INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

Description of the ifeu electricity model (ELMO) for the calculation of LCI datasets for power supply and district heating and cooling

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Content

1 Objective

The “master network” for the modelling of environmental impacts related to electricity production and transmission grids has been maintained and developed at ifeu since 2001. This network is set up in the material flow environment Umberto 5.6.

The ELMO model includes several generic power plant types and raw material upstream processes and allows for a flexible approach to all types of network composition, be it national networks, group based or other special scenarios (future or marginal mixes). Easy adaptation of the model to different investigation settings is achieved by a high level of parametrization. Among others, the adjustable parameters comprise the mix of primary energy sources, information about the raw material origin as well as a number of technical factors like electrical and thermal efficiency, exhaust gas treatment, transmission and distribution-related losses.

The system boundary of the model includes all energy and material flows related to the supply of electricity, district heating and district cooling; from the extraction of energy resources, transport, power plant processes to the distribution of electricity to the power outlet.

The network includes power plants, combined heat and power (CHP) generation plants, heating plants and cooling plants. The share of district heat as a co-product of electricity production is adjustable according to the power plant type. An allocation of the burdens to electricity and district heating is performed by several adjustable methods (e.g. exergy content, energy content, market price). Non-coupled production of district heat is covered by modelling of separate heating plants in the same way as for electricity supply, including heat pumps.

District cooling is modelled using the supply mix of both electricity and district heat in either adsorption or vapor-compression chillers.

Results for electricity are calculated for an amount of 1 kWh electric energy (functional unit), either at production (excluding transmission losses) or at consumer (including transmission losses), in either of the three voltage levels (high voltage 110-380 kV, medium voltage 10-35 kV, low voltage 100-240 V). Results for district heating and cooling are provided for 1 kWh thermal energy/cooling energy either at production (excluding transmission / distribution losses) or at consumer (including transmission / distribution losses).

2 Description of the ifeu electricity model ELMO

2.1 System boundary of the ELMO model

The **system boundary** of the ELMO model is shown in Figure 1 as a simplified flow chart and includes:

- the **power plant, combined heat and power plant and heating plant** processes for electricity and heat generation using hard coal, brown coal (lignite), fuel oil, natural and derived gases, biomass (solid and biogas), nuclear, municipal waste, photovoltaic, solar thermal, hydro, wind power (onshore and off-shore) and geothermal power generation,
- the **district cooling plant** process using adsorption or vapor-compression chillers driven by the electricity and heat production mix,
- the upstream chains for **fuel extraction and processing** (coal, lignite, natural gas, heavy fuel oil, nuclear fuel, biomass), and
- the **distribution** of electricity, heating and cooling energy to the consumer with appropriate management and transformer losses (optional).
- The production expenses of **capital goods** (mining infrastructure, power plants and distribution facilities) are optionally included (results can be calculated with or without capital goods).

2.2 Allocation methods

In this model, multifunctionality is generally addressed by allocation based on physical parameters, usually energy content (LHV) if dealing with fuels. Exceptions are described below.

In **combined heat and power** (CHP) plants burdens are allocated on a unit-process level based on **exergy content** of the products. Electric energy is assigned an exergy value of C_{el} = 1, while the exergy value of thermal energy (steam or hot water) is derived from the so-called **Carnot efficiency level**. This is a function of the thermodynamic mean temperature of the produced steam or hot water (feed/return) and the ambient temperature. The heat exergy value C_{heat} is calculated as follows (absolute temperatures with unit Kelvin [K]):

$$C_{heat} = 1 - \frac{T_{ambient}}{\frac{T_{feed} - T_{return}}{\ln(T_{feed}/T_{return})}}$$

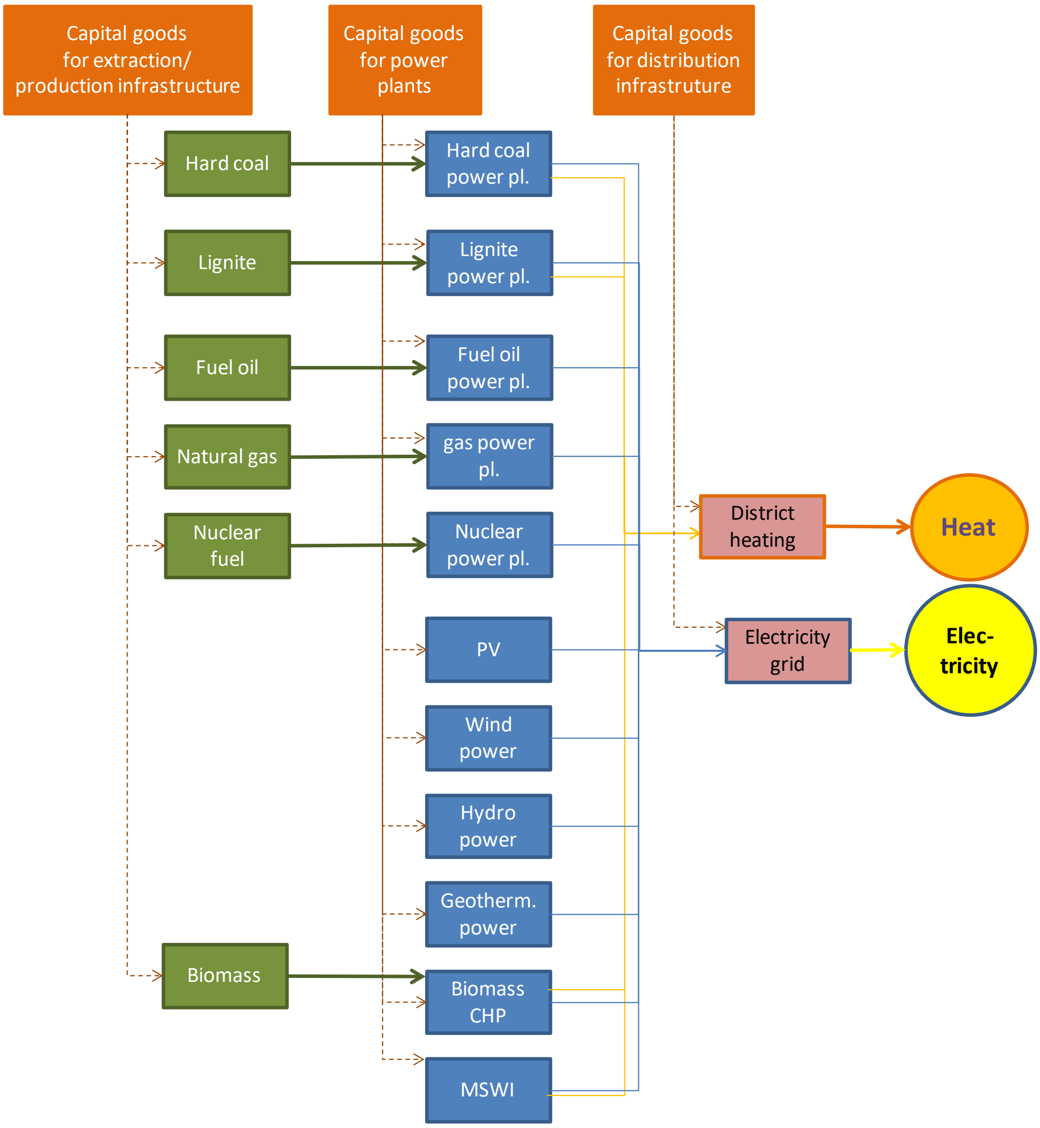

Figure 1: Schematic structure of the Umberto electricity model ELMO, subdivided into the modules fuel pre-chains (green), power plants (blue), distribution (lilac), capital goods (brown)

Exergy content of low pressure steam is usually in the order of C_{heat} = 0.3-0.4, such that 30 % to 40 % of the energy content of the heat product can be considered available for work. The typical exergy of district heating is between 0.16 and 0.25. The default value is 0.21 with a mean temperature of 84°C (T_{feed}/T_{return} is 110°C/60°C) and average ambient temperature of 10 °C. The allocation of emissions to steam and electricity via exergy instead of energy content leads to a decreased environmental burden for steam and an increased burden for the electricity product produced by the same CHP unit.

Environmental burdens from **municipal waste incineration** can be treated in several ways:

a) Base case: Waste incineration is considered fully inside the system boundary of waste treatment processes. Thus, all burdens of incineration are allocated to the sector of waste treatment; both electric and thermal energy from MSWI are produced at “zero” ecological cost.

b) Other allocation approaches can be chosen for different research questions or sensitivity assessments from the following non-exhaustive list:
    a. Allocation based on exergy content with exergy factors of 1.2 (Fratzscher und Stephan 2000) for waste (per MJ LHV), 1 for electric energy, 0.2 for thermal energy.
    b. Economic allocation with default values 150 €/t waste, 50 €/MWh electric energy, 10 €/MWh thermal energy (prices adjustable).
    c. Allocation of a fixed share (e.g. 50 %) of the MSWI process to the waste treatment sector and distributing the rest to electric and thermal energy by exergy content.
    d. Considering that the fuel is a waste and the MSWI is a waste treatment process, all upstream processes (lifecycle of the products ending up as waste in a municipal solid waste incinerator, MSWI) are attributed to the previous product lifecycle (=cut-off); distribution of process emissions to electric and thermal energy by exergy content.

2.3 Calculation approaches

In general, the ELMO model follows a strict bottom-up approach for the calculation of process related emissions. In the default setting, every lifecycle stage starts with the educts (e.g. resources, energy) as inputs, which are transformed to the products of each step, constituting the outputs. The transformation is either a fixed ratio (e.g. for each product y, some x amount of material a is needed, and some z amount of emission/waste b is produced) or, in most cases, input/output relations are described as a function. These functions (e.g. the combustion calculation of coal in the furnace to produce heat, emissions and waste) represent an as close as possible mathematical approximation of reality. The calculations are based on the material properties, e.g. the fuel composition, and external parameters such as efficiencies. In the bottom-up approach, the overall emission of a power plant is derived from a succession of process steps:

a) stoichiometric calculations of off-gas composition from fuel composition (CO_2, SO_2) and application of fuel and plant specific emission factors from literature and confidential ifeu projects (e.g. CO, NO_x, NMVOC, CH_4, dioxins, benzo(a)pyrene, polyaromatics, dust) (Rentz et al. 2002; Wernet et al. 2016)
b) reduction of specific species in the off-gas in several abatement technologies (electrostatic filters, DeNOx, desulfurization, …) using specific reduction factors per species and technology

As an alternative, a top-down approach was developed to align plant emissions from the model with reported values in public databases. This approach, however, is limited to

1) combustion power plants (lignite, hard coal, natural gas, fuel oil, solid biomass, e.g. power plants with a clear “point source”) and
2) the power plant operation itself and currently only to typical combustion related air-borne emissions (e.g. SO_2, NO_x, Hg, …[1]).

[1] The exact setting of emissions covered in the top-down approach is dependent on the available data and varies from energy chain to energy chain

All other lifecycle stages, upstream as well as downstream processes, are not affected by the choice of the calculation approach.

The top-down approach utilizes the fact that large power plants have to report their emissions in the European Pollutant Release and Transfer Register (E-PRTR) when a certain threshold is exceeded[1], with a delay of two years. From the reported emissions in the E-PRTR the fuel type specific emission factors were derived as follows:

- From national databases, a list of large-scale power plants was derived per type of fuel, ideally containing 5-10 specified plants per fuel.
- From the E-PRTR dataset all reported emissions for each of the pre-selected plants were extracted for the two last available years.
- The annual mass of each of the reported air-borne substance per plant was divided by the CO_2 emission of that plant in the same year and the average was calculated for the two years under investigation (= plant specific CO_2 related emission coefficient).
- For each fuel type and air-borne substance a weighted average of CO_2 related emission coefficients was calculated (weighting factor: total CO_2 emission).

To derive the emission of a specific substance *x* connected with electricity production in a certain power plant type the CO_2 related emission coefficient EF_x is multiplied by the total amount of CO_2 emitted per kWh ($Emission_{CO2}$):

$$Emission_x = EF_x * Emission_{CO_2}; [\frac{g}{kWh}]$$

EF_x : Emission factor for substance x derived from the weighted average of total emission of substance x in power plant n divided by the total CO_2 emission of power plant n with n > 5.

Relating the emission of other substances to the CO_2 production instead of electricity production is independent from confidential electricity production figures. Instead, ituses the (reported) carbon dioxide emission as a proxy for the fuel input and hence avoids dealing with differing power plant efficiencies.

A major drawback of this approach is that a certain number of power plants are needed which exceed the thresholds for the most interesting species emitted to air to derive robust emission factors. Furthermore, emissions are only calculated from large-scale plants and might underestimate emissions since it can be assumed that smaller plants might not be as well equipped with up-to-date abatement technologies.

In order to obtain a maximum of accuracy, the more power plants and respective substances (emissions), the better the result. A thorough analysis of the power plant capacities for each sub type is therefore essential for the validity of this approach. A minimum of five individual power plants, representing at least 30 % of total installed capacity of each sub type hence constitutes the minimum to consider / apply the top-down approach.

The results for a comparison between the default bottom-up approach and the top-down approach using lignite (2017) as an example for a choice of significant impact categories is presented in Figure 2. In general, emissions calculated with the top-down approach are

[1] Sample list of thresholds (per year load): NO_x: 100 t/a; CO: 500 t/a; SO_2: 150 t/a; PM_{10}: 50 t/a, CO_2: 100.000 t/a; N_2O: 10 t/a; NH_3: 10 t/a; NMVOC: 100 t/a; Hg 10 kg/a; For reference, see Annex II of Regulation (EC) No 166/2006 (European Commission 2006)

lower than those based on the bottom-up approach, which might be caused by outdated process emission figures inside the single power plant modules. Especially emissions of methane (affecting GWP), SO_2 (AP, POCP, PM), N_2O (GWP, EP, ODP) and NO_x (AP, EP, POCP, PM) are lower than in the bottom-up calculations.

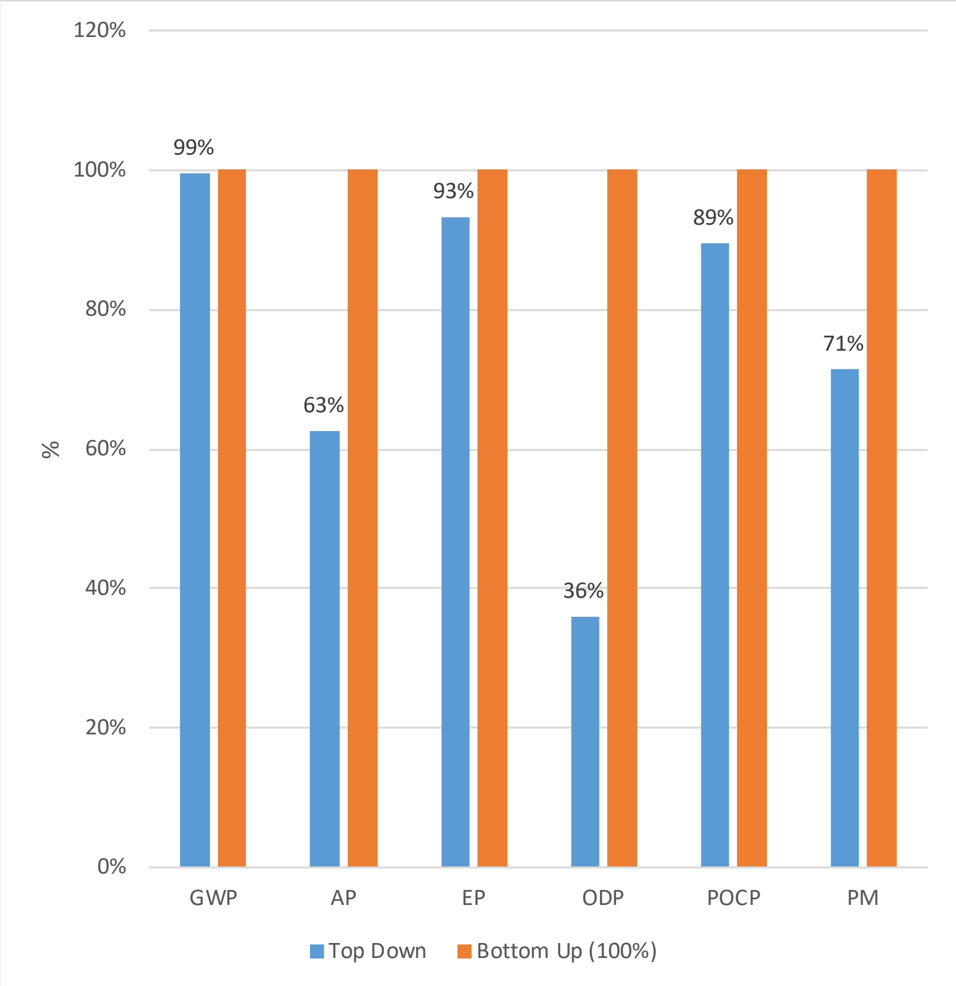

Figure 2: Comparison between top-down and bottom-up approaches within the ELMO model using lignite plants as an example (bottom-up values = 100%)

2.4 Power plants, upstream fuel chains and distribution

In the following sections, each module in the model is briefly described. Table 2.1 summarizes the input and output flows of the modules.

In general, wastes generated within the power plant boundaries are treated within the system. Wastes for recovery/recycling (e.g. inert granules or gypsum for building material) are leaving the system without any burdens (cut-off).

Auxiliary materials such as limestone, sodium hydroxide, ammonia are considered as input material for each power plant and covered with ecoinvent datasets.

2.4.1 Coal and fuel oil power plants

The power plant modules for hard coal, brown coal, and fuel oil are set up with the same set of sub-modules:

- drying/pulverizing coal (coal plants only),
- furnace/boiler,
- steam turbine generator,
- exhaust gas cleaning components:
  - electrostatic precipitators,
  - flue gas desulfurization (FGD) incl. waste water treatment,
  - catalytic denitrification (DENOX)

The boiler / steam-turbine system is a central sub-module, which includes the settings for both, gross thermal and gross electric efficiencies. The reference flow is net electricity produced considering the auxiliary power used within the plant.

2.4.2 Gas power plants

For gas power plants, four different types of technologies are covered:

- steam electric plant / steam turbine,
- gas turbine plant
- combined cycle gas turbine plant (CCGT),
- gas engine power plant

Gas-fired power plants do not have a complex exhaust gas purification system like coal and fuel oil power plants and are modelled simplified with the following sub-modules:

- compressor station
- boiler (for steam electric plant)
- gas turbine generator (for gas turbine plant and combined cycle power plant)
- heat recovery steam generator (for combined cycle power plant)
- steam turbine generator (for steam electric plant and combined cycle power plant)
- gas engine (for gas engine power plant)

Each plant type is modelled with specific and adjustable efficiencies and emission rates.

2.4.3 Nuclear power plants

This module describes the average state of nuclear power plants in Europe based on the conditions during the early 1990's. The considered technologies are pressurized water reactors (PWR) and boiling water reactors (BWR) feeding a steam turbine.

Process data and emissions are largely based on information from ecoinvent (based on Swiss power plants). Background data for modelling are taken from (IEA 2023). The burn-up values are set at 42.5 GWd/t of uranium (=3,672 GJ/kg) for PWR and at 40 GWd/t uranium (=3,456 GJ/kg) for BWR. The gross electrical efficiency is set at 33.3 %. The model also includes the reprocessing and the final disposal of nuclear wastes and / or spent fuel rods.

Table 2.1: Reference flows (input output) of the power plant modules of the ELMO electricity model

Input/Output	Module	Specification of input
INPUT		
Fuel calculated considering the lower heating value corresponding to the thermal energy needed for the produced electricity (net)	Hard coal power plant	Hard coal
	Lignite power plant	Lignite
	Gas power plant	Natural gas (the model allows the inclusion of derived gases, such as blast furnace gas, coke oven gas or refinery gas)
	Fuel oil power plant	Fuel oil
	Nuclear power plant	Nuclear fuel rods
	Biomass CHP	Woody biomass, Substrates for biogas fermentation
	MSWI	Household waste
Water	All thermal power plants	Boiler feed, process water, cooling water.
Other material input	Coal, fuel oil, nuclear and biomass power plant	Auxiliary material for flue gas cleaning (e.g. lime, ammonia) or other processing
OUTPUT		
Electricity (net)	All power plants	Reference flow
Useful heat (in case the plants is actually exporting heat)	Coal, gas, oil, waste and biomass power plant	For district heating
Direct airborne emissions from stack	All thermal power plants	• Greenhouse gases (CO_2, N_2O, CH_4) • Classical air pollutants (SO_2, NO_x, CO, fine particles, etc.) • Heavy metals (As, Sb, Cd, Hg, etc.) • Organic pollutants (PAH, PCB, dioxins, etc.) • Radionuclides, measured in kilo becquerel (kBq)
Direct waterborne emissions from flue gas cleaning processes (in case wet scrubbing is applied)	Coal, fuel oil, nuclear and biomass power plant	• COD, BOD, nutrients (N, P) • Sulphate and other salts • Heavy metals (As, Sb, Cd, Hg, etc.) • Radionuclides, measured in kilobecquerel (kBq)
Other downstream processes		e.g. Waste treatment (including required transports until or from gate)

2.4.4 Renewable power plants

Power plants based on renewable energy sources, are characterized by the absence of upstream fuel chains and, beyond that, have no significant upstream or downstream chains with regard to fuel supply. A primary energy (renewable CED) to electrical energy ratio of 1:1 is assumed except for geothermal energy where the thermal efficiency (10 %) is considered.

Infrastructure and capital goods for these plant, particularly wind turbines and PV systems are modelled on the basis of data supplied by manufacturers and constitute the current state of the art. The following renewable power plants are considered:

- Wind onshore, 3.6 MW
- Wind offshore, 8 MW
- Photovoltaic open ground installation, 570 kWp
- Photovoltaic slanted roof installation, 3 kWp
- Water power, run off river
- Water power, pumping storage (considered as energy loss without capital goods)
- Geothermal power, 5.5 MW (currently only Iceland as proxy)
- Solar thermal power, parabolic trough, 50 MW

2.4.5 Solid biomass power plant

The solid biomass (wood) power is modelled similar to coal power plants containing the following sub-modules:

- furnace/boiler,
- steam turbine generator,
- exhaust gas cleaning components:
  - electrostatic precipitators,
  - flue gas desulfurization (FGD) incl. waste water treatment,
  - catalytic denitrification (DENOX)

The boiler/steam-turbine system is a central sub-module, which includes the settings for both, gross thermal and gross electric efficiencies. The reference flow is net electricity produced considering the auxiliary power used within the plant.

2.4.6 Biogas power plant

Biogas plants (anaerobic digester), are fed with crops (e.g. maize, gras, etc.), bio-waste or manure, and the produced biogas is converted in a CHP plant (gas engine) to electricity and heat. The following sub-modules are covered:

- Anaerobic digester
- Gas engine
- Digestate storage/maturation with/without methane capture
- Field emissions from spreading of digestate

2.4.7 Waste incineration (MSWI)

This module describes the incineration of household waste in a plant that corresponds to a European state-of-the-art design (grate, heat recovery steam generators, and high standards of exhaust gas cleaning). The default settings refer to an average household waste with a heating value of 9 MJ/kg and a corresponding elemental composition. The energy efficiency complies with the average European situation of 10 % net electricity and 30 % useful heat. Emissions are calculated based on data from German MSWI plants considering the elemental composition of the feedstock.

2.5 Upstream fuel chains

The ELMO model includes a separate module for each fuel type (see Figure 2.1), covering the following process chains:

- Mining (fossil and nuclear fuels).
- Cultivation (wood or crops for biogas).
- Pre-processing, where needed, e.g. for natural gas, fuel oil (refinery) or nuclear fuel (enrichment, production of fuel elements).
- Transport / collection, intermediate as well as the final transport to the power plant; in correspondence with specific origins: e.g. oversea shipment for coal or uranium ore; pipeline for natural gas.

2.6 Transformation and Distribution

The electricity undergoes transformation and distribution losses during the transmission from the power plant to the consumer. The loss depends on the voltage level of the demanded electricity. Transformation and distribution losses are calculated country-specifically from Eurostat or IEA statistical data.

For district heating and cooling an average loss factor of 10 % is applied.

2.7 Data sources

2.7.1 Background data

The ELMO model utilizes external datasets for the modelling of the background system. Table 2.2 summarizes the applied background data, indicating where in the model these data are used.

Table 2.2: Applied background data within the electricity model

Subject	Used in the ELMO model	Further specification	Data source
Hard coal mining	Upstream fuel module for *hard coal*	Cradle to gate submodules for coal from: • Germany (deep and surface mining) • Western Europe (deep and surface mining) • Eastern Europa (deep and surface mining) • Russia (deep and surface mining) • RLA (surface mining) • RNA (deep and surface mining) • South Africa (deep and surface mining) • Eastern Asia (ID) (XXX mining) • Australia (surface mining)	ecoinvent 3.7.1
Lignite mining	Upstream fuel module for *lignite*	one cradle to gate module representing European technology	ecoinvent 3.7.1
Natural gas production	Upstream fuel module for *natural gas*	Cradle to gate submodules for gas from: • Germany (domestic supply) • Russia (on-shore/off-shore, long distance pipeline) • Norway (off-shore, long distance pipeline) • The Netherlands (on-shore/off-shore, long distance pipeline) • UK (on-shore/off-shore, long-distance pipeline) • Algeria (on-shore, long-distance pipeline) • Qatar (on-shore/off-shore, LNG shipping) • US (on-shore/off-shore, LNG shipping)	ecoinvent 3.9.1; natural gas, high pressure, import from XX to either DE or RoE
Other fuel gases	Coking gas Blast furnace gas	Coking gas and blast furnace gas are modelled as energy-containing co-products of the coking and pig iron production, respectively. Allocation of burdens was done by energy content.	ifeu iron and steel production model
	Refinery gas	Refinery gas is a co-product of refinery operations and was modelled using a European average Refinery.	ifeu refinery model
Fuel oil production	Upstream fuel module for *fuel oil*	Aggregation of crude oil extraction, refining and transport; origin of crude oil average mix in Europe (North Sea, Russia, OPEC) Fuel oil as co-product from refinery	crude oil from ecoinvent 3.9.1 refinery process from the ifeu refinery model
Nuclear fuel	upstream fuel module for *nuclear fuel*	Aggregation of mining, enrichment and production of fuel elements	ecoinvent 3.1
Woody biomass	upstream fuel module for biomass	Energy wood from forestry, chipped	ifeu biomass model

Maize, gras, other crops	upstream fuel module for *biomass*	European (German) average data including fertilizer, land machine, harvesting and yield levels	BioEm (Fehrenbach et al. 2016), BioGrace (Köppen und Fehrenbach 2015)
Transport	All upstream fuel modules	Truck transport, shipping (various distances)	TREMOD (2019)[1], ecoinvent 3.7.1 in hard coal subnet
	Upstream fuel module for *natural gas*	Gas pipeline	ecoinvent 3.9.1
Auxiliary materials	*hard coal power pl., lignite power pl., fuel oil power pl., biomass CHP*	Cradle to gate submodules for chemicals: lime, lime stone, caustic soda, ammonia, urea	ecoinvent 3.7.1
Infrastructure capital goods	All modules	Different steel alloys, copper, aluminium, cement, concrete	ecoinvent 3.7.1
	Lignite and hard coal infrastructure	Mining infrastructure	ecoinvent 3.7.1
	Wind power plant	Wind power plant (3.6 MW onshore, 8 MW offshore)	Confidential data from wind turbine producers (Hengstler et al. 2021)
	PV	PV modules (570 kWp open ground, 3 kWp slanted roof)	Modified ESU 2012 data acc. to (Hengstler et al. 2021)
	Water	Hydropower plant (run-off river)	ecoinvent 3.7.1
	Geothermal power	Geothermal power plant 5.5 MW	ecoinvent 3.7.1
	Concentrated Solar Power	Concentrated solar power plant 50 MW	ecoinvent 3.7.1

2.7.2 Foreground data

The following aspects are defined as foreground data in the sense of the Umberto model:

Selection of the fuel mix and provenance mix of fuels:

- The country-specific fuel mix follows data from Eurostat (2023) regarding the European countries; for countries outside of the EU28, data from IEA (2023) is applied.
- Moreover, different (singular) generic generation pathways (e.g. 100 % lignite, or 50 % lignite + 50 % hard coal) can be set up in the ifeu Umberto model.
- The model allows for the application of any further setting e.g. based on national or sector-specific statistics, or future scenarios.

Selection of technical level:

Each power plant module allows for the determination of the following technical parameters:

- Electrical efficiency (fuel-to-electricity conversion efficiency) and thermal efficiency in case of district heating.

[1] **Tr**ansport **E**mission **Mod**el of the German Environment Agency

- Technical level of the emission reduction measures for fuel-fired power plants; the model allows the selection of the following installations:
  - Electrostatic dust precipitation or fabric filter
  - Flue-gas desulfurization: wet, semi-dry, dry system
  - Nitrogen oxides removal by SCR or NSCR

The user is free to make any selection or to use a default setting for the current EU average, e.g. 25 % wet/25 % semi-dry/40% dry desulfurization, 50% DeNOx

For renewable energy, the following parameters can be adjusted:

- Full load hours for wind and PV plants according to location
- Composition of biomass feedstock
- Share of digestate storage with/without methane capture

2.8 Issues not covered by the current ELMO model

The trade of Power Purchase Agreements and other certificates is not covered in the model. Any exchange between electricity markets is assessed purely based on physical connections.

Emissions of the greenhouse gas SF_6 by transformers or other infrastructure are not explicitly covered in the model. They may be included in future versions. Background: according to (REFINE SOURCE) these emissions of SF_6 contribute only about 0.2 % to global greenhouse gas emissions in 2020, while absolute emissions of SF_6 are expected to double by 2050, increasing their contribution to the total GWP to 11 %.

2.9 Results

2.9.1 Electricity production and supply mixes

The production and supply mix of electricity in different countries can both be calculated by the ELMO model. Depending on imports and exports of electricity, the supply differs from the production mix of a country. Keep in mind that ELMO is not considering Power Purchase Agreements or certificate trade but only physical exchanges across international borders.

Figure 4 shows gives an overview of production and supply mixes (GWP) for different countries in 2021 (some from 2019-20). A few countries show higher burdens in their electricity supply mix than in their own production (HR, LV, SK, LU), while other countries decrease the GWP of their electricity mix via imports (most significantly EE), based on their specific imports and exports of electricity from countries with different productions situations.

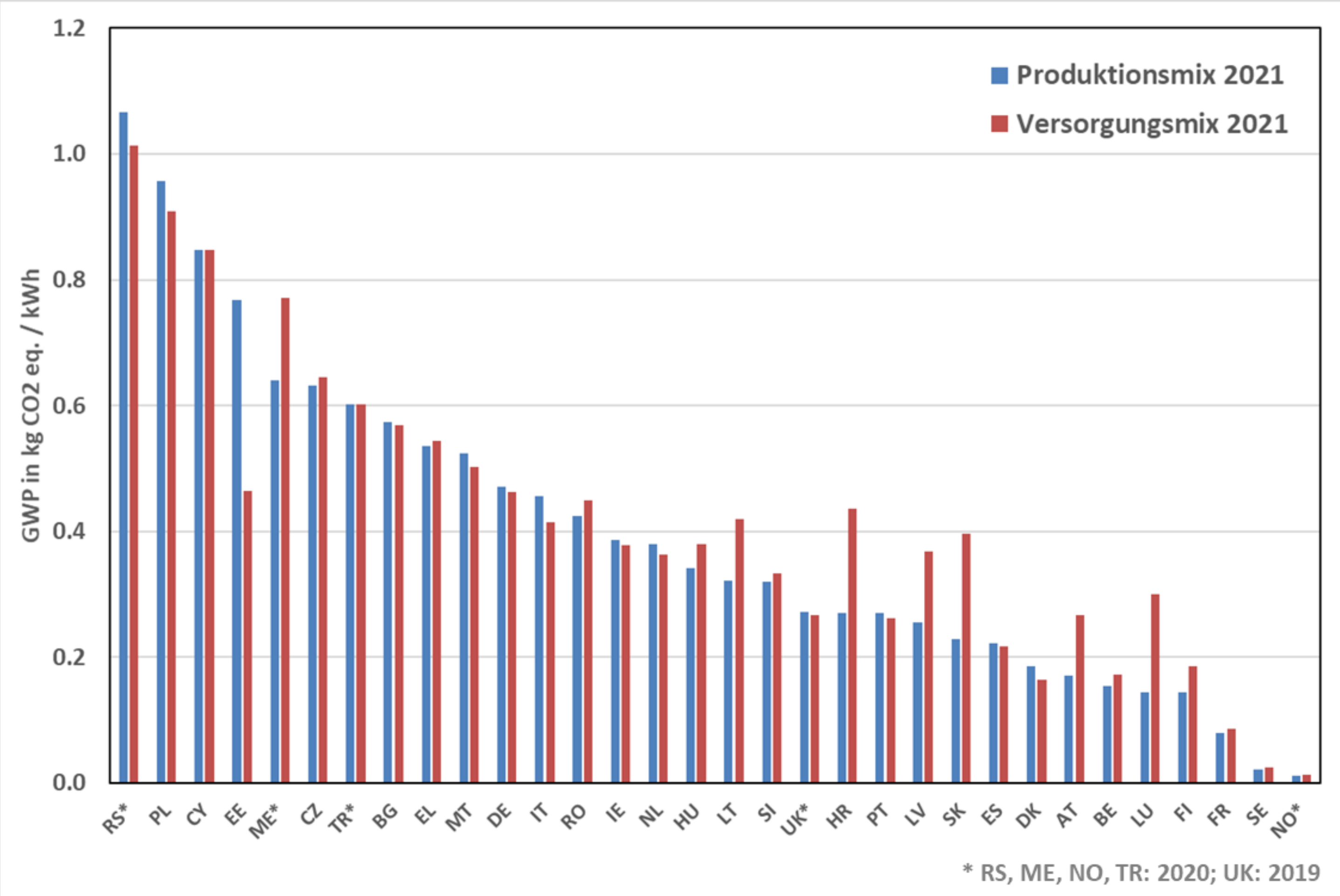

Figure 3: GWP results in kg CO_2e/kWh for the electricity production (blue) and supply mixes (red, "Versorgungsmix") for different countries in 2021.

2.9.2 German electricity mix in different databases

This section shows selected results generated by the ELMO model and compares them to three other sources of emission factors for the electricity production/supply in Germany. The comparison is conducted based on GWP results at different voltage levels, depending on the output specifics of each model, illustrated in Table 2.3 and Figure 3.

Table 2.3: Comparison of GWP results in g CO_2e/kWh for the German grid electricity production by ifeu ELMO, ecoinvent, UBA and GEMIS for the available years between 2019-2023.

		2019	2020	2021	2022	2023
ifeu ELMO model						
Production mix, medium/low voltage	gCO_2e/kWh	471	429	473	505	452

Supply mix, medium/low voltage	gCO_2e/kWh	-	-	447	482	413
ecoinvent 3.10						
High voltage	gCO_2e/kWh	-	424	-	-	-
Medium voltage	gCO_2e/kWh	-	421	-	-	-
Low voltage	gCO_2e/kWh	-	393	-	-	-
Umweltbundesamt (UBA)						
Including upstream	gCO_2e/kWh	474	432	475	498	-
Excluding upstream	gCO_2e/kWh	418	377	418	442	-
GEMIS 5.1						
At production plant	gCO_2e/kWh	411	370	396	426	-
Low voltage (customer)	gCO_2e/kWh	424	383	409	439	-

Sources: Fritsche und Greß 2023 (GEMIS 5.1); Icha und Lauf 2023 (UBA); Wernet et al. 2016 (ecoinvent 3.10)

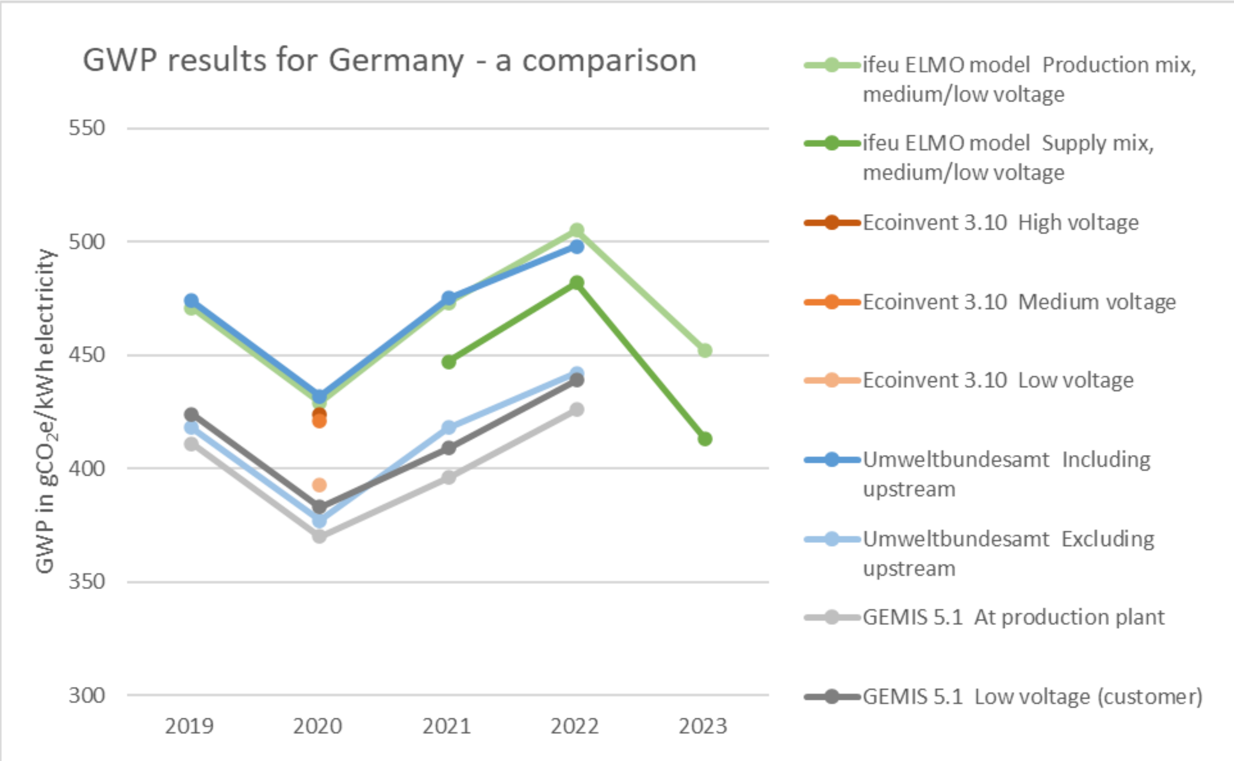

Figure 4: Comparison of GWP results in g CO_2e/kWh for the German grid electricity production by ifeu ELMO (green), ecoinvent (red), UBA (glue) and GEMIS (grey) for the available years between 2019-2023.

The following subsections give a more detailed insight into the methodologies and assumptions on which the emission factors of ecoinvent, UBA and GEMIS are relying. This compilation is supposed to highlight the differences and similarities of the models.

2.9.2.1 ecoinvent 3.10

Ecoinvent assumes that the different power plant types are only available on the specific voltage level at which they feed electricity into the grid. More specifically, this assumption leads to the following restrictions in terms of power sources for each voltage level:

- The low voltage level is generated by transformation of power from the medium voltage level and from electricity generated by PV.
- The medium voltage level is generated by transformation of power from the high voltage level and from electricity generated by municipal waste incineration.
- The high voltage level is generated by all other types of power plants including wind energy. Imports and exports of electricity also contribute to the high voltage power level.

This assumption leads to a situation where electricity generated from PV cannot enter the medium voltage level. Furthermore, electricity from PV and waste incineration cannot contribute to the high voltage level. Additionally, power from these sources cannot be part of international or interregional trade (at high voltage). the contribution of PV to the mix generates a much higher rate of renewability on the level of low voltage than on the medium or high voltage levels, making low voltage electricity more “green” than the higher voltage levels by using the above assumptions (see 2020 low voltage results in Figure 3).

Starting with ecoinvent 3.10 the burdens of waste incineration are attributed to the generated electricity and heat. The ELMO model (as did earlier versions of ecoinvent) attributes the incineration burdens to the waste disposal system.

Considering the allocation of burdens from the cogeneration of heat and power ecoinvent is based on similar assumptions as the ELMO model: the allocation by exergy of the heat and power products. The allocation factors are 1 for electricity and 0.18 for district heating.

Both ecoinvent and the ELMO model provide supply mixes (with the differences mentioned above). They both cover capital goods as well as upstream processes of fuels. The trade with certificates or Power Purchase Agreements is not addressed by either, ecoinvent or ifeu.

The most recent available data on electricity by ecoinvent 3.10 are based on the production of 2020. It is visible in Figure 3 that ecoinvent results are lower than those of the ELMO model in the available year 2020.

2.9.2.2 Umweltbundesamt (UBA)

UBA is the Federal Environmental Agency of Germany . UBA provides calculations for the specific greenhouse gas emissions of the German electricity mix between 1990 and 2022 according to the following methodology (Icha und Lauf 2023):

- German production mix without imports
- Upstream of fuels and energy carriers are covered in publications since 2023
- The construction of plants and power transmission infrastructure are covered
- The allocation of burdens from the cogeneration of heat and power follows the "Finnish method"[1] (or "alternative generation method").
- Waste incineration emissions are included, assuming 50 % of carbon to be fossil
- Electricity based on renewable energy sources and nuclear power are generally associated with zero CO_2 emissions. However, when upstream processes are included, the provision of infrastructure is covered. (documentation for renewable energy carriers in (Lauf et al. 2023)).
- The internal consumption of power plants, transmission losses and pumping losses are considered.

The provided results comprise production mixes including upstream processes (since 2023 upstream burdens are shown separately). UBA results are rather close to ifeu production mix results, if upstream burdens are included by UBA (see Figure 3, ifeu production mix).

UBA results refer to the German situation and cover years up to 2022.

2.9.2.3 GEMIS

GEMIS 5.1 (Fritsche und Greß 2023) supplies the grid electricity production mix at plant or at customer (low voltage). Upstream processes and energy carriers / fuels as well as

[1] The „Finnish method" starts with the calculation of the primary energy savings caused by the use of cogeneration of heat and power. This calculation uses reference efficiencies of separate production of electricity (40 %) and heat (80 %) based on the energy efficiency directive 2012/27/EU. A degree of utilisation is then calculated from the fuel demand of the electricity/heat generation and the associated primary energy savings.

transportation, infrastructure and the internal consumption of the production facilities are included. Imports of electricity are not included.

The allocation of burdens from the cogeneration of heat and power follows the "Finnish method"[1] (or "alternative generation method").

When comparing results it is visible that the GEMIS values are significantly (ca. 15 %) lower than those values calculated by the ELMO model, but also lower than the results supplied by ecoinvent and UBA (all including upstream emissions). The reason for these lower results of GEMIS may an overestimation of the efficiencies of power plants and/or an underestimation of network losses (3.2 % in GEMIS compared to 6 % within the ELMO model).

In recent years, all of ifeu's attempts to discuss and solve these issues with GEMIS (Uwe Fritsche, IINAS) remained unanswered. Due to this lack of transparency we must advise against using GEMIS results.

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Annex

Table 3 provides an overview of the different electricity chains and derived Top-down emission factors.

Table 4 Overview of energy chains with respective Top-down emission factors

Technology	NO_x	SO_2	N_2O	PM_{10}	Heavy metals[1]	Chlorides, Fluorides etc.	CO	CH_4
Lignite	✓	✓	✓	✓	✓	✓	✓	-
Hard Coal	✓	✓	✓	✓	✓	✓	-	-
Fuel Oil	✓	✓	-	✓	✓	-	-	
Natural Gas	✓	✓	✓	-	-	-	✓	✓
Solid Biomass	✓	✓	✓	-	-	✓	-	-

Generally speaking, the greater the number of investigated power plants, the more robust the resulting parameters. This is because the thresholds within the PRTR are absolute figures and not relative, e.g. to a set amount of energy. Hence, data quality for electricity chains with increasing centralization level (fewer, but bigger power plants) like hard coal and lignite-fired power plants is assessed to be higher when compared to smaller, more decentralized electricity chains, such as biomass-fired plants or natural gas and fuel oil. For the latter, analysis was extended to include European power plants in order to broaden the number of power plants under investigation and to foster significance.

Lignite and hard coal, as mentioned above, are sufficiently covered with well over 75% of installed capacity in Germany accounted for. While natural gas is covered by 50% German power plants, the rest consists of British (4) and one French power plant. Fuel oil and biomass power plants due to their small installed capacity and share are even less likely to exceed the thresholds of E-PRTR. Therefore, analysis focused on the most relevant power plants in Europe, following their individual size.

[1] Such as, among others: Arsenic, Cadmium, Copper, Zinc, Mercury, etc.

Regarding the top-down approach, the following power plants **were chosen according to their relevance (installed capacity)** and investigated:

1) Lignite:

- Grevenbroich / KW Neuenrath
- Niederaußem / KW Bergheim
- Eschweiler Weisweiler
- Jänschwalde
- Boxberg
- Lippendorf
- Schwarze Pumpe
- Schkopau
- Frimmersdorf

2) Hard Coal:

- DampfKW Karlsruhe
- Mannheim
- Hamburg Moorburg
- Duisburg-Walsum
- Voerde
- Ruhrort (Thyssen)
- Scholven
- Ibbenbüren
- Hamm
- Heyden
- Werne
- Bergkamen
- Wilhelmshafen

3) Fuel Oil:

- Walheim
- Setubal (Portugal)
- Galati (It)
- Peterhead (UK)
- Dhekelia (Cyprus)
- Eesti (It)
- Porcheville (Fr)

4) Natural Gas:

- Altbach
- Berlin Charlottenburg
- Berlin Klingenberg
- Berlin Lichterfelde
- Berlin Mitte
- Pembroke Power Station (UK)
- Seabed Power Station (UK)
- Medway Power Station (UK)

- Grain Power Station (UK)
- Martigues (Fr)

5) Solid Biomass:

- Alholmenskraft (Fi)
- Toppilan (Fi)
- Kymijarvi (Fi)
- Rodenhuize (Be)
- Ironbridge (UK)