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Documentation for the UMBERTO based ifeu electricity model

Status: 06/2016

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Heidelberg, June 2016

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1 Objective

The present UMBERTO based "master network" for the modelling of grid power was developed in 2001 by ifeu and has been maintained and updated on a regular basis. The network model comprises basic power plant types and raw material upstream processes, and allows for a flexible approach to different types of network composition, e.g. national power grid networks, group based or other special scenarios, including future or marginal mixes. The parameterisation of the model is realized via relative adjustments concerning the energy mix, information input regarding raw material origin, and the customization of technical parameters (efficiencies, exhaust gas treatment, etc.).

The model is applied on a regular basis to quantify the environmental impacts of the electricity supply for Germany as well as other European or non-European countries covered by the EUROSTAT and the International Energy Agency (IEA) data service. In addition it is applied to determine the impacts of regional mixes (e.g. EU28 or UCTE). Updates are conducted annually for European countries and biennially for other countries.

The current status documented in the following paper is June 2016; the reference year of presented data and calculation results is 2013.

2 Total System Network

The overall electricity grid is calculated using the material flow modelling software UMBERTO. The basic network features a set of individual modules representing basic energy sources and power plant types (see Figure 1). The modules themselves are layered subnets, comprising more detailed modules representing separate process steps. The applied fuel mix and essential technical characteristics of the energy supply systems are adjustable via a series of parameters (referred to as network, subnet or transition parameters).

2.1 System definition and system boundary

The system boundary of the entire model encompasses the following sections (illustrated in Figure 1):

- upstream fuel chains (coal, lignite, natural gas, coke and blast furnace gas, nuclear fuel, biomass)
- power plant processes for electricity generation using the above listed fuels and solar, hydroelectric and wind power, as well as waste for incineration
- distribution of electricity to the consumer with appropriate distribution and transformation losses

The input and output material flows crossing the system boundaries almost exclusively represent elementary streams. All upstream and downstream processes are included in the material flow model with the exception of marginal flows, which are disregarded due to their irrelevance. The waste input or output flows crossing the system boundary are to be understood as secondary material for recycling (e.g. gypsum as building material). Accordingly, the burden of recovery as well as the benefit from recycling is not accounted for. Waste to landfill and incineration are included and cross the system boundary as information output (e.g. “landfill volume”).

The expenses of can be included or exclude within the model by modifying the respective central network parameters. Expanses of capital goods include the provision of the most important building materials (steel alloy in different stages, various non-ferrous metals, plastics, cement, concrete, bitumen, etc.) as well as the energy use for the production of these goods (data are taken from ECOINVENT).

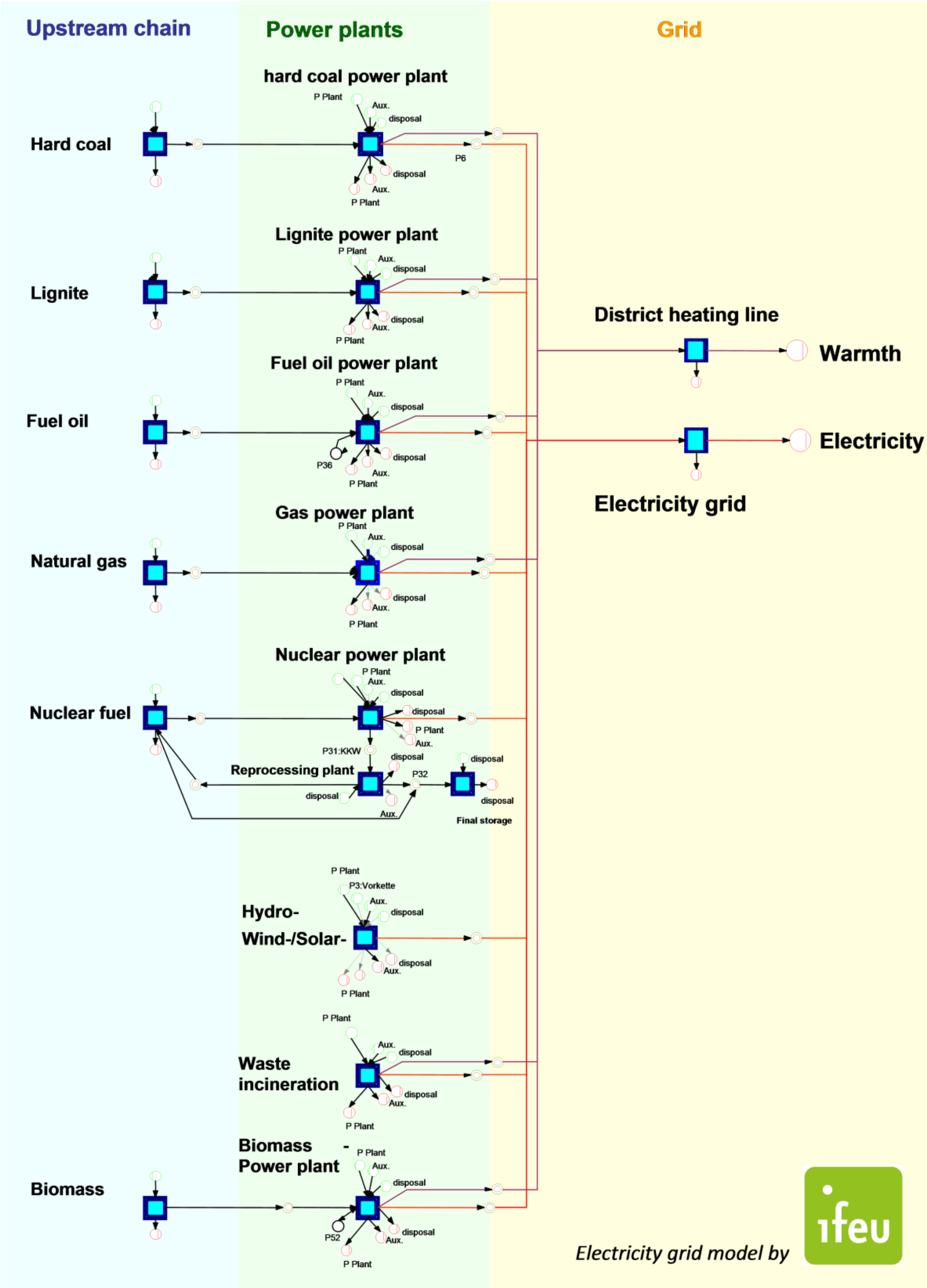

Figure 1 Umberto network of the entire power grid

The input of renewable energy sources such as wind or hydropower are summarized as cumulated renewable energy demand (“CED, renewable”) in supply chains and during production processes within the model. Pumped storage hydropower plants are not part of the primary power generating facilities but are categorized as an intermediate storage of base load electricity, including the corresponding losses from multiple energy conversions. Other expenditures or emissions from renewable energy sources are neglected. The primary energy utilisation for renewable energy sources is set to 100% according to AGEB (2015) methodology.

The generated electricity from all sources experiences losses during power transformation and distribution along the distance between power plant and consumer. The overall loss rate depends on the applied voltage level (e.g. for Germany: 1.5% at high-voltage, 2.6 % at medium-voltage and 5.4 % at low-voltage). Average loss rates without the consideration of voltage levels can be applied according to country specific values from EUROSTAT and IEA statistics (e.g. 4.1% for Germany). The selection of voltage level loss rates or average loss rates for electricity is accessible via network parameters.

The settings for average electricity consumption on different voltage levels can be selected. Default settings for the situation in Germany (2013) are:

- High-voltage 2 %
- Medium-voltage 46 %
- Low-voltage 52 %

Figure 2 illustrates the general electricity grid setting, including generation, distribution and consumption.

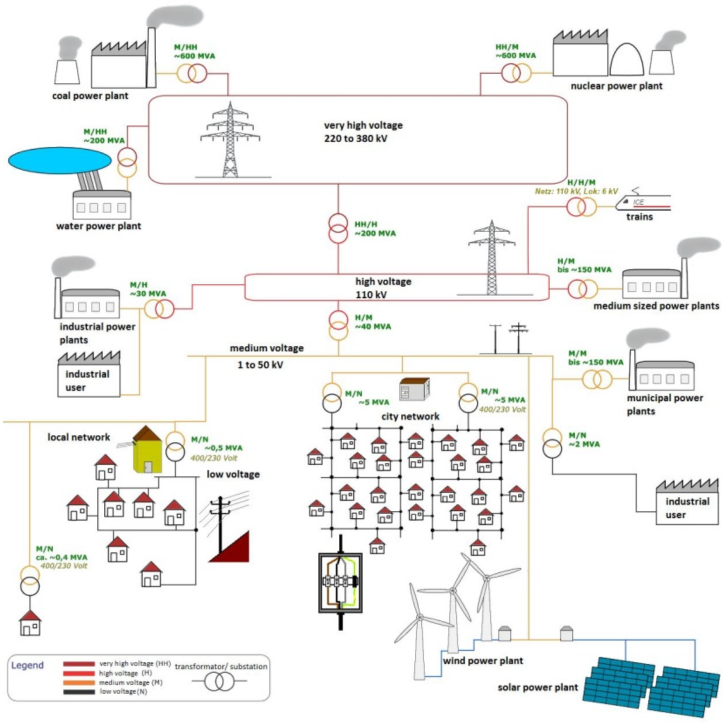

Figure 2 Electricity supply grid. Source: https://upload.wikimedia.org/wikipedia/commons/e/ed/Stromversorgung.png)

2.2 Allocation

Combined heat and power generation

The network also includes the combined production of electricity and district heat with adjustable shares of heat and power, according to the power plant type. An assignment of the respective burdens on electricity and district heat is realized through allocation based on the concept of exergy. The assignment of an exergy value to the generated electricity is performed by applying a factor of $C_{el} = 1$, implying that all energy from electricity can be made available for mechanical work. The exergy content of heat is evaluated using the Carnot efficiency, which is calculated via the following formula:

$$C_h = \frac{T_h - T_0}{T_h}$$

with T_h = temperature of available heat in Kelvin and

T_0 = environmental temperature, set to 273 Kelvin (0°C)

Waste incineration

The emissions from and resource requirements for waste incineration are allocated to the waste disposal service as a default setting. As a consequence the supply of energy from waste incineration does not carry any ecological burdens.

3 Subsystem Power Plants

The model features the following modules, representing basic types of power generating plants and systems. The respective UMBERTO subnets are discussed in detail within the subsections of this chapter:

- 3.1 Coal power plant
- 3.2 Lignite power plant
- 3.2 Thermal Oil power plant
- 3.4 Gas power plant
- 3.5 Nuclear power plant
- 3.6 Water, wind and geothermal power plant, photovoltaic systems
- 3.7 Biomass power plant
- 3.8 Waste incineration

The system boundary of each power plant subnet encompasses the actual power plant processes for electricity production, the upstream supply chains and materials (such as limestone, ammonia), and the disposal of non-recyclable waste from the process going to landfill for inert materials (e.g. ash, granules) or hazardous waste landfill, e.g. flue gas desulfurization (FGD) sludge.

The emissions from all power plants are calculated in accordance with recommendations of the German Federal Environment Agency (UBA) as far as possible. Exceptions to the application of these recommendations may be e.g. fuel related restrictions.

3.1 Coal power plant

The hard coal power plant subnet illustrated in Figure 2 consists of a network of separate modules for the process steps:

- coal drying and pulverization within the coal mill
- heating unit (furnace) and boiler
- exhaust gas treatment modules

Technical information about these processes is based on data sets from various individual plants collected by ifeu, process information from ECOINVENT, as well as data from Rentz and Martel [1998].

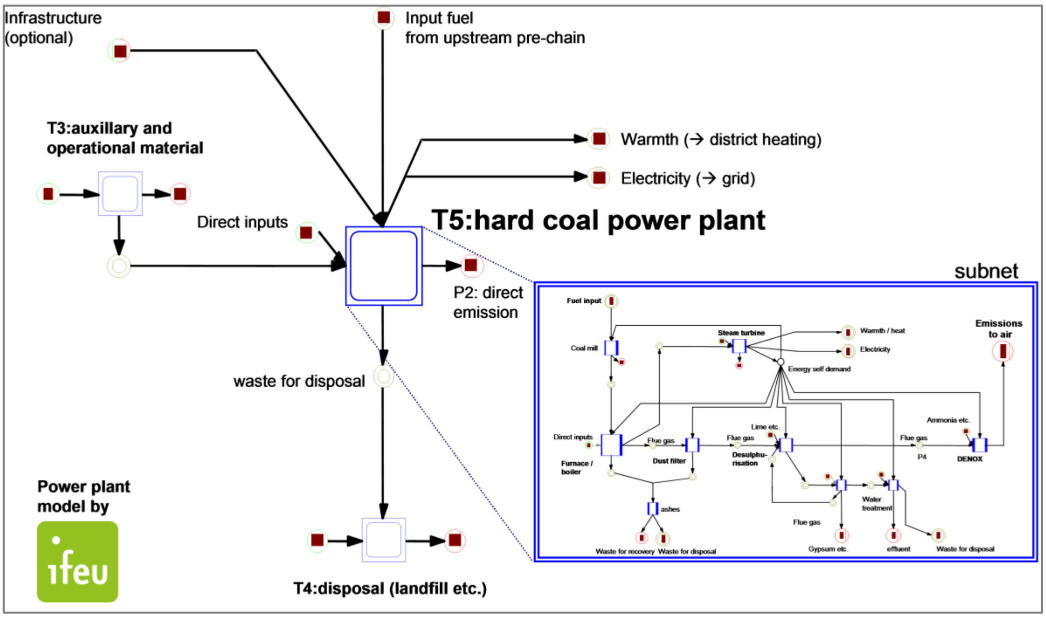

Figure 3 Umberto network of a coal power plant (exemplary for other thermal power plants)

The overall energy efficiency of the coal power plant is specified for each individual country according to the respective statistical information (IEA 2013, see Table 2). The net electricity supply into the power grid is calculated as the overall electricity production minus the technology specific internl power consumption (e.g. 6.2% for 2006 German technology standards). Pre-chains include ground limestone, lime and ammonia as auxiliary and operational resources (Patyk 1997).

The coal power plant subnet features a mix of combustion technologies. The default settings for the shares of technologies mirror the typical situation in Germany as follows:

- 62% dust or dry combustion
- 36% slag tap firing
- 2% fluidised bed combustion
- <1% grate combustion (ignored)

The mix of combustion technologies is adjustable within the coal power plant subnet (see Table 2 for country specific settings). The desired fuel mix is accessed via pre-chain settings. The applied fuels and the mix of technologies with different release rates influence the quantities and quality of emitted flue gas and ash. Assumptions for these emissions of coal power plants are listed in Table 1 for Germany.

The exhaust gas treatment modules include a dust filter (electrostatic precipitator), a flue gas desulfurization unit (FGD, country specific settings for the proportion of wet, dry and quasi dry FGD), and a DENOX catalytic converter with 80% efficiency for denitrification. The country specific share of plants using DENOX facilities can be addressed by parameter settings. The wet FGD requires an additional treatment of washing water, resulting in wastewater emissions.

The composition of gas output from the coal power plan subnet is a result of the applied fuel mix and the release rates of the individual gases, depending on the combustion technology. The carbon dioxide emissions are calculated from the carbon content of the fuel.

Waste recycling is not included within the subnet. The following wastes are considered: boiler slag (recycled 100%), filtered ash from dust combustion (80% recovered, 20% inert materials landfill), coarse ash from dust combustion (20% recovered, 80% inert materials landfill), FGD gypsum (recycled 100%), and precipitated sludge from FGD (100% hazardous waste landfill).

Table 1 Default settings for the emissions from coal power plants for Germany

Substance	Value	Unit	Source
SO_2	184.8	mg/Nm³	Rentz
NO_X	176.2	mg/Nm³	Rentz
CO	23.9	mg/Nm³	Rentz
Dust	10.2	mg/Nm³	Rentz
N_2O	11.8	mg/Nm³	Rentz
HCl	9.9	% emission after	ECOINVENT 2000
HF	27	% emission after	ECOINVENT 2000
Particles	7.95	kBq/TJ_{in}	ECOINVENT 2000
As	1.57	g/TJ_{in}	Gromke, Detzel
Cd	0.11	g/TJ_{in}	Gromke, Detzel
Cr	0.88	g/TJ_{in}	Gromke, Detzel
Cu	1.29	g/TJ_{in}	Gromke, Detzel
Hg	1.13	g/TJ_{in}	Gromke, Detzel
Ni	1.77	g/TJ_{in}	Gromke, Detzel
Pb	4.04	g/TJ_{in}	Gromke, Detzel
Se	0.12	g/TJ_{in}	Gromke, Detzel
Zn	6.42	g/TJ_{in}	Gromke, Detzel
Methane	1	kg/TJ_{in}	ECOINVENT 2000
NMVOC	2	kg/TJ_{in}	ECOINVENT 2000
Formaldehyde	60	g/TJ_{in}	ECOINVENT 2000
PAH	1	g/TJ_{in}	ECOINVENT 2000
B(a)P	0.2	mg/TJ_{in}	ECOINVENT 2000
Dioxin	7	$\mu g/TJ_{in}$	ECOINVENT 2000
Radionuclide Rn 220	273	kBq/TJ_{in}	ECOINVENT 2000
Radionuclide Rn 222	485	kBq/TJ_{in}	ECOINVENT 2000

Table 2 Technical data for selected European countries and EU-28 (2013): hard coal power plant

	Europe EU-28	Germany	France	United Kingdom
General				
Power Consumption of Power Plant	8.0%	8.0%	8.0%	8.0%
Combustion Technology				
Wet Bottom Boiler	36.0%	45.0%	36.0%	36.0%
Dry Bottom Boiler	62.0%	50.0%	62.0%	62.0%
Fluidised Bed Combustion	2.0%	5.0%	2.0%	2.0%
Exhaust Gas Cleaning				
Wet FGD*	5.0%	80.0%	50.0%	50.0%
Semi-dry FGD*	25.0%	15.0%	25.0%	25.0%
Dry FGD*	40.0%	5.0%	25.0%	25.0%
Catalytic Denitrification	20.0%	100.0%	50.0%	50.0%
Coke Adsorption	0.0%	0.0%	0.0%	0.0%
Energy Efficiency				
Overall	44%	47%	38%	39%
Gross Electric Efficiency	37.0%	36.9%	37.9%	39.2%
Thermal Efficiency (for District Heating)	7.4%	9.7%	0.4%	0.0%

* Flue Gas Desulfurization (FGD)

3.2 Lignite power plant

The internal structure of the lignite power plant subnet resembles the coal power plant.

Technical information about these processes is based on data sets from various individual plants collected by ifeu, and process information from ECOINVENT.

The overall energy efficiency of the lignite power plant is specified for each individual country. Pre-chains include ground limestone, lime and ammonia as auxiliary and operational resources (Patyk 1997).

The lignite power plant subnet features a mix of combustion technologies. The default settings for the shares of technologies in Germany are the following:

- 95% dust combustion
- 5% fluidised bed combustion

The mix of combustion technologies is adjustable within the lignite power plant subnet (see Table 4 for country specific settings). The applied fuels and the mix of technologies with different release rates influence the quantities and quality of emitted flue gas and ash.

The exhaust gas treatment modules include a dust filter (electrostatic precipitator) and a flue gas desulfurization unit (FGD, country specific settings are used for the proportion of wet, dry and quasi dry FGD). The use of a DENOX catalytic convertor is usually avoided.

NO_x emissions are reduced to a standard value of 250 mg/m^3 by other methods. The wastewater from wet FGD is used to treat filter dusts for further use in the land re-cultivation of surface mining areas. Long term aquatic releases are included in the model based on ECOINVENT assumptions.

Waste recycling is not included within the subnet. The following wastes are considered: Ash (recycled 100% into the open pit including installation costs, for long term emissions see above), coarse ash from dust combustion (20% recovered, 80% inert materials landfill), and FGD gypsum (recycled 100%).

Table 3 Default settings for the emissions from lignite power plants for Germany

Substance	Value	Unit	Comment	Source
SO_2	184.8	mg/Nm³		Rentz
NO_X	176.2	mg/Nm³		Rentz
CO	23.9	mg/Nm³		Rentz
Dust	10.2	mg/Nm³		Rentz
N_2O	11.8	mg/Nm³		Rentz
HCl	9.9	% emission after FGD		ECOINVENT 2000
HF	27	% emission after FGD		ECOINVENT 2000
Particles	7.95	kBq/TJ_{in}		ECOINVENT 2000
As	0.38	g/TJ_{in}		Gromke, Detzel
Cd	0.08	g/TJ_{in}		Gromke, Detzel
Cr	0.35	g/TJ_{in}		Gromke, Detzel
Cu	0.67	g/TJ_{in}		Gromke, Detzel
Hg	0.5	g/TJ_{in}		Gromke, Detzel
Ni	0.63	g/TJ_{in}		Gromke, Detzel
Pb	0.44	g/TJ_{in}		Gromke, Detzel
Se	-	g/TJ_{in}		Gromke, Detzel
Zn	0.77	g/TJ_{in}		Gromke, Detzel
Methane	1	kg/TJ_{in}		ECOINVENT 2000
NMVOC	2	kg/TJ_{in}		ECOINVENT 2000
Formaldehyde	60	g/TJ_{in}		ECOINVENT 2000
PAH	1	g/TJ_{in}		ECOINVENT 2000
B(a)P	0.2	mg/TJ_{in}		ECOINVENT 2000
Dioxin	7	µg/TJ_{in}		ECOINVENT 2000
Radionuclide Rn 220	138	kBq/TJ_{in}		ECOINVENT 2000
Radionuclide Rn 222	245	kBq/TJ_{in}		ECOINVENT 2000

Table 4 Technical data for selected European countries and EU-28 (2013): lignite power plant

	Europe EU-28	Germany	France	United Kingdom
General				
Power Consumption of Power Plant	7.8%	7.8%	7.8%	7.8%
Combustion Technology				
Dry Bottom Boiler	95.0%	95.0%	95.0%	95.0%
Fluidised Bed Combustion	5.0%	5.0%	5.0%	5.0%
Exhaust Gas Cleaning				
Wet FGD*	5.0%	80.0%	80.0%	80.0%
Semi-dry FGD*	25.0%	15.0%	15.0%	15.0%
Dry FGD*	40.0%	5.0%	5.0%	5.0%
Catalytic Denitrification	0.0%	0.0%	0.0%	0.0%
Coke Adsorption	0.0%	0.0%	0.0%	0.0%
Energy Efficiency				
Overall	40%	41%	40%	35%
Gross Electric Efficiency	35.2%	38.3%	35.2%	35.2%
Thermal Efficiency (for District Heating)	4.9%	2.7%	4.9%	0.0%

* Flue Gas Desulfurization (FGD)

3.3 Thermal Oil power plant

The internal structure of the thermal oil power plant subnet resembles the preceding subnets. The oil power plant exhaust gas treatment module consists of flue gas desulfurization only (FGD, country specific settings are used for the proportion of wet, dry and quasi dry FGD, see Table 5).

The emissions of SO_2 and dust from the oil power plant are not in accordance with recommendations of the German Federal Environment Agency (UBA) due to their strong dependence on the used fuel. The same applies for cadmium, mercury and selenium.

Table 5 Technical data for selected European countries and EU-28 (2013): thermal oil power plant

	Europe EU-28	Germany	France	United Kingdom
General				
Power Consumption of Power Plant	8.4%	8.4%	8.4%	8.4%
Exhaust Gas Cleaning				
Wet FGD*	0.0%	0.0%	0.0%	0.0%
Semi-dry FGD*	25.0%	50.0%	50.0%	50.0%
Dry FGD*	35.0%	30.0%	30.0%	30.0%
Catalytic Denitrification	0.0%	0.0%	0.0%	0.0%
Coke Adsorption	0.0%	0.0%	0.0%	0.0%
Energy Efficiency				
Overall	54%	44%	55%	40%
Gross Electric Efficiency	39.7%	39.7%	37.8%	39.7%
Thermal Efficiency (for District Heating)	14.6%	3.8%	17.0%	0.0%

* Flue Gas Desulfurization (FGD)

3.4 Gas power plant

The internal structure of the gas power plant subnet resembles the preceding subnets.

The country specific gross electric and thermal energy efficiencies are determined by statistics of EUROSTAT and IEA. In addition to natural gas, the gas power plant may use technical gases such as blast furnace gas, coke oven gas, and refinery gas, each with country specific shares.

The gas power plant subnet features a mix of combustion technologies. The default settings for the shares of technologies in Germany (2006) are the following:

- 80% combined cycle cogeneration (CHP, combined heat and power) plants
- 15% gas-fired boiler/steam turbine
- 5% motor block CHP plants
- 0% gas turbine

The mix of combustion technologies is adjustable within the gas power plant subnet (see Table 6 for country specific settings). The overall energy efficiency of the gas power plant depends on the applied mix of combustion technologies.

Information on gas emissions is partly taken from Rentz [2002] (NO_x, CO, dust, N_2O). Other combustion related emissions (methane, NMVOC, etc.) are derived from ECOINVENT Erdgas and GEMIS 4.1. Input-related emissions (CO_2, SO_2, mercury (ECOINVENT)) are influenced by the gas composition. The carbon dioxide emissions are calculated from the carbon content of the gas (average carbon content of natural gas: 54%). Country specific settings are provided in Table 6. The emissions of SO_2 are not in accordance with recommendations of the German Federal Environment Agency (UBA) due to their strong dependence on the used fuel.

Table 6 Technical data for selected European countries and EU-28 (2013): gas power plant

	Europe EU-28	Germany	France	United Kingdom
General				
Power Consumption of Power Plant	3.5%	3.5%	3.5%	3.5%
Combustion Technology				
Boiler/ Steam Turbine	80.0%	20.0%	70.0%	70.0%
Gas Turbine	10.0%	0.0%	5.0%	5.0%
Combined Cycle CHP	10.0%	75.0%	20.0%	20.0%
Motor Cogeneration Plant	0.0%	5.0%	5.0%	5.0%
Energy Efficiency				
Overall	62%	64%	62%	50%
Gross Electric Efficiency - Boiler/ Steam Turbine	46.0%	44.0%	40.7%	50.2%
Gross Electric Efficiency - Gas Turbine	46.0%	44.0%	40.7%	50.2%
Gross Electric Efficiency - Combined Cycle CHP	46.0%	44.0%	40.7%	50.2%
Gross Electric Efficiency - Motor Cogen. Plant	46.0%	44.0%	40.7%	50.2%
Thermal Efficiency* - Boiler/ Steam Turbine	16.0%	20.2%	21.4%	0.0%
Thermal Efficiency* - Gas Turbine	16.0%	20.2%	21.4%	0.0%
Thermal Efficiency* - Combined Cycle CHP	16.0%	20.2%	21.4%	0.0%
Thermal Efficiency* - Motor Cogeneration Plant	16.0%	20.2%	21.4%	0.0%

* for Distinct Heating

3.5 Nuclear power plant

This nuclear power plant subnet describes the average situation of nuclear power plants in Europe based on the conditions during the early 90's. The data rely mainly on information from ECOINVENT, which again is based on data from Switzerland.

The gross electrical efficiency of the nuclear power plant is set to 33%. Internal power consumption reduces the net electricity supply into the power grid to 31% (relative to the energy input from uranium fuel).

The pre-chain subsystem holds all information on nuclear fuel. Further upstream or downstream processes are disregarded due to the negligible mass flows.

The technologies applied include the following assumptions:

- 70% pressurized water reactors (PWR, with 3.5% uranium-235 enrichment)
- 30% boiling water reactors (BWR, with 3.4% uranium-235 enrichment)

The country specific mix of these technologies is adjustable within the nuclear power plant subnet, based on IAEA values (2009) (see Table 7). The energy burn-up values are set to

6,375 MJ/kg uranium for PWR and at 6,000 MJ/kg uranium for BWR. Radionuclide emissions are based on information from ECOINVENT.

Table 7 Technical data for selected European countries and EU-28 (2013): nuclear power plant

	Europe EU-28	Germany	France	United Kingdom
General				
Power Consumption of Power Plant	5.3%	5.3%	5.3%	5.3%
Share of Boiling Water Reactor	0.0%	32.0%	0.0%	0.0%
Energy Efficiency				
Gross Electric Efficiency	33.3%	33.3%	33.3%	33.3%

3.6 Water, wind and geothermal power plant, photovoltaic systems

These power plants are based on renewable energy sources and characterised by the absence of upstream fuel chains. Moreover, they feature no significant upstream or downstream chains at all. The relationship between primary energy input from the environment (renewable CED) and the electrical energy output is assumed to be 1:1.

3.7 Biomass power plant

The internal structure of the biomass power plant subnet resembles the coal power plant.

The overall energy efficiency of the biomass power plant is specified for each individual country (see Table 8). Pre-chains include ground limestone, lime and ammonia as auxiliary and operational resources (Patyk 1997).

The biomass power plant subnet features a mix of combustion technologies. The default settings for the shares of technologies in Germany are the following:

- 50% grate combustion
- 50% fluidised bed combustion

The mix of combustion technologies is adjustable within the biomass power plant subnet and affects the ash quality. Emissions are assumed to comply with limit values for waste incineration. Average wood quality and combustion behaviour are based on Obernberger [1998] in order to calculate the fuel dependent flue gas before treatment.

The exhaust gas treatment modules include a dust filter (electrostatic precipitator) and dry absorption with an activated carbon/calcium hydroxide mixture. For country specific settings see Table 8.

Waste recycling is not included within the subnet. The following wastes are considered: filter ash (recycled 100%), grade ash (20% recovered, 80% inert materials landfill), and old absorbent (100% landfill).

Table 8 Technical data for selected European countries and EU-28 (2013): biomass power plant

	Europe EU-28	Germany	France	United Kingdom
General				
Power Consumption of Power Plant	8.5%	8.5%	8.5%	8.5%
Combustion Technology				
Dry Bottom Boiler	50.0%	50.0%	50.0%	50.0%
Fluidised Bed Combustion	50.0%	50.0%	50.0%	50.0%
Exhaust Gas Cleaning				
Dry Flue Gas Desulfurization (FGD)	50.0%	90.0%	90.0%	90.0%
Catalytic Denitrification	0.0%	0.0%	0.0%	0.0%
Coke Adsorption	50.0%	90.0%	90.0%	90.0%
Energy Efficiency				
Overall	54%	48%	47%	36%
Gross Electric Efficiency	35.2%	42.9%	21.0%	35.9%
Thermal Efficiency (for District Heating)	18.7%	5.1%	26.1%	0.0%

3.8 Waste incineration

The subnet for waste incineration describes the combustion of household or household-like waste within an incineration power plant according to German best available technology. The specifications of the default plant mirrors the average situation of the German incineration plants for municipal solid waste. The individual plants within this set exhibit a variety of different energy use concepts, ranging from pure electricity generation to pure process steam generation. The subnet comprises the following technology modules:

- combustion unit (grate)
- high-standard exhaust gas treatment with heat recovery

Technical specifications of the waste incineration plant are based on detailed analyses of individual plants as well as an in-depth review of the entire set of plants in Germany (Fehrenbach et al. 2008).

The net energy outputs of the default incineration plant are 10% for electricity and 30% for useable heat in relation to the energy input of waste, according to the average situation of waste incineration in Germany. These values are associated with the heating value (from combustion) of the waste input. Fuel input for the waste incineration plant comprises all household and household-like waste (mixed, solid, fragments, non-hazardous) with heating values of 5-14 MJ/kg. The default waste input represents average household waste with a heating value of 9 MJ/kg and the corresponding material composition.

The flue gas treatment system is designed such that it ensures a very efficient pollutant retention as well as a differentiated waste output generation to allow for best possible recycling properties. Residues and flue gas treatment products represent additional material flows. The system also serves as an optimised utilisation of heat.

The main emissions of the incineration plant are due to the release of treated flue gas through the stack. With average waste composition the concentrations of pollutants within the treated flue gas lie well below the limits specified by German law (17. BImSchV, Federal Immission Control Ordinance in Germany). Emission data for other input waste compositions are based on data sets from various individual plants collected by ifeu. The system operates without an output of process waste water. The emissions are allocated to the waste input instead of the produced electricity (see Chapter 2.2) for the standard parameter settings. The allocation is calculated as follows:

- Combustion-related emissions (e.g. CO, NO_x, dioxins and other organics):
  The total load is divided according to the exhaust volume created by the input wastes. A combustion calculation which takes into account the combustion specific excess air values (Lambda value) is applied.

- Emissions of waste input-related substances (SO_2, HCl, heavy metals):
  The calculation considers the inventory of substances in the input wastes, the pollutant transfer into the flue gas, and the behaviour during exhaust gas cleaning.

4 Subsystem Upstream Chains

The following fuel types are considered as input for the basic types of power generating plants:

- 4.1 Hard Coal
- 4.2 Lignite
- 4.3 Fuel oil
- 4.4 Gases
- 4.5 Nuclear fuel rods
- 4.6 Biomass

The system boundary of each upstream chain extends from the mining to the factory gate of respective power plant, and includes transportation, processing and the required refining steps. The figures also include the auxiliary and operational material consumption as well as the elimination of resulting non-recyclable waste.

4.1 Hard coal

The hard coal upstream chain subnet considers datasets for the following exporting countries and regions: Germany, Western Europe, Eastern Europe, Russia, South Africa, North America, South America, Australia and East Asia. The major difference between the data sets for German and Western European hard coal lies in transport by ship, which is omitted in the case of hard coal both extracted and used in Germany. Generally, all upstream chains take into account the transportation of materials to the power generating country of interest. ECOINVENT *Kohle* serves as the basis for the data. The assumptions for selected individual countries can be found in the Table 9.

Table 9 Shares of hard coal by country for national import mixes of selected European countries

	Imports to Germany	Imports to France	Imports to United Kingdom
Import share in %	77.1%	100%	84.0%
Exporting countries / regions			
Australia	10.6%	32.5%	11.1%
Germany	0.0%	0.6%	0.1%
North America	9.5%	15.0%	8.4%
East Asia	0.0%	2.9%	1.1%
Eastern Europe	14.1%	2.6%	0.3%
Russia	17.0%	6.9%	40.6%
South America	11.2%	14.0%	7.5%
Western Europe	0.0%	1.2%	0.1%
South Africa	14.5%	24.4%	15.0%

4.2 Lignite

The extraction and processing data within the lignite upstream chain subnet are based on ECOINVENT *Kohle*, combining data from various European countries (Germany, Czech Republic and Slovakia, Greece, former Yugoslavia, Spain and Austria). Infrastructure is not considered. Transportation expenditures comprise belt conveyors directly and continuously supplying treatment facilities with raw lignite.

The applied standard elemental composition of lignite is based on the German situation in 2007 due to a lack of information on lignite composition from other countries. The German lignite mix is assumed according to DIW 2007 for the year 2006 (Rhenish field: 56%, Central Germany: 11%, Lausitz: 33%). Accordingly, an average water content of 55.7% and a heating value of 9.11 MJ/kg are assumed.

4.3 Fuel oil

The fuel oil upstream chain subnet is divided into two main sections:

- recovery and transportation to the refinery (crude oil upstream chain)
- refining and transportation to the power plant

The first section is modelled on the basis of ECOINVENT data and comprises exploration, recovery (primary, secondary, and tertiary), refining and transportation by tanker (OPEC) and pipeline (North Sea, CIS). The import mix of crude oil is generally subject to strong fluctuations regarding the countries or regions of origin. Thus, a constant average mix of 30% of OPEC, 30% North Sea, 30% CIS and 10% Germany is assumed for German crude oil imports. The same simplified assumption is applied for other countries with a significant share of fuel oil based power generation (e.g. Italy, Portugal, Ireland).

The modelling of refineries is conducted via the refinery model developed at ifeu. Underlying data are based on Hedden and Jess, the Association of the German Petroleum Industry, and various sets of corporate data researched by ifeu.

Heavy fuel oil

The allocation of loads to the refinery co-product heavy fuel oil is based on the following principle: Generally loads are allocated based on mass. The load from cracking processes serving the reduction of heavy residues are not allocated to respective residue.

The considered heavy fuel oil composition results from mix of vacuum and cracker residues (70%) and lightweight, highly desulphurised fuel oil (30%). An average sulphur content of 1.3% and concentrations of 40 mg nickel/kg and 100 mg vanadium/kg are assumed.

Light fuel oil

The upstream chain for light fuel oil was added for smaller heating plants. The UMBERTO library module is used temporarily, which is based on GEMIS 4.1 and ECOINVENT.

4.4 Gases

The upstream chain subnet for gases comprises natural gas processing from extraction to delivery at the gas power plant gate. Data are based on GEMIS 4.1, complemented by ECOINVENT data on heavy metal release rates (e.g. mercury and POP). The module for natural gas exports by the UK is supplied separately (based on ECOINVENT Erdöl).

The German natural gas consumption mix comprises gas from Germany (10.7 Vol.-%), CIS (38.0 Vol.-%), Norway (17.8 Vol.-%), and The Netherlands (33.5 Vol.-%). This natural gas mix has an average heating value of 47.1 MJ/kg and a density of 0,786 kg/m^3. Import mixes for other countries are listed in the Table 10.

The overall gas use in Germany comprises a mix of

- 56.2 Vol.-% blast furnace gas (heating value 2.5 MJ/kg, density 1.4 kg/m^3)
- 41.3 Vol.-% natural gas (heating value 47 MJ/kg, density 0.79 kg/m^3)
- 2.5 Vol.-% coke oven gas (heating value 35 MJ/kg, density 0.5 kg/m^3)
- 0.0 Vol.-% refinery gas (heating value: 49 MJ/kg, density 1.0 kg/m^3)

The respective upstream processes were developed by ifeu in a separate model.

Table 10 Shares of natural gas by country for national import mixes of selected European countries, Eurostat annual statistics for 2007, edition 2009

	Imports to Germany	Imports to France	Imports to United Kingdom
Import share in %	84.74%	97.64%	28.72%
Exporting countries / regions			
Germany	0.00%	0.00%	0.00%
Russia	36.61%	13.18%	0.00%
The Netherlands	10.79%	13.56%	4.30%
Norway	26.54%	30.53%	19.18%
North Africa	0.00%	26.82%	0.94%
United Kingdom	10.79%	13.56%	4.30%

4.5 Nuclear fuel rods

The upstream fuel chain subnet encompasses the following steps:

- uranium ore mining (40% surface mining, 60% deep mining)
- preparation (from 0.25 to 0.73% uranium concentration within the ore)
- conversion to uranium hexafluoride (to 67.6 %)
- enrichment (24% via diffusion, 76% via centrifugation)
- fuel rod production
- intermediate storage of waste
- vitrification of waste and final storage
- reprocessing to mixed oxide fuel for fuel rod production

4.6 Biomass

The importance of this energy source is increasing rapidly. Current biomass is mainly based on biogas and wood, including fresh wood (e.g. from forest thinning) and scrap wood with varying levels of pollution.

The specification of characteristics for this energy carrier with respect to a particular reference year is challenging. The simplified assumption used within the biomass subnet is based on the typical upstream chain. The biomass subnet comprises the following production steps for this substitute material:

- Agriculture/forestry
- Energy and utility production
- Processing
- Transportation

5 Country Specific Settings

The introduced subsystems and subnets within the complete grid network “overall power generation” can be adapted to virtually any power grid specification using parameter settings. The quality of this grid may be national, international, regional or group specific. The application of the model for the calculation of national power generation grids or the mix of EU member states is widespread. Details on the country specific use of technologies for power generation can be found in Table 11. The shown energy parameter settings of different countries refer to 2013 as a reference year. EUROSTAT (2015) was used as the source.

Table 11 Energy carrier mix of electricity production for selected European countries in 2013

	Europe EU-28	Germany	France	United Kingdom
Hard coal	16.5%	19.2%	3.8%	36.9%
Brown coal	10.2%	25.3%	0.0%	0.0%
Fuel oil	1.9%	1.1%	0.4%	0.6%
Gas	16.5%	12.5%	3.5%	27.3%
Nuclear	27.1%	15.6%	74.4%	19.0%
Water	11.9%	3.8%	12.9%	1.4%
Wind	7.6%	8.7%	3.0%	8.4%
Solar	2.8%	5.3%	0.9%	0.6%
Geothermal	0.2%	0.0%	0.0%	0.0%
Biomass, biogas	4.2%	6.5%	0.5%	4.7%
Waste	1.2%	1.9%	0.7%	1.2%

The European statistics database (EUROSTAT 2015) contains data only for European countries. For other countries the International Energy Agency (IEA 2015) is the main data provider; the IEA statistics contains data for 85 countries including Europe. The alternative data sources (e.g. national energy statistics) used for the remaining countries do not provide the same level of detail for all countries, e.g. individual renewable sources may not be differentiated, or waste incineration may not be accounted for. However, these technologies generally play a minor role within the overall power generation, such that the respective shortcomings do not influence the calculation results significantly.

6 Data Selection and Quality

Main energy processes are considered first during the selection of data categories. Other materials are considered as obligatory for superordinate reasons, required by legal regulations, or essential with respect to consistency. The resulting list of materials is shown in Table 11 to Table 13. The overall assessment includes further materials and substances introduced by upstream and downstream chains.

Table 12 Data selection and quality, inputs

Input	**Reason for inclusion**		**Data quality**		
	Overall importance	Consistency	Good	Average	Low
Resources					
Fuel deposits (RiL)					
Natural gas	X		X		
Petroleum	X		X		
Lignite	X		X		
Coal	X		X		
Uranium	X			X	
As cumulative energy demand (CED)					
CED, total fossil fuel	X		X		
CED (Nuclear energy)	X		X		
CED (Hydropower)	X		X		
CED, other renewable	X			X	
Non-Fuels (RiL)					
Bauxite		X		X	
Limestone		X		X	
Sodium Chloride		X		X	
Sand		X		X	
Sulfur		X		X	
Chromium (Cr)		X		X	
Iron (Fe)	X	X		X	
Nickel (Ni)		X		X	
Nature Area			X		
Area K2	X		X		
Area K3	X				X
Area K4	X				X
Area K5	X				X
Area K7	X			X	
Water					
diverse output quality	X	X		X	

Table 13 Data selection and quality, emissions to air

Output	Reason for inclusion			Data quality		
	Overall importance	Regulation a)	Consistency	Good	Average	Low
Emissions (Air)						
Carbon dioxide, fossil	X			X		
Carbon dioxide, renewable			X	X		
Carbon monoxide			X	X		
Particles, unspecific			X		X	
Dust (>PM10)			X		X	
Dust (PM10)	X	X		X		
Sulfur dioxide	X	X		X		
NOx	X	X		X		
Hydrochloric	X	X			X	
Hydrogen fluoride	X	X			X	
Ammonia	X				X	
Nitrous oxide	X				X	
Metals (L)						
Antimony		X			X	
Arsenic		X			X	
Beryllium		X				X
Lead		X			X	
Cadmium		X			X	
Chrome		X			X	
Cobalt		X			X	
Copper		X			X	
Manganese		X			X	
Nickel		X			X	
Palladium		X				X
Platinum		X				X
Mercury		X			X	
Rhodium		X				X
Selenium		X				X
Tellurium		X				X
Thallium		X			X	
Uranium	X					X
Vanadium		X			X	
Zinc		X				X
Tin		X			X	
Compounds (L)						
Methane, fossil	X			X		
Methane, renewable	X				X	
Benzene	X	X				
Toluene		X	X			
Xylene		X	X			
PCDD, PCDF	X	X		X		
Benzo(a)pyrene	X	X			X	
PAH, unspecific			X		X	
NMVOC, unspecific	X				X	
Radionuclides (L)						
41 individual radionuclides	X					X

a) The regulations that apply are the EU Incineration Directive, the German TA Luft, and the EPER/PRTR list as far as it is affected by energy processes.

Table 14 Data selection and quality, emissions to water

Output	Reason for inclusion: Overall importance	Regulation a)	Consistency	Data quality: Good	Average	Low
Emissions (Wasser)						
AOX	X	X			X	
BSB-5	X	X			X	
CSB	X	X			X	
TOC	X	X			X	
Nitrogen compounds as N	X	X			X	
Ammonium	X	X			X	
Phosphorous comp. as P	X	X			X	
Sulfate		X	X		X	
Sulfide		X	X		X	
Chloride		X			X	
Fluoride		X	X		X	
Cyanide	X	X			X	
Metals (W)						
Aluminium		X				X
Arsenic	X	X			X	
Barium		X				X
Lead	X	X			X	
Cadmium	X	X			X	
Chrome		X			X	
Chromium VI	X	X			X	
Cobalt		X				X
Copper	X	X			X	
Nickel	X	X			X	
Mercury	X	X			X	
Vanadium		X			X	
Zinc	X	X			X	
Tin		X				X
Radionuclides (W)						
33 individual radionuclides	X					X
Compounds, organic (W)						
PCDD, PCDF	X	X				
PCB		X				X
Benzene		X				X
Benzo(a)pyren	X	X				X
PAK, unspecific		X				X
Phenols		X				X
Hydrocarbons, unspecific		X				X
Tributylphosphate		X				X

a) The regulations that apply are appendix IX of the EU-Water-Framework Directive and the EPER/NPTR list, as long as it is affected by the energy processes, as well as the appendices 29, 31, 33, 39, 47 of the waste water ordinance (AbwV)

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