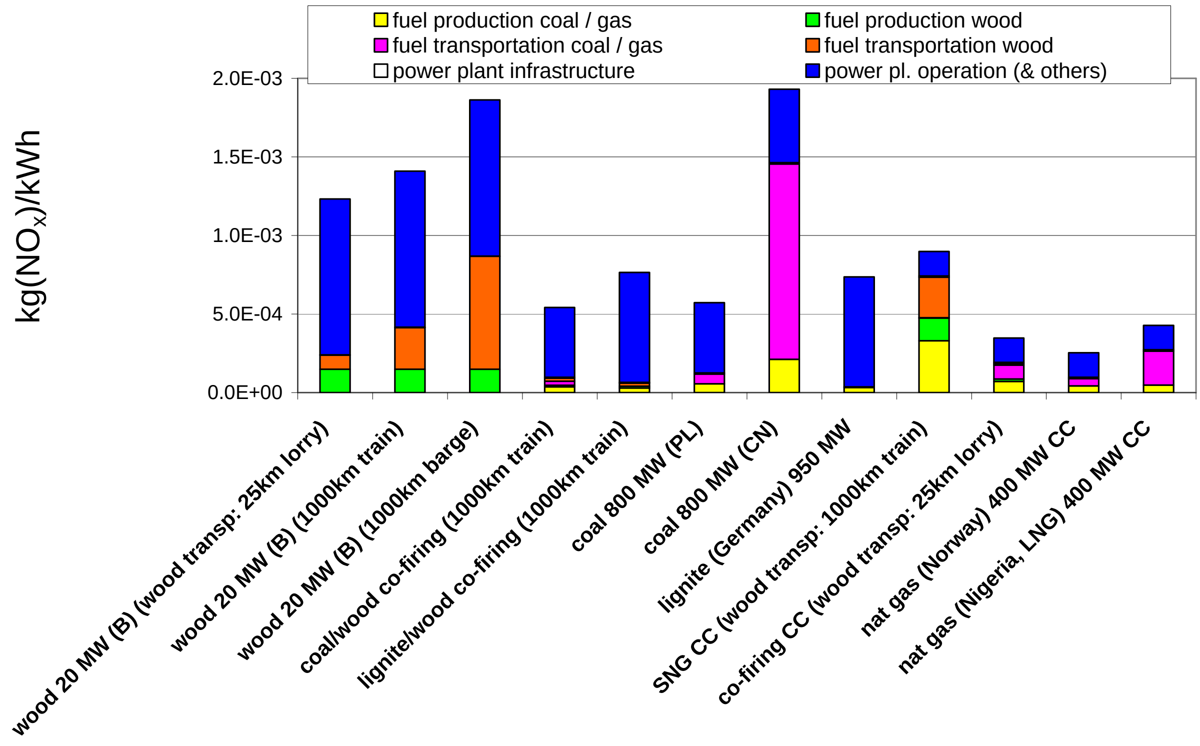

Figure 4.39 Breakdown of NO_x emissions from selected energy chains.

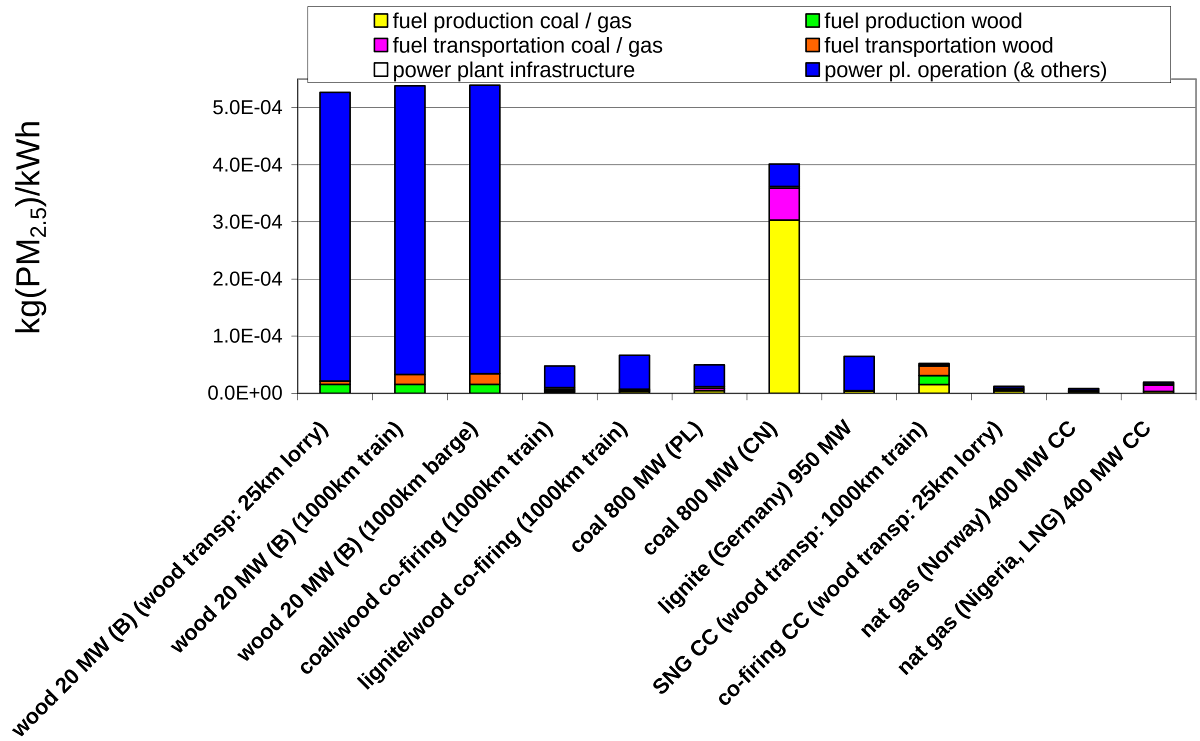

Figure 4.40 Breakdown of $PM_{2.5}$ emissions from selected energy chains.

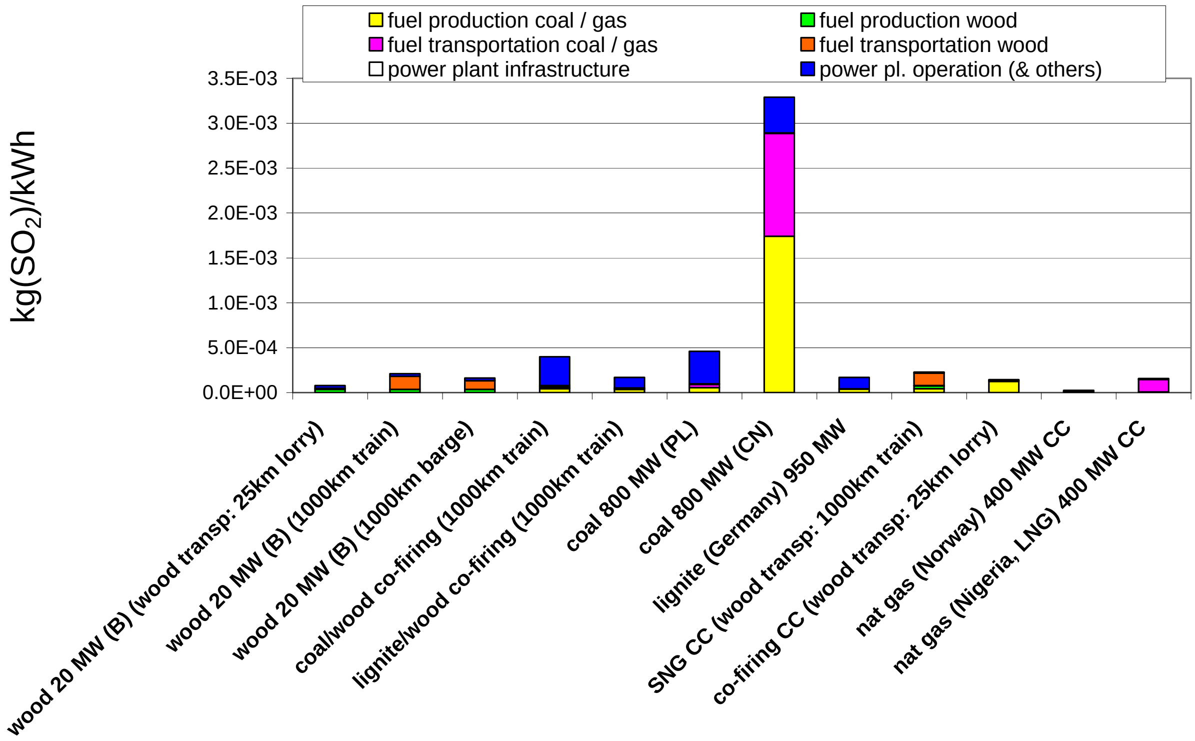

Figure 4.41 Breakdown of SO_2 emissions from selected energy chains.

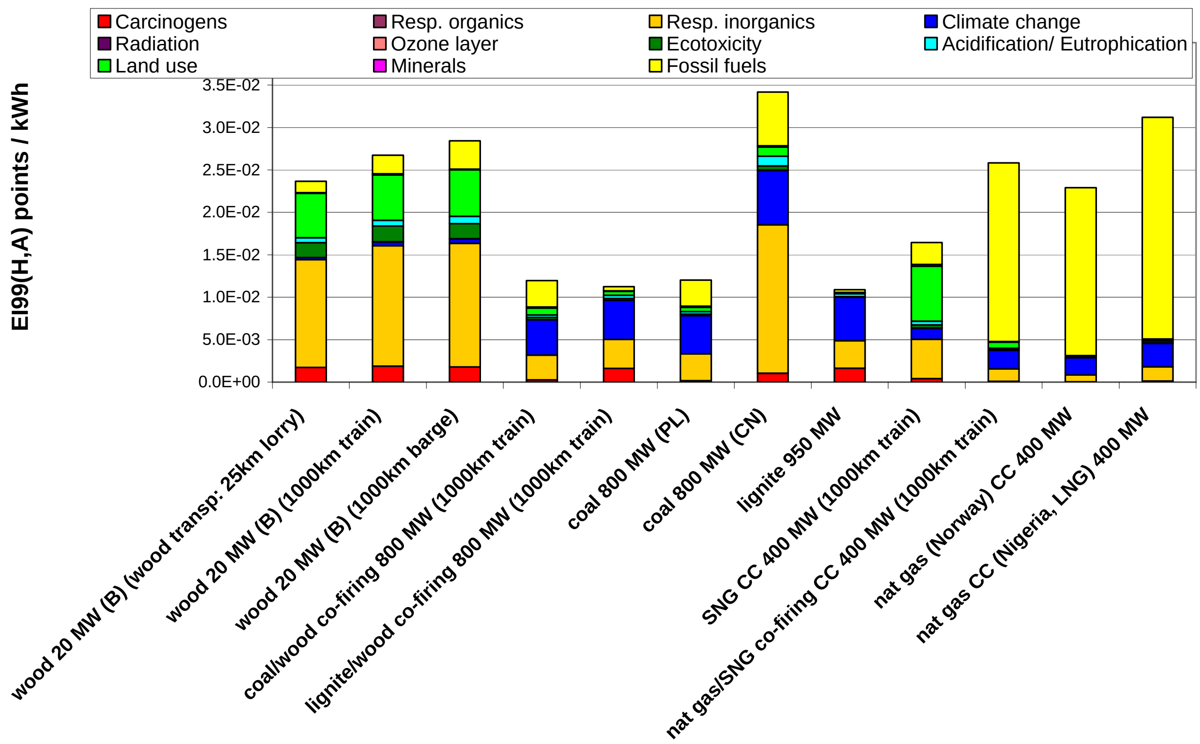

Figure 4.42 Comparison of selected energy chains based on Eco-Indicator'99 (H, A).

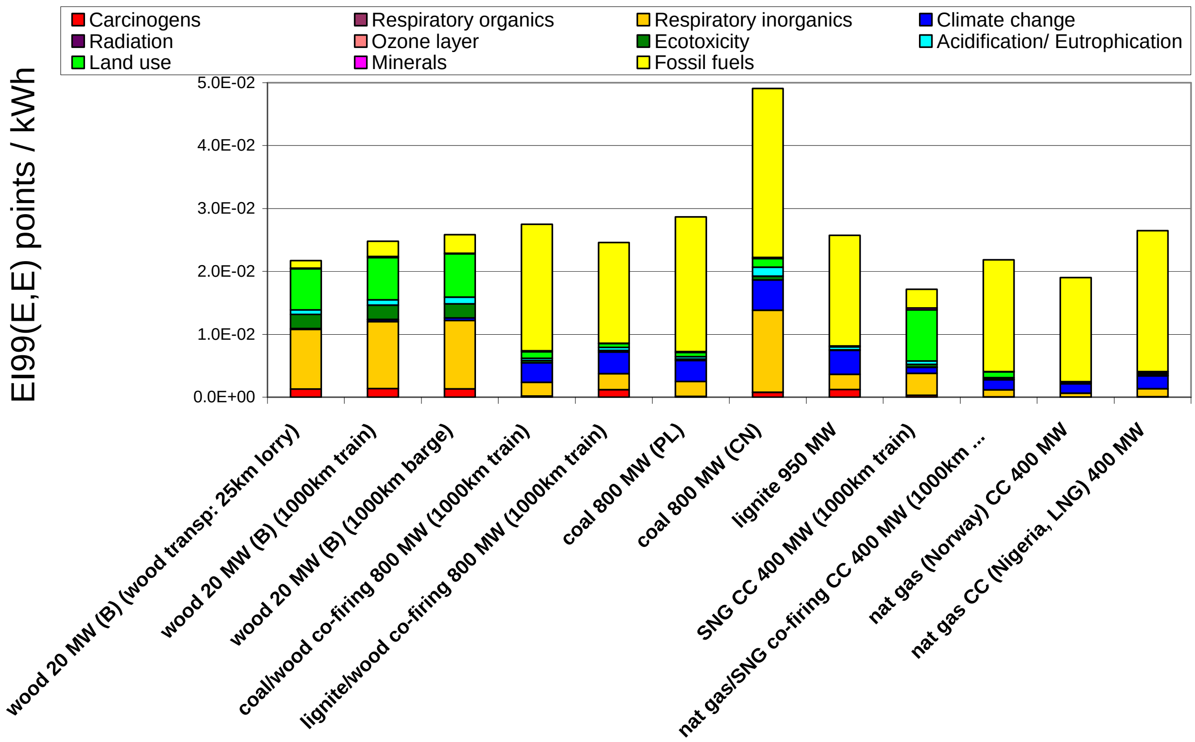

Figure 4.43 Comparison of selected energy chains based on Eco-Indicator'99 (E, E).

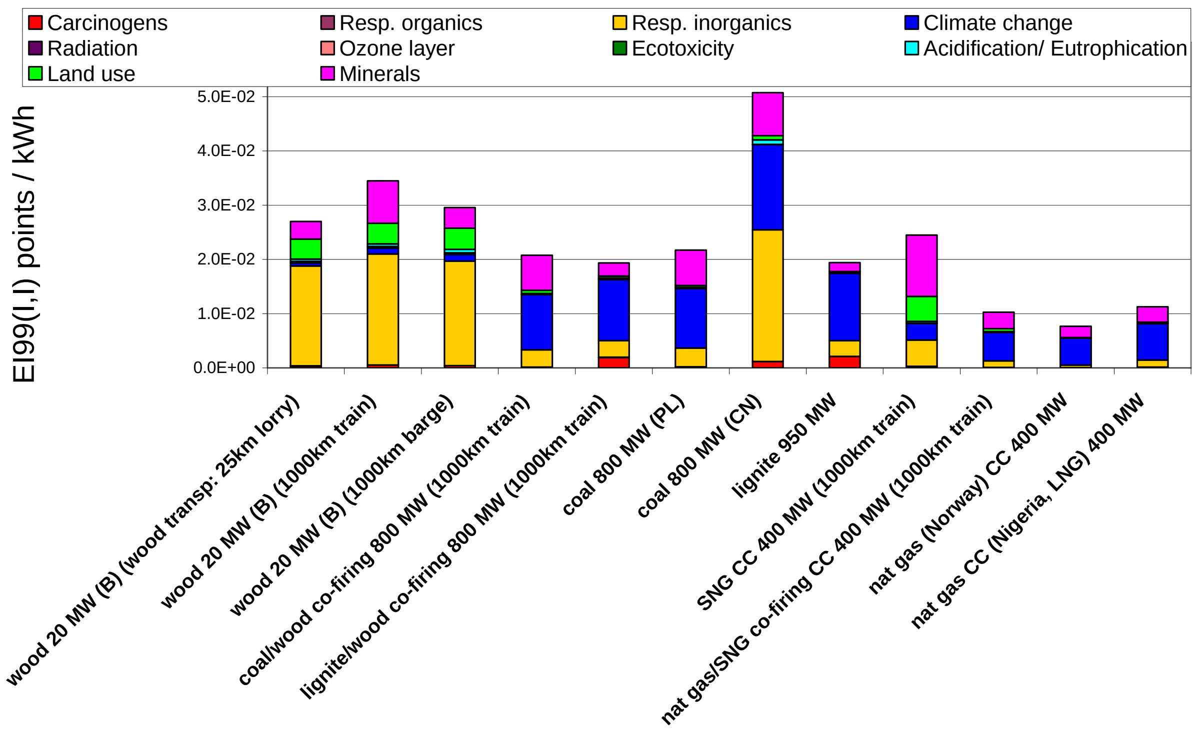

Figure 4.44 Comparison of selected energy chains based on Eco-Indicator'99 (I, I).

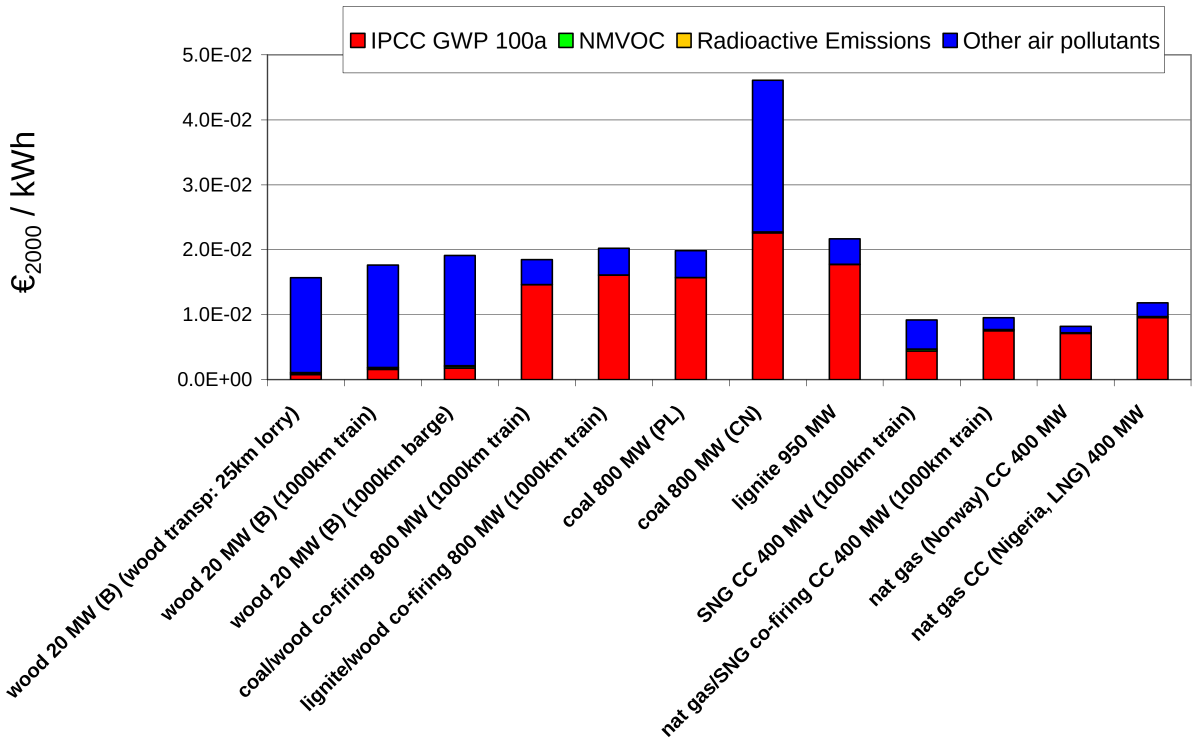

Figure 4.45 Comparison of selected energy chains based on external costs.

5 Appendix

The Appendix provides the numerical results of this project (Table 5.1 through Table 5.7; only the selected indicators for the interpretation of results, see chapter 4, are shown).

Table 5.1 Selected LCA results for wood chains, incl. breakdown of different steps in the entire chains.

			wood, 20 MW (B) (wood transp: 25km lorry)	wood, 20 MW (B) (wood transp: 1000km train)	wood, 20 MW (B) (wood transp: 1000km barge)	wood, 20 MW (A) (wood transp: 25km lorry)	wood, 20 MW (A) (wood transp: 1000km train)	wood, 20 MW (A) (wood transp: 1000km barge)
GHG total		**kg CO2-eq / kWh**	**3.82E-02**	**7.95E-02**	**9.16E-02**	**3.82E-02**	**7.95E-02**	**9.16E-02**
	fuel production	coal / gas						
	fuel production	wood	1.82E-02	1.82E-02	1.82E-02	1.82E-02	1.82E-02	1.82E-02
	fuel transportation	coal / gas						
	fuel transportation	wood	1.13E-02	5.23E-02	6.46E-02	1.13E-02	5.23E-02	6.46E-02
	power plant infrastructure		6.43E-04	6.43E-04	6.43E-04	6.43E-04	6.43E-04	6.43E-04
	power pl. operation (& others)		8.12E-03	8.39E-03	8.18E-03	8.12E-03	8.39E-03	8.18E-03
CO2		**kg/kWh**	**2.84E-02**	**6.77E-02**	**7.97E-02**	**2.84E-02**	**6.77E-02**	**7.97E-02**
	fuel production	coal / gas						
	fuel production	wood	1.68E-02	1.68E-02	1.68E-02	1.68E-02	1.68E-02	1.68E-02
	fuel transportation	coal / gas						
	fuel transportation	wood	1.07E-02	4.98E-02	6.19E-02	1.07E-02	4.98E-02	6.19E-02
	power plant infrastructure		6.12E-04	6.12E-04	6.12E-04	6.12E-04	6.12E-04	6.12E-04
	power pl. operation (& others)		3.18E-04	5.68E-04	3.68E-04	3.18E-04	5.68E-04	3.68E-04
NOx		**kg/kWh**	**1.23E-03**	**1.41E-03**	**1.86E-03**	**5.07E-03**	**5.25E-03**	**5.70E-03**
	fuel production	coal / gas						
	fuel production	wood	1.49E-04	1.49E-04	1.49E-04	1.49E-04	1.49E-04	1.49E-04
	fuel transportation	coal / gas						
	fuel transportation	wood	8.95E-05	2.65E-04	7.19E-04	8.95E-05	2.65E-04	7.19E-04
	power plant infrastructure		1.91E-06	1.91E-06	1.91E-06	1.91E-06	1.91E-06	1.91E-06
	power pl. operation (& others)		9.92E-04	9.94E-04	9.93E-04	4.83E-03	4.83E-03	4.83E-03
PM2.5		**kg/kWh**	**5.27E-04**	**5.39E-04**	**5.40E-04**	**3.07E-04**	**3.18E-04**	**3.19E-04**
	fuel production	coal / gas						
	fuel production	wood	1.57E-05	1.57E-05	1.57E-05	1.57E-05	1.57E-05	1.57E-05
	fuel transportation	coal / gas						
	fuel transportation	wood	5.73E-06	1.73E-05	1.84E-05	5.73E-06	1.73E-05	1.84E-05
	power plant infrastructure		2.91E-07	2.91E-07	2.91E-07	2.91E-07	2.91E-07	2.91E-07
	power pl. operation (& others)		5.05E-04	5.05E-04	5.05E-04	2.85E-04	2.85E-04	2.85E-04
SO2		**kg/kWh**	**7.78E-05**	**2.12E-04**	**1.62E-04**	**2.32E-03**	**2.46E-03**	**2.41E-03**
	fuel production	coal / gas						
	fuel production	wood	3.51E-05	3.51E-05	3.51E-05	3.51E-05	3.51E-05	3.51E-05
	fuel transportation	coal / gas						
	fuel transportation	wood	1.28E-05	1.46E-04	9.68E-05	1.28E-05	1.46E-04	9.68E-05
	power plant infrastructure		9.69E-07	9.69E-07	9.69E-07	9.69E-07	9.69E-07	9.69E-07
	power pl. operation (& others)		2.89E-05	2.95E-05	2.90E-05	2.27E-03	2.27E-03	2.27E-03

Table 5.2 Selected LCA results for hard coal/wood co-firing and hard coal chains, incl. breakdown of different steps in the entire chains.

		hard coal/wood co-firing 400 MW (wood transp: 50km lorry)	hard coal/wood co-firing 400 MW (1000km train)	hard coal/wood co-firing 400 MW (1000km barge)	hard coal/wood co-firing 800 MW (50km lorry)	hard coal/wood co-firing 800 MW (1000km train)	hard coal/wood co-firing 800 MW (1000km barge)	hard coal (Germany) 400 MW	hard coal (Germany) 800 MW
GHG total	**kg CO2-eq / kWh**	**8.89E-01**	**8.91E-01**	**8.92E-01**	**7.70E-01**	**7.72E-01**	**7.73E-01**	**9.80E-01**	**8.52E-01**
fuel production	coal / gas	1.10E-01	1.10E-01	1.10E-01	9.60E-02	9.60E-02	9.60E-02	1.23E-01	1.07E-01
fuel production	wood	1.45E-03	1.45E-03	1.45E-03	1.27E-03	1.27E-03	1.27E-03		
fuel transportation	coal / gas	6.07E-03	6.07E-03	6.07E-03	5.07E-03	5.07E-03	5.07E-03	6.75E-03	5.64E-03
fuel transportation	wood	1.80E-03	4.19E-03	5.18E-03	1.57E-03	3.65E-03	4.50E-03		
power plant infrastructure		4.88E-03	4.88E-03	4.88E-03	2.76E-03	2.76E-03	2.76E-03	3.54E-03	2.75E-03
power pl. operation (& others)		7.64E-01	7.64E-01	7.64E-01	6.63E-01	6.63E-01	6.64E-01	8.47E-01	7.37E-01
CO2	**kg/kWh**	**7.78E-01**	**7.80E-01**	**7.81E-01**	**6.74E-01**	**6.76E-01**	**6.77E-01**	**8.58E-01**	**7.46E-01**
fuel production	coal / gas	1.10E-02	1.10E-02	1.10E-02	9.58E-03	9.58E-03	9.58E-03	1.22E-02	1.06E-02
fuel production	wood	1.34E-03	1.34E-03	1.34E-03	1.17E-03	1.17E-03	1.17E-03		
fuel transportation	coal / gas	5.78E-03	5.78E-03	5.78E-03	4.83E-03	4.83E-03	4.83E-03	6.42E-03	5.37E-03
fuel transportation	wood	1.71E-03	3.99E-03	4.96E-03	1.49E-03	3.47E-03	4.32E-03		
power plant infrastructure		4.41E-03	4.41E-03	4.41E-03	2.55E-03	2.55E-03	2.55E-03	3.31E-03	2.58E-03
power pl. operation (& others)		7.54E-01	7.54E-01	7.54E-01	6.54E-01	6.54E-01	6.54E-01	8.36E-01	7.28E-01
NOx	**kg/kWh**	**6.31E-04**	**6.38E-04**	**6.75E-04**	**5.35E-04**	**5.42E-04**	**5.73E-04**	**6.00E-04**	**5.20E-04**
fuel production	coal / gas	4.17E-05	4.17E-05	4.17E-05	3.62E-05	3.62E-05	3.62E-05	4.63E-05	4.03E-05
fuel production	wood	1.20E-05	1.20E-05	1.20E-05	1.04E-05	1.04E-05	1.04E-05		
fuel transportation	coal / gas	3.08E-05	3.08E-05	3.08E-05	2.58E-05	2.58E-05	2.58E-05	3.43E-05	3.16E-05
fuel transportation	wood	1.43E-05	2.13E-05	5.77E-05	1.24E-05	1.85E-05	5.02E-05		
power plant infrastructure		1.11E-05	1.11E-05	1.11E-05	6.73E-06	6.73E-06	6.73E-06	8.71E-06	6.75E-06
power pl. operation (& others)		5.21E-04	5.21E-04	5.22E-04	4.44E-04	4.44E-04	4.44E-04	5.11E-04	4.41E-04
PM2.5	**kg/kWh**	**1.26E-04**	**1.26E-04**	**1.26E-04**	**4.76E-05**	**4.80E-05**	**4.81E-05**	**5.36E-05**	**4.62E-05**
fuel production	coal / gas	3.37E-06	3.37E-06	3.37E-06	2.93E-06	2.93E-06	2.93E-06	3.74E-06	3.26E-06
fuel production	wood	1.26E-06	1.26E-06	1.26E-06	1.09E-06	1.09E-06	1.09E-06		
fuel transportation	coal / gas	2.01E-06	2.01E-06	2.01E-06	1.68E-06	1.68E-06	1.68E-06	2.24E-06	1.87E-06
fuel transportation	wood	9.16E-07	1.39E-06	1.48E-06	7.97E-07	1.21E-06	1.28E-06		
power plant infrastructure		5.35E-06	5.35E-06	5.35E-06	3.12E-06	3.12E-06	3.12E-06	3.97E-06	3.12E-06
power pl. operation (& others)		1.13E-04	1.13E-04	1.13E-04	3.79E-05	3.79E-05	3.79E-05	4.37E-05	3.80E-05
SO2	**kg/kWh**	**5.65E-04**	**5.75E-04**	**5.71E-04**	**3.91E-04**	**3.99E-04**	**3.96E-04**	**4.92E-04**	**4.27E-04**
fuel production	coal / gas	4.84E-05	4.84E-05	4.84E-05	4.21E-05	4.21E-05	4.21E-05	5.38E-05	4.68E-05
fuel production	wood	2.81E-06	2.81E-06	2.81E-06	2.44E-06	2.44E-06	2.44E-06		
fuel transportation	coal / gas	1.69E-05	1.69E-05	1.69E-05	1.41E-05	1.41E-05	1.41E-05	1.88E-05	1.57E-05
fuel transportation	wood	2.05E-06	1.17E-05	7.75E-06	1.78E-06	1.02E-05	6.75E-06		
power plant infrastructure		1.43E-05	1.43E-05	1.43E-05	8.22E-06	8.22E-06	8.22E-06	1.05E-05	8.22E-06
power pl. operation (& others)		4.80E-04	4.80E-04	4.80E-04	3.22E-04	3.22E-04	3.22E-04	4.09E-04	3.56E-04

Table 5.3 Selected LCA results for lignite and lignite/wood co-combustion chains, incl. breakdown of different steps in the entire chains.

		lignite/wood co-firing 950 MW (wood transport: 50km lorry)	lignite/wood co-firing 950 MW (1000km train)	lignite/wood co-firing 950 MW (1000km barge)	lignite (Germany) 950 MW
GHG total	**kg CO2-eq / kWh**	**8.44E-01**	**8.46E-01**	**8.47E-01**	**9.33E-01**
fuel production	coal / gas	1.43E-02	1.43E-02	1.43E-02	1.59E-02
fuel production	wood	1.35E-03	1.35E-03	1.35E-03	
fuel transportation	coal / gas				
fuel transportation	wood	1.67E-03	3.87E-03	4.78E-03	
power plant infrastructure		1.48E-03	1.48E-03	1.48E-03	1.24E-03
power pl. operation (& others)		8.25E-01	8.25E-01	8.25E-01	9.16E-01
CO2	**kg/kWh**	**8.32E-01**	**8.34E-01**	**8.35E-01**	**9.21E-01**
fuel production	coal / gas	9.32E-03	9.32E-03	9.32E-03	1.04E-02
fuel production	wood	1.24E-03	1.24E-03	1.24E-03	
fuel transportation	coal / gas				0.00E+00
fuel transportation	wood	1.59E-03	3.69E-03	4.59E-03	
power plant infrastructure		1.36E-03	1.36E-03	1.36E-03	1.14E-03
power pl. operation (& others)		8.18E-01	8.18E-01	8.18E-01	9.09E-01
NOx	**kg/kWh**	**7.58E-04**	**7.65E-04**	**7.98E-04**	**7.37E-04**
fuel production	coal / gas	2.95E-05	2.95E-05	2.95E-05	3.28E-05
fuel production	wood	1.11E-05	1.11E-05	1.11E-05	
fuel transportation	coal / gas				0.00E+00
fuel transportation	wood	1.32E-05	1.97E-05	5.33E-05	
power plant infrastructure		4.27E-06	4.27E-06	4.27E-06	3.56E-06
power pl. operation (& others)		7.00E-04	7.00E-04	7.00E-04	7.00E-04
PM2.5	**kg/kWh**	**6.64E-05**	**6.68E-05**	**6.69E-05**	**6.46E-05**
fuel production	coal / gas	3.53E-06	3.53E-06	3.53E-06	3.92E-06
fuel production	wood	1.16E-06	1.16E-06	1.16E-06	
fuel transportation	coal / gas				0.00E+00
fuel transportation	wood	8.48E-07	1.28E-06	1.36E-06	
power plant infrastructure		1.23E-06	1.23E-06	1.23E-06	1.02E-06
power pl. operation (& others)		5.96E-05	5.96E-05	5.96E-05	5.97E-05
SO2	**kg/kWh**	**1.59E-04**	**1.68E-04**	**1.64E-04**	**1.68E-04**
fuel production	coal / gas	3.46E-05	3.46E-05	3.46E-05	3.84E-05
fuel production	wood	2.60E-06	2.60E-06	2.60E-06	
fuel transportation	coal / gas				0.00E+00
fuel transportation	wood	1.89E-06	1.08E-05	7.17E-06	
power plant infrastructure		4.18E-06	4.18E-06	4.18E-06	3.47E-06
power pl. operation (& others)		1.16E-04	1.16E-04	1.16E-04	1.26E-04

Table 5.4 Selected LCA results for natural gas and SNG chains, incl. breakdown of different steps in the entire chains.

		nat gas (CH mix) 400 MW CC	nat gas (EU mix) 400 MW CC	SNG 400 MW CC (wood transp: 25km lorry)	SNG 400 MW CC (wood transp: 1000km train)	SNG 400 MW CC (wood transp: 1000km barge)
GHG total	**kg CO2-eq / kWh**	**4.14E-01**	**4.13E-01**	**5.72E-02**	**9.73E-02**	**1.09E-01**
fuel production	coal / gas	1.75E-02	1.61E-02	2.26E-02	2.28E-02	2.27E-02
fuel production	wood			1.76E-02	1.76E-02	1.76E-02
fuel transportation	coal / gas	5.07E-02	5.16E-02	2.35E-03	2.35E-03	2.30E-03
fuel transportation	wood			1.09E-02	5.07E-02	6.26E-02
power plant infrastructure		1.81E-03	1.81E-03	1.81E-03	1.81E-03	1.81E-03
power pl. operation (& others)		3.44E-01	3.44E-01	1.99E-03	1.99E-03	1.99E-03
CO2	**kg/kWh**	**3.89E-01**	**3.89E-01**	**4.58E-02**	**8.39E-02**	**9.55E-02**
fuel production	coal / gas	1.37E-02	1.31E-02	1.64E-02	1.66E-02	1.64E-02
fuel production	wood			1.62E-02	1.62E-02	1.62E-02
fuel transportation	coal / gas	3.14E-02	3.21E-02	1.06E-03	1.06E-03	1.05E-03
fuel transportation	wood			1.04E-02	4.83E-02	6.01E-02
power plant infrastructure		1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03
power pl. operation (& others)		3.42E-01	3.42E-01	4.90E-05	4.90E-05	4.90E-05
NOx	**kg/kWh**	**3.13E-04**	**3.06E-04**	**7.26E-04**	**8.98E-04**	**1.34E-03**
fuel production	coal / gas	4.21E-05	4.27E-05	3.28E-04	3.30E-04	3.29E-04
fuel production	wood			1.45E-04	1.45E-04	1.45E-04
fuel transportation	coal / gas	1.06E-04	9.92E-05	2.10E-06	2.20E-06	3.00E-06
fuel transportation	wood			8.64E-05	2.57E-04	6.97E-04
power plant infrastructure		8.43E-06	8.43E-06	8.43E-06	8.43E-06	8.43E-06
power pl. operation (& others)		1.57E-04	1.56E-04	1.56E-04	1.56E-04	1.56E-04
PM2.5	**kg/kWh**	**8.76E-06**	**8.94E-06**	**4.11E-05**	**5.25E-05**	**5.34E-05**
fuel production	coal / gas	3.32E-06	2.87E-06	1.53E-05	1.54E-05	1.54E-05
fuel production	wood			1.52E-05	1.52E-05	1.52E-05
fuel transportation	coal / gas	6.82E-07	1.25E-06	2.40E-07	2.50E-07	2.40E-07
fuel transportation	wood			5.54E-06	1.68E-05	1.79E-05
power plant infrastructure		1.69E-06	1.69E-06	1.69E-06	1.69E-06	1.69E-06
power pl. operation (& others)		3.07E-06	3.13E-06	3.07E-06	3.06E-06	3.07E-06
SO2	**kg/kWh**	**1.79E-04**	**1.49E-04**	**9.94E-05**	**2.29E-04**	**1.81E-04**
fuel production	coal / gas	1.65E-04	1.34E-04	4.11E-05	4.24E-05	4.12E-05
fuel production	wood			3.40E-05	3.40E-05	3.40E-05
fuel transportation	coal / gas	2.91E-06	4.38E-06	1.22E-06	1.20E-06	1.20E-06
fuel transportation	wood			1.24E-05	1.41E-04	9.38E-05
power plant infrastructure		7.50E-06	7.50E-06	7.50E-06	7.50E-06	7.50E-06
power pl. operation (& others)		3.20E-06	3.10E-06	3.17E-06	3.20E-06	3.20E-06

Table 5.5 Selected LCA results for natural gas/SNG co-combustion chains, incl. breakdown of different steps in the entire chains.

		natural gas/SNG co-firing 400 MW CC (wood transp: 25km lorry)	natural gas/SNG co-firing 400 MW CC (wood transp: 1000km train)	natural gas/SNG co-firing 400 MW CC (wood transp: 1000km barge)
GHG total	**kg CO2-eq / kWh**	**3.78E-01**	**3.82E-01**	**3.83E-01**
fuel production	coal / gas	1.67E-02	1.68E-02	1.67E-02
fuel production	wood	1.76E-03	1.76E-03	1.76E-03
fuel transportation	coal / gas	4.67E-02	4.67E-02	4.67E-02
fuel transportation	wood	1.09E-03	5.07E-03	6.26E-03
power plant infrastructure		1.81E-03	1.81E-03	1.81E-03
power pl. operation (& others)		3.09E-01	3.09E-01	3.09E-01
CO2	**kg/kWh**	**3.54E-01**	**3.58E-01**	**3.59E-01**
fuel production	coal / gas	1.34E-02	1.34E-02	1.34E-02
fuel production	wood	1.62E-03	1.62E-03	1.62E-03
fuel transportation	coal / gas	2.90E-02	2.90E-02	2.90E-02
fuel transportation	wood	1.04E-03	4.83E-03	6.01E-03
power plant infrastructure		1.70E-03	1.70E-03	1.70E-03
power pl. operation (& others)		3.07E-01	3.07E-01	3.07E-01
NOx	**kg/kWh**	**3.48E-04**	**3.65E-04**	**4.09E-04**
fuel production	coal / gas	7.12E-05	7.14E-05	7.13E-05
fuel production	wood	1.45E-05	1.45E-05	1.45E-05
fuel transportation	coal / gas	8.95E-05	8.95E-05	8.96E-05
fuel transportation	wood	8.64E-06	2.57E-05	6.97E-05
power plant infrastructure		8.43E-06	8.43E-06	8.43E-06
power pl. operation (& others)		1.56E-04	1.56E-04	1.56E-04
PM2.5	**kg/kWh**	**1.22E-05**	**1.33E-05**	**1.34E-05**
fuel production	coal / gas	4.12E-06	4.13E-06	4.12E-06
fuel production	wood	1.52E-06	1.52E-06	1.52E-06
fuel transportation	coal / gas	1.14E-06	1.15E-06	1.14E-06
fuel transportation	wood	5.54E-07	1.68E-06	1.79E-06
power plant infrastructure		1.69E-06	1.69E-06	1.69E-06
power pl. operation (& others)		3.13E-06	3.13E-06	3.13E-06
SO2	**kg/kWh**	**1.44E-04**	**1.57E-04**	**1.52E-04**
fuel production	coal / gas	1.24E-04	1.24E-04	1.24E-04
fuel production	wood	3.40E-06	3.40E-06	3.40E-06
fuel transportation	coal / gas	4.06E-06	4.06E-06	4.06E-06
fuel transportation	wood	1.24E-06	1.41E-05	9.38E-06
power plant infrastructure		7.50E-06	7.50E-06	7.50E-06
power pl. operation (& others)		3.11E-06	3.11E-06	3.11E-06

Table 5.6 Selected LCA results for hard coal chains with hard coal supply from different mining regions, incl. breakdown of different steps in the entire chains.

		hard coal 800 MW (AU)	hard coal 800 MW (CN)	hard coal 800 MW (CO)	hard coal 800 MW (D)	hard coal 800 MW (PL)	hard coal 800 MW (RU)	hard coal 800 MW (US)	hard coal 800 MW (ZA)
GHG total	**kg CO2-eq / kWh**	**8.53E-01**	**1.20E+00**	**7.99E-01**	**8.52E-01**	**8.30E-01**	**9.08E-01**	**8.15E-01**	**8.38E-01**
fuel production	coal / gas	2.80E-02	3.51E-01	1.15E-02	1.07E-01	7.65E-02	9.68E-02	3.19E-02	3.54E-02
fuel production	wood								
fuel transportation	coal / gas	8.36E-02	1.01E-01	4.52E-02	5.64E-03	1.22E-02	6.94E-02	4.12E-02	6.04E-02
fuel transportation	wood								
power plant infrastructure		2.75E-03	2.75E-03	2.75E-03	2.75E-03	2.75E-03	2.75E-03	2.75E-03	2.75E-03
power pl. operation (& others)		7.39E-01	7.43E-01	7.40E-01	7.37E-01	7.39E-01	7.39E-01	7.39E-01	7.39E-01
CO2	**kg/kWh**	**8.20E-01**	**1.02E+00**	**7.85E-01**	**7.46E-01**	**7.57E-01**	**8.19E-01**	**7.80E-01**	**7.98E-01**
fuel production	coal / gas	7.44E-03	1.85E-01	8.30E-03	1.06E-02	1.33E-02	2.10E-02	8.20E-03	7.60E-03
fuel production	wood								
fuel transportation	coal / gas	8.11E-02	9.75E-02	4.37E-02	5.37E-03	1.16E-02	6.60E-02	3.97E-02	5.85E-02
fuel transportation	wood								
power plant infrastructure		2.58E-03	2.58E-03	2.58E-03	2.58E-03	2.58E-03	2.58E-03	2.58E-03	2.58E-03
power pl. operation (& others)		7.29E-01	7.33E-01	7.30E-01	7.28E-01	7.29E-01	7.30E-01	7.29E-01	7.29E-01
NOx	**kg/kWh**	**1.81E-03**	**1.93E-03**	**1.46E-03**	**5.20E-04**	**5.72E-04**	**1.10E-03**	**1.11E-03**	**1.43E-03**
fuel production	coal / gas	2.92E-04	2.12E-04	4.78E-04	4.03E-05	5.63E-05	2.00E-04	2.32E-04	2.67E-04
fuel production	wood								
fuel transportation	coal / gas	1.06E-03	1.24E-03	5.26E-04	3.16E-05	6.21E-05	4.46E-04	4.25E-04	7.03E-04
fuel transportation	wood								
power plant infrastructure		6.75E-06	6.75E-06	6.75E-06	6.75E-06	6.75E-06	6.75E-06	6.75E-06	6.75E-06
power pl. operation (& others)		4.49E-04	4.69E-04	4.54E-04	4.41E-04	4.47E-04	4.50E-04	4.48E-04	4.50E-04
PM2.5	**kg/kWh**	**8.31E-05**	**4.02E-04**	**7.27E-05**	**4.62E-05**	**4.99E-05**	**7.44E-05**	**6.37E-05**	**7.26E-05**
fuel production	coal / gas	8.08E-06	3.03E-04	1.32E-05	3.26E-06	4.54E-06	9.00E-06	6.62E-06	7.43E-06
fuel production	wood								
fuel transportation	coal / gas	3.36E-05	5.59E-05	1.77E-05	1.87E-06	4.05E-06	2.39E-05	1.56E-05	2.37E-05
fuel transportation	wood								
power plant infrastructure		3.12E-06	3.12E-06	3.12E-06	3.12E-06	3.12E-06	3.12E-06	3.12E-06	3.12E-06
power pl. operation (& others)		3.83E-05	3.93E-05	3.87E-05	3.80E-05	3.82E-05	3.84E-05	3.83E-05	3.83E-05
SO2	**kg/kWh**	**1.39E-03**	**3.29E-03**	**8.73E-04**	**4.27E-04**	**4.60E-04**	**7.60E-04**	**7.74E-04**	**1.04E-03**
fuel production	coal / gas	2.56E-05	1.74E-03	2.09E-05	4.68E-05	5.64E-05	8.33E-05	3.15E-05	2.82E-05
fuel production	wood								
fuel transportation	coal / gas	9.93E-04	1.14E-03	4.78E-04	1.57E-05	3.41E-05	3.04E-04	3.72E-04	6.42E-04
fuel transportation	wood								
power plant infrastructure		8.22E-06	8.22E-06	8.22E-06	8.22E-06	8.22E-06	8.22E-06	8.22E-06	8.22E-06
power pl. operation (& others)		3.64E-04	3.96E-04	3.66E-04	3.56E-04	3.62E-04	3.64E-04	3.63E-04	3.63E-04

Table 5.7 Selected LCA results for natural gas chains with natural gas from different production regions, incl. breakdown of different steps in the entire chains.

		nat gas (EU mix) 400 MW CC	nat gas (Russia) 400 MW CC	nat gas (Algeria, pipeline) 400 MW CC	nat gas (Algeria, LNG) 400 MW CC	nat gas (UK) 400 MW CC	nat gas (Netherlands) 400 MW CC	nat gas (Norway) 400 MW CC	nat gas (Germany) 400 MW CC	nat gas (Nigeria, LNG) 400 MW CC
GHG total	**kg CO2-eq / kWh**	**4.13E-01**	**4.85E-01**	**3.85E-01**	**4.48E-01**	**3.63E-01**	**3.79E-01**	**3.75E-01**	**3.85E-01**	**5.02E-01**
fuel production	coal / gas	1.61E-02	3.54E-02	1.49E-02	1.71E-02	2.70E-03	1.18E-02	1.01E-02	2.47E-02	1.80E-02
fuel production	wood									
fuel transportation	coal / gas	5.16E-02	1.04E-01	2.42E-02	8.59E-02	1.44E-02	2.13E-02	1.97E-02	1.51E-02	1.39E-01
fuel transportation	wood									
power plant infrastructure		1.81E-03	1.81E-03	1.81E-03	1.81E-03	1.81E-03	1.81E-03	1.81E-03	1.81E-03	1.81E-03
power pl. operation (& others)		3.44E-01	3.44E-01	3.44E-01	3.44E-01	3.44E-01	3.44E-01	3.44E-01	3.44E-01	3.44E-01
CO2	**kg/kWh**	**3.89E-01**	**4.24E-01**	**3.71E-01**	**4.32E-01**	**3.55E-01**	**3.70E-01**	**3.67E-01**	**3.76E-01**	**4.84E-01**
fuel production	coal / gas	1.31E-02	2.08E-02	9.92E-03	1.14E-02	2.49E-03	1.12E-02	9.58E-03	2.33E-02	1.20E-02
fuel production	wood									
fuel transportation	coal / gas	3.21E-02	5.99E-02	1.79E-02	7.75E-02	9.13E-03	1.52E-02	1.38E-02	9.66E-03	1.29E-01
fuel transportation	wood									
power plant infrastructure		1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03	1.70E-03
power pl. operation (& others)		3.42E-01	3.42E-01	3.42E-01	3.42E-01	3.42E-01	3.42E-01	3.42E-01	3.42E-01	3.42E-01
NOx	**kg/kWh**	**3.06E-04**	**4.35E-04**	**2.64E-04**	**2.98E-04**	**2.16E-04**	**2.65E-04**	**2.53E-04**	**2.26E-04**	**4.28E-04**
fuel production	coal / gas	4.27E-05	5.72E-05	3.94E-05	4.53E-05	2.25E-05	5.11E-05	4.37E-05	3.05E-05	4.78E-05
fuel production	wood									
fuel transportation	coal / gas	9.92E-05	2.13E-04	6.09E-05	8.85E-05	2.89E-05	5.02E-05	4.54E-05	3.16E-05	2.16E-04
fuel transportation	wood									
power plant infrastructure		8.43E-06	8.43E-06	8.43E-06	8.43E-06	8.43E-06	8.43E-06	8.43E-06	8.43E-06	8.43E-06
power pl. operation (& others)		1.56E-04	1.56E-04	1.56E-04	1.56E-04	1.56E-04	1.56E-04	1.56E-04	1.56E-04	1.56E-04
PM2.5	**kg/kWh**	**8.94E-06**	**1.00E-05**	**8.37E-06**	**1.26E-05**	**8.01E-06**	**8.98E-06**	**8.42E-06**	**6.44E-06**	**1.96E-05**
fuel production	coal / gas	2.87E-06	3.41E-06	2.75E-06	3.15E-06	2.71E-06	3.47E-06	2.97E-06	1.13E-06	3.33E-06
fuel production	wood									
fuel transportation	coal / gas	1.25E-06	1.87E-06	8.65E-07	4.64E-06	5.36E-07	7.48E-07	6.94E-07	5.61E-07	1.15E-05
fuel transportation	wood									
power plant infrastructure		1.69E-06	1.69E-06	1.69E-06	1.69E-06	1.69E-06	1.69E-06	1.69E-06	1.69E-06	1.69E-06
power pl. operation (& others)		3.13E-06	3.06E-06	3.07E-06	3.06E-06	3.07E-06	3.07E-06	3.07E-06	3.07E-06	3.08E-06
SO2	**kg/kWh**	**1.49E-04**	**3.28E-04**	**2.28E-05**	**4.53E-05**	**2.69E-05**	**2.47E-05**	**2.34E-05**	**5.14E-04**	**1.57E-04**
fuel production	coal / gas	1.34E-04	3.10E-04	5.19E-06	5.95E-06	1.04E-05	7.47E-06	6.39E-06	4.98E-04	6.29E-06
fuel production	wood									
fuel transportation	coal / gas	4.38E-06	6.80E-06	6.90E-06	2.87E-05	5.83E-06	6.52E-06	6.35E-06	5.70E-06	1.40E-04
fuel transportation	wood									
power plant infrastructure		7.50E-06	7.50E-06	7.50E-06	7.50E-06	7.50E-06	7.50E-06	7.50E-06	7.50E-06	7.50E-06
power pl. operation (& others)		3.10E-06	3.20E-06	3.18E-06	3.17E-06	3.17E-06	3.17E-06	3.17E-06	3.20E-06	3.10E-06

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