Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: electricity generation

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Abstract

Purpose Life cycle inventories (LCI) of electricity generation and supply are among the main determining factors regarding life cycle assessment (LCA) results. Therefore, consistency and representativeness of these data are crucial. The electricity sector has been updated and substantially extended for ecoinvent version 3 (v3). This article provides an overview of the electricity production datasets and insights into key aspects of these v3 inventories, highlights changes and describes new features.

Methods Methods involved extraction of data and analysis from several publically accessible databases and statistics, as well as from the LCA literature. Depending on the power generation technology, either plant-specific or region-specific average data have been used for creating the new power generation inventories representing specific geographies. Whenever possible, the parent–child relationship was used between global and local activities. All datasets include a specific technology level in order to support marginal mixes used in the consequential version of ecoinvent. The use of parameters, variables and mathematical relations enhances transparency. The article focuses on documentation of LCI data on the unlinked unit process level and presents direct emission data of the electricity-generating activities.

Results and discussion Datasets for electricity production in 71 geographic regions (geographies) covering 50 countries are available in ecoinvent v3. The number of geographies exceeds

the number of countries due to partitioning of power generation in the USA and Canada into several regions. All important technologies representing fossil, renewable and nuclear power are modelled for all geographies. The new inventory data show significant geography-specific variations: thermal power plant efficiencies, direct air pollutant emissions as well as annual yields of photovoltaic and wind power plants will have significant impacts on cumulative inventories. In general, the power plants operating in the 18 newly implemented countries (compared to ecoinvent v2) are on a lower technology level with lower efficiencies and higher emissions. The importance of local datasets is once more highlighted.

Conclusions Inventories for average technology-specific electricity production in all globally important economies are now available with geography-specific technology datasets. This improved coverage of power generation representing 83 % of global electricity production in 2008 will increase the quality of and reduce uncertainties in LCA studies worldwide and contribute to a more accurate estimation of environmental burdens from global production chains. Future work on LCI of electricity production should focus on updates of the fuel chain and infrastructure datasets, on including new technologies as well as on refining of the local data.

Keywords Country-specific · ecoinvent v3 · Electricity · Life cycle inventories · Power generation technology

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1 Introduction

The objective of the work presented in this paper is to provide an overview of the updated and extended life cycle inventories of electricity-producing technologies in the new version 3 (v3) of the ecoinvent database. The new electricity markets, which are supplied by these technology datasets, are discussed in

(Treyer and Bauer 2013). Providing complete documentation of power generation activities in v3 is not the goal of this article, only key elements of the inventories are highlighted and summarized. This means that all results represent the inventory data (e.g. direct emissions) of the unlinked unit process datasets (i.e. before allocation in case of the attributional system model) and neither cumulative life cycle inventories (LCI) data nor life cycle impact assessment (LCIA) results. Calculation procedures and data sources for all exchanges in the inventories as well as the associated uncertainties are transparently documented in the single activity datasets. This paper focuses on the processes (activities) generating the reference or by-product electricity on different voltage levels. Neither datasets of fuel supply chains for fossil and nuclear power plants nor the infrastructure datasets of these have been updated in the context of ecoinvent v3 and are therefore not part of this paper.

Electricity supply is a key element in many recent life cycle assessment (LCA) studies regarding LCA results, be it in the production phase or in the use phase of products and services (e.g. Bousquin et al. 2012; Heinonen and Junnila 2011; Teehan and Kandlikar 2012; Hirschier and Baudin 2010; Mohr et al. 2009; Torrellas et al. 2012; Mendoza et al. 2012; Kendall and McPherson 2012; Milà i Canals et al. 2011; Hawkins et al. 2012). Accurate and representative inventory data are required according to international standards such as Publicly Available Specification (PAS) 2050 (PAS 2011) and ISO 14040, 14044 (ISO 2006a, b). PAS 2050 states that “for electricity and heat delivered via a larger energy transmission system, secondary data that is as specific to the product system as possible (e.g. average electricity supply emission factor for the country in which the electricity is used)” should be used. According to the ISO standards, “for the production and delivery of electricity, account shall be taken of the electricity mix, the efficiencies of fuel combustion, conversion, transmission and distribution losses.” Ecoinvent v3 supports these requirements with significantly improved country- or region-

specific inventory data for power generation representing almost 85 % of global production. Furthermore, the new structure of the data offers the possibility of case-specific adaptation of key parameters such as power plant efficiencies, yields of renewable systems like wind turbines and photovoltaic modules, loss factors in the power grid, etc.

2 General information

2.1 Geographical coverage

Version 2 of the ecoinvent database contained LCI data of electricity mixes (production and supply, reference year 2004) and country-specific electricity generation datasets of 32 countries, representing about 64 % of global power generation. With ecoinvent version 3, LCI data for 18 additional countries are available, reducing the “rest of the world” net electricity production to around 17 % of global generation. The total number of countries with country-specific LCI data for electricity production and supply is raised to 50 (Fig. 1). All countries producing more than 1 % of the global electricity are included, plus some additional ones. The complete list of countries represented in ecoinvent v3 including the annual production volume in 2008 is available in Table i in the electronic supplementary material (ESM). All Organisation for Economic Co-operation and Development (OECD) countries except of Estonia, Iceland, Israel and New Zealand are now represented in ecoinvent v3 with specific electricity production and market datasets. The electricity markets in the USA and Canada are further subdivided into the ten regions of the North American Energy Reliability Corporation (NERC) and the 13 national Canadian provinces, respectively (see Table i in the ESM). This results in electricity markets and generation technology datasets for 71 geographical regions, further called “geographies” in this paper.

Fig. 1 Countries with specific LCI data for power generation and electricity supply (mixes) in ecoinvent v2 and v3

2.2 Time period and annual production volume

According to Weidema et al. (2013), the time period indicates the “period for which the dataset is intended to be valid. The data may be originally collected for a different time period, and inter- or extrapolated to the time period of validity”. Electricity-producing datasets normally have inputs of infrastructure, supporting material and outputs of emissions and by-products. These exchanges are generally valid for several years, which is reflected by the time period of the activities. Power plant infrastructure and fuel supply chains have not been updated for the release version 3, i.e. time periods are those of v2, but these datasets are still supposed to represent today's electricity production chains.

The annual production volume (APV) of a reference product or a by-product determines the share of the producing activity on the market of that product. For electricity, the APV are valid for the reference year 2008. The year 2008 was chosen at the time work presented in this paper started, since consistent statistics were only available for 2008 at that time. All electricity annual production volumes have been updated (datasets already existing in v2) or set (new datasets) to 2008. The only exceptions are the annual production volumes for Switzerland and the regions of the USA, which are valid for 2009. In general, all annual production data were taken from Itten et al. (2012) or International Energy Agency (IEA) and OECD (2010a). Data for the US regions are taken from EPA (2012). Data for Canada are taken from IEA and OECD (2010a) and partitioned to the 13 provinces with information from StatCan (2009).

2.3 Structural changes and new features

According to the ecoinvent Data Quality Guidelines (Weidema et al. 2013), some structural changes and new features have been implemented for version 3 datasets concerning electricity production:

- Region-specific technology datasets have been created for all electricity market geographies. Thus, proxy datasets from other countries are no longer used as contributors to the electricity market (previously, supply mix) of a region or country. As example, the electricity markets for Bulgaria (BG) and Romania (RO) in v2 were modelled with an input of electricity production with oil in Slovakia (proxy dataset) each. To ensure the correct market mix of electricity in BG and RO, a copy of the dataset for Slovakian electricity production with oil was made for both countries for v3. In these datasets, exchanges and parameters such as the efficiency can now easily be adapted to local conditions. Such an adaptation has not taken place for all new such datasets, which is commented on in the dataset.

- Electricity production with fossil fuels in v2 was modelled with a dataset for the combustion of 1 MJ fuel (containing all inputs and emissions for the combustion) and the production of 1 kWh of electricity (representing the conversion from the required amount of fuel to 1 kWh electricity) each. In version 3, these two types of datasets are merged: the electricity production activities directly contain all inputs for and emissions of the production of 1 kWh at the power plant.
- A global as well as local datasets¹ have been created for all electricity-producing activities. In this situation, a dataset with the geographical location Rest-Of-World (ROW) is normally automatically calculated (Weidema et al. 2013). In the case of the electricity datasets, the ROW datasets are generated as copies of the global activities in order to avoid inconsistencies as a consequence of this automatic calculation (see Moreno Ruiz et al. (2013) for discussion).
- Wherever possible, the global dataset serves as parent for local datasets. This parent/child relationship² has not been implemented for country-specific datasets which already existed in v2 (see Chapter 2.4).
- In ecoinvent v3, the technology level defines the marginal electricity mix for consequential life cycle modelling (Weidema et al. 2013). Only electricity generation datasets with the technology level “modern” contribute to the marginal mix in consequential system modelling. These are the technologies that can and will be able to increase their output by expansion of generation capacity when demand increases (i.e. they are “unconstrained” suppliers) (Weidema et al. 2013), while technologies that are constrained retain the technology level “current”. The implemented categorization is provided in Table ii in the ESM. This modelling and the consequences are discussed in Treyer and Bauer (2013).
- Parameters, variables and mathematical relations were introduced in the inventories concerning, e.g. efficiency, capacity, lifetime of infrastructure or load hours of power plants in order to increase transparency.
- All electricity datasets hold tags so that they can be grouped according to technology classes (see Table ii in the ESM).

¹ A global (GLO) dataset is supposed to represent the average global production of a certain good (or service). Currently, many of the global datasets are just extrapolated from one of the existing regional (local) datasets. The GLO datasets provide a basis for approximation for countries where a certain activity does not yet exist in the ecoinvent database (Weidema et al. 2013, Chapter 1.2.5).

² A global dataset can be the parent of the local datasets, which is useful for groups of closely related datasets. The local datasets inherit all information from their global parent; whenever necessary, the data can be adapted to the local conditions (Weidema et al. 2013, Chapters 1.2.5 and 1.2.6).

- The geography “Serbia and Montenegro” (CS) was substituted by the geography “Serbia” (RS). No data for Montenegro were available.

2.4 “Version 2” and “version 3” datasets

In the release version 3 of ecoinvent, the electricity datasets are not harmonized yet. There are differences between electricity datasets for the 32 countries for which electricity generation activities and electricity mixes were already modelled in version 2 and the 18 new countries for v3 as described in the following paragraphs.

1. For the 32 v2 countries:

- Existing electricity generation datasets were automatically transferred from v2 to v3 with only basic automatic changes—such as adaptation of the exchange names to new v3 naming conventions. Their content corresponds to the ecoinvent reports for version 2.2, i.e. no emission or efficiency values have been updated to 2008. They might not in all aspects comply with the Data Quality Guidelines (Weidema et al. 2013). The annual production volume was manually updated and reflects year 2008. These datasets are not implemented as children, but as not inheriting local datasets.
- In cases where a proxy dataset from another country supplied a market in v2 (e.g. electricity production with oil from Slovakia used on the electricity market for Bulgaria), the proxy dataset was copied and the geographic region changed. In general, the exchanges in these copies were not modified (see Table 7.5 in Moreno Ruiz et al. (2013) for details). Uncertainties were adapted accordingly.
- Datasets for newly implemented technologies (i.e. technologies which were not available in v2) were created as child datasets of the global activities to supply the electricity markets of v2 countries.

2. All datasets for the 18 new v3 countries are new and have been created as child datasets of the global activities. These datasets are partly based on data from version 2 with country-specific key parameters such as power plant efficiencies or wind load hours implemented. The exchange amounts in the global parent dataset are calculated in different ways, depending on the technology: either as average of v2 countries, average of v3 countries, or copies of a specific local dataset. The particular procedure is documented in the datasets.

Few exceptions from this procedure are present in the database with specific documentation in the datasets. Table ii in the ESM contains complete information concerning inheritance. Future updates of the electricity datasets should aim for consistency in all these power generation activities.

2.5 Transforming activities

All electricity production datasets are modelled as “Ordinary Transforming Activities”. All activities that are not of a special type in ecoinvent v3 are Ordinary Transforming Activities. According to Weidema et al. 2013, “transforming activities are human activities that transform inputs, so that the output of the activity is different from the inputs, e.g. a hard coal mine that transforms hard coal in ground to the marketable product hard coal.” They can be categorized as “normal” electricity-producing activities, heat and power co-generation activities, and treatment activities.

Ecoinvent v3 contains power generation datasets for the following energy sources: coal (hard coal, lignite, peat), industrial gases (blast furnace gas, coke oven gas), natural gas (conventional/combined cycle with/without combined heat and power (CHP)), petroleum products, nuclear (boiling water reactor, pressure water reactor), hydropower (reservoir plants, run-of-river plants, pumped storage plants), photovoltaics (building integrated and open ground), wind (on- and offshore), geothermal, biomass (biogas, wood) and waste. Some of these technologies are new in v3: electricity from large natural gas plants with CHP, electricity from large wind turbines (2 MW, 4.5 MW), open ground photovoltaic and geothermal power. No data are available for wave and tidal power and solar thermal power—these technologies hold only very small shares in electricity production, though. See Table ii in the ESM for all details on dataset name and type, reference product, tags, technology level and geographies.

2.5.1 Electricity-generating activities

Most of the electricity-producing activities represent power plants with the reference product 1 kWh net electricity (high or low voltage). Their activity name starts with “electricity production”, followed by the technology and further specifications if needed (e.g. “electricity production, nuclear, boiling water reactor”). They have inputs of infrastructure, materials and substances directly needed for the electricity production. Their outputs are emissions into the diverse compartments as well as by-products.

2.5.2 Heat and power co-generation activities

CHP production with natural gas, diesel and wood in co-generation plants is modelled as co-generation activity. The activity name begins with “heat and power co-generation”, followed by the fuel and further specifications if needed (e.g. “heat and power co-generation, natural gas, at conventional power plant”). In contrast to the “normal” electricity-producing activities, heat is the reference product of these datasets, whereas electricity is a by-

product. According to Weidema et al. (2013), “the reference products are those products for which a change in demand will affect the production volume of the activity.” This means that in these cases, the production of electricity correlates with the amount of heat produced with a certain fuel and cannot be independently varied.

2.5.3 Treatment activities

Combustion of industrial gases, biogas and municipal and industrial waste are modelled as treatment activities with a negative reference product³ being treated and electricity (and sometimes heat) as a by-product. Their activity name normally begins with “treatment of”, followed by the substance being treated and further specifications if needed (e.g. “treatment of blast furnace gas, in power plant”)⁴.

2.5.4 Special electricity types

There are two special types of electricity modelled in ecoinvent v3: label-certified electricity generated in Switzerland by hydropower, wind, photovoltaics and biomass plants and electricity for (company) internal use. The label-certified electricity does not contribute to the normal Swiss electricity market but constitutes a separate “market for electricity, [voltage level], label-certified”. The certification is awarded by the official Swiss certification association for environmentally sound energy (www.naturemade.ch) on two different levels for ecologically produced electricity from renewable power sources. Swiss citizens in specific parts of Switzerland can choose to buy such labelled electricity from their electricity provider. In Switzerland, electricity from reservoir and run-of-river hydropower plants, photovoltaic plants, wind turbines and wood combustion can be labelled. As such labels also exist in other countries, this concept could be expanded within the ecoinvent database. However, the inventory data of conventional and label-certified electricity production are identical, as issues evaluated by the labels such as better living conditions for fish or alike are not covered by the LCI data. All datasets for label-certified electricity hold the tag “certified electricity”.

Electricity for company internal uses is directly used (autoproducers) and does not enter the public electricity markets. This type of electricity is called “electricity, high voltage, [specification], for internal use” or “electricity, high voltage, for [company name]”. In ecoinvent v3, there are three of such autoproducers electricity types: for Swiss Federal Railways

(Itten et al. 2012), for internal use at coal mines in China, and for the aluminium industry (Lesage 2012).

3 Life cycle inventory of electricity generation technologies

3.1 Hard coal, lignite, peat

Coal types can be classified according to EPIA (2011) into “hard coal” (bituminous coal and anthracite) and “brown coal” (sub-bituminous coal and lignite). In ecoinvent v3, the datasets “electricity production, hard coal” generally include anthracite and bituminous coal. However, in line with Itten et al. (2012), hard coal includes sub-bituminous coal for Australia, Canada, Hungary, Mexico, South Korea, Spain and the US NERC regions. Except for these seven countries, brown coal is calculated as the sum of sub-bituminous coal and lignite and is represented by the datasets “electricity production, lignite”.

LCA of fossil power generation shows that direct power plant emissions from fuel combustion are usually the main contributors to life cycle impacts on human health as well as climate change per kilowatt hour electricity generated, i.e. that the operation of the power plant is the most important life cycle phase. Among these direct emissions, CO₂ is dominating in terms of effects on climate change (global impacts), while nitrogen oxides (NO_x) and sulphur dioxide (SO₂) emissions are both substantially contributing to regional and local impacts such as photochemical oxidation as well as particulate matter formation (due to formation of secondary particulates). Emissions of primary particles, especially the smaller size fractions (PM_{2.5}, PM₁₀), are another key element for regional impacts on human health (von Stackelberg 2011; Whitaker et al. 2012; Corsten et al. 2013; Liang et al. 2013; Volkart et al. 2013). Furthermore, coal is an important energy source for power generation in many electricity markets (Treyer and Bauer 2013). Therefore, high quality and high geographical resolution of these emission parameters are a crucial factor for ecoinvent as a background LCA database. For all v2 countries, the data have been taken over from Dones et al. (2007). For all new v3 countries, country-/region-specific data have been calculated for SO₂, NO_x and particulate matter (PM) emissions as well as the amounts of SO₂ and NO_x removed from the flue gas based on a database on single coal-fired power plants (IEA 2012). Data on capacity, coal type and use of other fuels, coal origin, coal properties (sulphur/ash/moisture content) as well as installed particle control systems, denitrification and desulfurization systems from individual coal-fired power plants were used and are implemented in the new inventory data, calculated as country-averages. However, data quality differs a lot from country to country, which is documented in the uncertainty information in the datasets.

In the global datasets, these key emissions are calculated as production volume weighted averages of old v2 countries and

³ “Negative reference product” means that the activity is supplying the service of treating or disposing of the reference product (Weidema et al. 2013).

⁴ The datasets “heat and power co-generation, biogas, in gas engine” are also treatment activities, even if this is not indicated by the name.

new v3 countries. All other emissions in the global dataset are calculated as production volume 2008 weighted average using the emission parameters per megajoule fuel burned in the v2 datasets and the fuel-specific global average power plant efficiencies. The new v3 countries inherit these exchange amounts from the global (GLO) parent dataset; the amounts are adjusted using parameters according to country-specific power plant efficiencies.

Power plant efficiencies for the 18 new v3 countries and the GLO dataset have been calculated with data from the IEA and OECD statistics (IEA and OECD 2010a, b). Efficiency values for the v2 countries are from Dones et al. (2007). Country-specific losses from gross to net electricity production are calculated according to Itten et al. (2012). According to IEA and OECD (2010a), CHP plants in OECD countries generate 6.3 and 15.2 % of the total electricity production from hard coal and lignite, respectively. However, due to lack of country-specific statistical data, combined heat production in CHP plants could not be taken into account. This limitation will result in a minor overestimation of cumulative LCI and LCIA results for electricity generation in the allocated system model, since the impacts are not allocated to both electricity and heat according to their prices. However, since the price of electricity is substantially higher than the one of heat and the CHP shares are low (i.e. also the amount of heat generated), this simplified approach can be justified.

Tables 1 and 2 show the geographical variations in the key direct emission factors of hard coal and lignite power plants as well as their average country-specific net electrical efficiencies, mainly determining the CO₂ emissions, for the unlinked unit process data. Emission and efficiency data for the countries existing already in v2 have not been changed and are documented in Dones et al. (2007).

The global and the local datasets for electricity production with peat are copies of lignite datasets, but with specific data regarding peat combustion for the direct emissions of SO₂, NO_x, particles and carbon dioxide (CO₂) according to Table 9.28 in Dones et al. (2007)) as well as peat-specific adaptations of the electrical efficiency. No information was available on desulphurization and denitrification in peat power plants. The country-specific power plant efficiencies are calculated based on (IEA and OECD 2010a, b). CHP plants have not been taken into account.

3.2 Natural gas

Modelling of electricity production from natural gas in new v3 countries is split into four sub-categories:

- Electricity production in a conventional power plant with/without CHP
- Electricity production in a natural gas combined cycle power plant (NGCC) with/without CHP

Worldwide, 26 % of electricity from natural gas is generated in CHP plants (IEA and OECD 2010a). Furthermore, natural gas power plants are today often designed with combined cycles (estimated 25–30 % of installed capacity). As a consequence, all these four power plant types are modelled in the new v3 countries. Natural gas-based power generation activities in v2 countries were not modified and represent electricity production in a conventional power plant without CHP (Faist Emmenegger et al. 2007). Future work on the ecoinvent data should aim to introduce all four natural gas power plant types also to the v2 countries.

No data on the installed capacities of the four different power types were available, so that the shares of the four types in each country had to be estimated. Table 3 shows these shares of electricity generation in CHP and non-CHP natural gas plants as well as shares of combined cycle vs. conventional plants with the associated efficiencies in the new v3 countries. The country-specific shares of CHP plants and the country-specific average efficiencies of electricity and heat production with natural gas (first three columns) are directly calculated from IEA statistics (IEA and OECD 2010a, b). These provide data concerning fuel input and the amount of produced electricity and heat, hence the associated uncertainties of average country-specific efficiencies are low. In order to be able to estimate the average efficiency for the different natural gas power plant types, the basic electrical efficiencies of combined cycle power plants and conventional plants without CHP were estimated to amount to 53 and 33 %, respectively. Calculated average efficiency values above 33 % indicate operation of combined cycle power plants and were used for estimation of NGCC shares. The assumptions for the shares have to be interpreted as first estimations with considerable uncertainties.

Key direct emission factors for CO₂ and NO_x from all four power plant types are listed in Table 4 (conventional natural gas power plants without CHP) and Table 5 (conventional natural gas power plants with CHP and combined cycle power plants with and without CHP) and discussed in the results section.

3.3 Industrial gases

Electricity from two types of industrial gases is modelled:

- “Treatment of blast furnace gas, in power plant” representing the treatment (i.e. combustion) of 1 MJ of blast furnace gas with 0.075 to 0.126 kWh electricity (high voltage) as by-product.
- “Treatment of coal gas, in power plant” representing the treatment (i.e. combustion) of 1 MJ of coke oven gas with 0.075 to 0.126 kWh electricity (high voltage) as by-product. In v2, this type of gas was called “coke oven gas”.

All datasets are copies of the former v2 datasets for Europe (RER) (Faist Emmenegger et al. 2007). All exchanges except

Table 1 Average net efficiencies of hard coal power plants and main emission parameters SO₂, NO_x, CO₂ and particulates <2.5 µm. Efficiencies in italics are extrapolated values. Maximum and minimum values are in bold. Regions with grey shading belong to the newly implemented countries in v3

		Electrical efficiency	SO ₂	NO _x	Particulates <2.5 µm	CO ₂	Sources ^a
		—	kg/kWh	kg/kWh	kg/kWh	kg/kWh	η , SO ₂ , NO _x , PM _{2.5} , CO ₂
Austria	AT	0.404	4.12E-04	5.46E-04	2.42E-05	0.838	1, 1, 1, 1, 1
Australia	AU	0.310	3.58E-03	2.55E-03	6.78E-05	1.109	3, 2, 2, 1/2, 5
Bosnia and Herzegovina	BA	0.322	6.06E-03	3.04E-03	3.32E-04	1.057	Inherited from GLO
Belgium	BE	0.360	3.47E-03	1.57E-03	2.06E-04	0.948	1, 1, 1, 1, 1
Bulgaria	BG	0.332	6.06E-03	3.04E-03	3.32E-04	1.057	Inherited from GLO
Brazil	BR	0.332	4.72E-03	1.87E-03	2.24E-04	1.004	Copy of PL
Canada	CA ^b	0.378	6.94E-03	1.90E-03	7.60E-05	0.910	3, 6, 6, 6, 5
Chile	CL	0.335	4.12E-03	4.85E-03	1.59E-02	1.061	4, 2, 2, 1/2, 5
China	CN	0.357	7.81E-03	4.12E-03	4.27E-04	0.960	1, 1, 1, 1, 1
Czech Republic	CZ	0.294	6.39E-04	1.87E-03	5.84E-05	1.135	1, 1, 1, 1, 1
Germany	DE	0.359	6.56E-04	6.21E-04	4.73E-05	0.922	1, 1, 1, 1, 1
Denmark	DK	0.350	1.13E-03	5.31E-04	2.36E-05	0.814	Copy of NORDEL v2
Spain	ES	0.358	7.31E-03	3.62E-03	4.85E-04	0.960	1, 1, 1, 1, 1
Finland	FI	0.350	1.13E-03	5.31E-04	2.36E-05	0.814	Copy of NORDEL v2
France	FR	0.355	4.54E-03	1.96E-03	2.44E-04	0.949	1, 1, 1, 1, 1
Great Britain	GB	0.333	4.72E-03	1.87E-03	2.24E-04	1.004	Copy of PL
Croatia	HR	0.355	2.53E-03	2.87E-03	1.24E-04	0.949	1, 1, 1, 1, 1
Hungary	HU	0.333	4.72E-03	1.87E-03	2.24E-04	1.004	Copy of PL
Ireland	IE	0.333	4.72E-03	1.87E-03	2.24E-04	1.004	Copy of PL
India	IN	0.239	7.19E-03	4.12E-03	4.27E-04	1.439	4, 7, copy of CN, copy of CN, 5
Italy	IT	0.373	3.78E-03	1.89E-03	2.36E-04	0.907	1, 1, 1, 1, 1
Japan	JP	0.360	3.47E-03	1.57E-03	2.06E-04	0.948	Copy of BE
South Korea	KR	0.358	5.22E-04	2.55E-03	1.28E-05	0.960	3, 2, copy of AU, 1/2, 5
Mexico	MX	0.328	1.18E-02	3.46E-03	1.04E-03	1.048	4, 2, copy of ZA/2, 1/2, 5
Malaysia	MY	0.274	4.02E-03	1.74E-03	2.57E-03	1.255	4, 2, copy of TH/2, 1/2, 5
The Netherlands	NL	0.353	6.19E-04	8.02E-04	1.86E-05	0.949	1, 1, 1, 1, 1
Norway	NO	0.350	1.13E-03	5.31E-04	2.36E-05	0.814	Copy of NORDEL v2
Peru	PE	0.279	4.12E-03	4.12E-03	1.59E-02	1.232	4, copy of CL, copy of ZA/2, copy of CL, 5
Poland	PL	0.332	4.72E-03	1.87E-03	2.24E-04	1.004	1, 1, 1, 1, 1
Portugal	PT	0.375	5.14E-03	2.52E-03	1.40E-04	0.902	1, 1, 1, 1, 1
Romania	RO	0.333	4.72E-03	1.87E-03	2.24E-04	1.004	Copy of PL
Russia	RU	0.238	9.02E-03	5.03E-03	1.68E-03	1.445	4, 2, 2, 1/2, 5

Table 1 (continued)

Sweden	SE	0.350	1.13E−03	5.31E−04	2.36E−05	0.814	Copy of NORDEL v2
Slovenia	SI	0.353	2.53E−03	2.87E−03	1.24E−04	0.949	Copy of HR
Slovakia	SK	0.384	5.12E−03	1.63E−03	1.87E−03	0.872	1, 1, 1, 1, 1
Thailand	TH	0.366	2.07E−03	8.27E−04	2.26E−04	0.939	4, 2, 2, 1/2, 5
Turkey	TR	0.358	1.81E−03	2.96E−03	3.42E−05	0.960	3, 2, 2, 1/2, 5
Taiwan	TW	0.333	2.07E−03	8.27E−04	1.24E−03	1.020	4, copy of TH, copy of TH, copy of TH, 5
Tanzania	TZ	0.293	7.63E−03	4.12E−03	3.60E−03	1.173	4, copy of ZA, copy of ZA, copy of ZA, 5
Ukraine	UA	0.260	8.35E−03	5.03E−03	8.00E−05	1.322	4, 2, copy of RU, 1/2, 5
South Africa	ZA	0.332	7.63E−03	4.12E−03	8.00E−05	1.036	8, 8, 8, 8, 5
United States – North American Energy Reliability Corporation Regions (NERC)							
Alaska Systems Coordinating Council	ASCC	0.318	3.78E−03	2.29E−03	4.59E−05	1.306	1, 1, 1, 1, 1
Florida Reliability Coordinating Council	FRCC	0.375	2.90E−03	2.04E−03	3.25E−05	0.924	1, 1, 1, 1, 1
Hawaiian Islands Coordinating Council	HICC	0.318	7.63E−03	4.12E−03	8.00E−05	1.036	1, 1, 1, 1, 1
Midwest Reliability Organization	MRO	0.260	4.00E−03	2.71E−03	4.69E−05	1.342	1, 1, 1, 1, 1
Northeast Power Coordinating Council	NPCC	0.323	5.72E−03	1.33E−03	3.78E−05	1.061	1, 1, 1, 1, 1
Reliability First Corporation	RFC	0.332	6.82E−03	1.84E−03	3.68E−05	1.050	1, 1, 1, 1, 1
SERC Reliability Corporation	SERC	0.327	5.47E−03	1.64E−03	3.73E−05	1.065	1, 1, 1, 1, 1
Southwest Power Pool	SPP	0.266	3.78E−03	2.29E−03	4.59E−05	1.306	1, 1, 1, 1, 1
Texas Regional Entity	TRE	0.308	2.72E−03	7.45E−04	3.96E−05	1.127	1, 1, 1, 1, 1
Western Electricity Coordinating Council	WECC	0.311	1.70E−03	2.10E−03	3.92E−05	1.123	1, 1, 1, 1, 1
World	GLO	0.322	6.06E−03	3.04E−03	3.32E−04	1.057	

^a The figures in this column stand from left to right for the source used for the efficiency η , emissions of sulphur dioxide (SO₂), nitrogen oxide (NO_x), particulate matter (PM_{2.5}) and carbon dioxide (CO₂)

^b For all Canadian provinces, average data for Canada have been used

1 value taken from ecoinvent report “Kohle” (Dones et al. 2007), 2 value calculated from a compilation of data from the IEA Clean Coal Database with data on single coal power plants (IEA 2012), 3 value calculated with data from the IEA/OECD Electricity information 2010: fuel input and electricity output (IEA and OECD 2010a), 4 value calculated with data from the IEA/OECD Energy balances of non-OECD countries: fuel input and electricity output (IEA and OECD 2010b), 5 value extrapolated from the global parent with an efficiency factor (average net country-specific electrical efficiency divided by the average net global electrical efficiency), 6 value calculated from a compilation of data from the Canadian National Pollutant Release Inventory (EC 2011), 7 value taken from (Ministry 2009; Shekar and Venkataraman 2002), 8 personal communication with Philippa Notten, The Green House, South Africa

Table 2 Average net efficiencies of lignite power plants and main emission parameters SO₂, NO_x, CO₂ and particulates <2.5 µm. Efficiencies in *italics* are extrapolated values. Maximum and minimum values are in **bold**. Countries with grey shading are the newly implemented countries in v3

	Electrical efficiency	SO ₂	NO _x	Particulate s <2.5 µm	CO ₂	Sources ^a
	–	kg/kWh	kg/kWh	kg/kWh	kg/kWh	η,SO ₂ ,NO _x ,PM _{2.5} ,CO ₂
AU	0.279	2.60E–03	1.91E–03	6.70E–05	1.38	3,2,2,2,5
BA	0.296	2.29E–02	2.92E–03	1.45E–03	1.28	1, 1, 1, 1, 1
BG	0.343	5.41E–03	1.49E–03	3.43E–04	1.10	Extrapolated from PL
BR	0.309	5.56E–03	2.26E–03	8.80E–03	1.26	Inherited from GLO
CA ^b	0.362	3.16E–03	1.58E–03	3.25E–05	1.11	3, 6, 6, 6, 5
CZ	0.332	2.14E–03	1.78E–03	7.51E–05	1.13	1, 1, 1, 1, 1
DE	0.331	5.74E–04	7.79E–04	5.28E–05	1.18	1, 1, 1, 1, 1
GR	0.352	5.97E–03	1.36E–03	9.02E–04	1.25	1, 1, 1, 1, 1
HU	0.279	1.91E–03	1.39E–03	1.11E–04	1.35	1, 1, 1, 1, 1
HR	0.309	5.56E–03	2.26E–03	8.80E–03	1.26	Inherited from GLO
ID	0.312	3.57E–03	4.12E–03	3.88E–02	1.23	3, 2, copy of hard coal CN, 1/2, 5
IN	<i>0.240</i>	8.73E–03	4.12E–03	6.23E–02	1.61	4, 7, copy of hard coal CN, 1/2, 5
MK	0.309	5.56E–03	2.26E–03	8.80E–03	1.26	Inherited from GLO
PL	0.351	5.30E–03	1.46E–03	3.37E–04	1.08	1, 1, 1, 1, 1
RO	0.343	5.41E–03	1.49E–03	3.43E–04	1.10	Extrapolated from PL
RS	0.298	1.57E–02	2.27E–03	2.27E–03	1.31	1, 1, 1, 1, 1
RU	0.225	1.33E–02	4.63E–03	1.47E–02	1.71	4, 2, 2, 1/2, 5
SI	0.324	2.11E–02	2.86E–03	4.82E–04	1.17	1, 1, 1, 1, 1
SK	0.231	1.89E–02	3.17E–03	1.56E–03	1.64	1, 1, 1, 1, 1
TH	<i>0.348</i>	2.98E–03	3.46E–03	6.54E–04	1.11	4, 2, 2, 1/2, 5
TR	0.322	9.28E–03	2.81E–03	2.29E–02	1.20	3, 2, 2, 1/2, 5
TW	<i>0.320</i>	2.98E–03	3.46E–03	3.60E–03	1.20	4, 2, 2, copy of TH/2, 5
UA	0.250	1.33E–02	4.63E–03	5.36E–03	1.54	3, copy of RU, copy of RU, 1/2, 5
GLO	0.309	5.56E–03	2.26E–03	8.80E–03	1.26	

^a The figures in this column stand from left to right for the source used for the efficiency η, emissions of sulphur dioxide (SO₂), nitrogen oxide (NO_x), particulate matter (PM_{2.5}) and carbon dioxide (CO₂)

^b For all Canadian provinces, average data for Canada have been used

1 value taken from ecoinvent report “Kohle” (Dones et al. 2007), 2 value calculated from a compilation of data from the IEA Clean Coal Database with data on single coal power plants (IEA 2012), 3 value calculated with data from the IEA/OECD Electricity information 2010: fuel input and electricity output (IEA and OECD 2010a), 4 value calculated with data from the IEA/OECD Energy balances of non-OECD countries: fuel input and electricity output (IEA and OECD 2010b), 5 value extrapolated from the global parent with an efficiency factor (average net country-specific electrical efficiency divided by the average net global electrical efficiency), 6 value calculated from a compilation of data from the Canadian National Pollutant Release Inventory (EC 2011), 7 value taken from (Ministry 2009; Shekar and Venkataraman 2002)

for the amount of electricity and heat produced from the treatment of 1 MJ of gas are identical. The specific electrical and thermal efficiencies defining the amount of electricity and heat produced from the treatment of 1 MJ of blast furnace or coal gas were estimated based on IEA and OECD (2010b) or taken from Faist Emmenegger et al. (2007) (see Table iii in the ESM). The IEA efficiency values had to be extrapolated from the overall value of the fuel category “coal &

peat” to which electricity from hard coal, lignite, peat and industrial gases belong.

3.4 Oil

The term “oil” represents fuel oil, diesel and other petroleum products, which are used as fuel inputs for electricity production. The GLO dataset was calculated as production weighted average

Table 3 Estimated shares and efficiencies of natural gas CHP plants as well as combined cycle gas turbine power plants in new ecoinvent v3 countries producing electricity with natural gas. Shares of CHP plants and efficiencies in the first three columns were calculated based on (IEA and OECD 2010a). Other shares and efficiencies based on (Faist

Emmenegger et al. 2007) and own estimations. The two shares “conventional, with CHP” and “combined cycle, with CHP” add up to the column “Share CHP”. The two shares “combined cycle, without CHP/with CHP” add up to the column “Share CC”

	Share CHP%	Efficiency		Share CC (%)	Conventional				Combined Cycle			
		Electrical	Thermal		Without CHP		With CHP		Without CHP		With CHP	
					Share (%)	Electrical efficiency	Share (%)	Electrical efficiency	Share (%)	Electrical efficiency	Share (%)	Electrical efficiency
AU	19	0.33	0.339	34	53.2	0.29	12.8	0.25	27.4	0.49	6.6	0.40
CA ^a	16	0.531	0.213	80	3.6	0.33	16.4	0.21	80.0	0.53	—	—
CL	0	0.369	—	20	80.4	0.33	—	—	19.6	0.53	—	—
ID	0	0.369	—	19	80.7	0.33	—	—	19.3	0.53	—	—
IN	0	0.420	—	45	55.2	0.33	—	—	44.8	0.53	—	—
IR	0	0.378	—	24	76.2	0.33	—	—	23.8	0.53	—	—
KR	21	0.491	0.361	81	15.4	0.33	4.0	0.28	64.0	0.53	16.6	0.37
MX	0	0.434	—	52	48.2	0.33	—	—	51.8	0.53	—	—
MY	0	0.375	—	22	77.6	0.33	—	—	22.4	0.53	—	—
PE	0	0.396	—	33	67.0	0.33	—	—	33.0	0.53	—	—
RU	100	0.213	—	6	—	—	93.7	0.25	—	—	6.3	0.37
SA	0	0.245	—	5	95.3	0.24	—	—	4.7	0.53	—	—
TH	0	0.407	—	39	61.4	0.33	—	—	38.6	0.53	—	—
TR	7	0.504	0.294	87	11.9	0.33	5.9	0.28	85.9	0.53	1.3	0.37
TW	0	0.436	—	53	46.8	0.33	—	—	53.2	0.53	—	—
TZ	0	0.332	—	0	100	0.33	—	—	—	—	—	—
UA	78	0.298	0.245	0	22.0	0.30	78.0	0.245	—	0.53	—	—
GLO	26.5	0.401	0.311	36	47.4	0.33	17.1	0.28	26.1	0.53	9.4	0.37

^a For all Canadian provinces, average data for Canada have been used

of electricity generation in v2 countries. Exchanges in the local datasets were not modified and correspond to Jungbluth (2007). As no specific emission data for the new v3 countries were collected, the exchange amounts in the new v3 datasets are determined with an efficiency factor departing from the parent GLO activity. First, average efficiencies of oil power plants in the new v3 geographies were calculated with data from (IEA and OECD 2010a, b) (see Table iv in the ESM). The global data were then extrapolated to the local ones using a factor “efficiency of the local geography divided by the average global efficiency”.

3.5 Nuclear

Two types of nuclear power plants are modelled: boiling water reactors (BWR) and pressure water reactors (PWR). The datasets for the new v3 countries are child datasets of the two global datasets, which are copies of ecoinvent v2 datasets for Switzerland (Dones et al. 2009) with exchanges scaled with geography-specific power plant efficiencies. These were calculated for all new v3 countries based on all individual reactors in a country according to IAEA (2009) and WNA (2009); as

opposed to IEA and OECD (2010a), which provides a “standard factor” for the efficiency of nuclear plants of 31 %. Using data from the individual reactors results in a range of average country-specific efficiencies of 23–33 % (see Table v in the ESM). The global dataset is a copy of a Swiss dataset; in both geographies, the net efficiency is 31 %.

3.6 Wind

Electricity production with wind turbines was split into four categories according to capacity and location: capacity of <1 MW, 1–3 MW, >3 MW, onshore, and 1–3 MW offshore (see Table vi in the ESM for technology details). The shares of the four different wind classes in all v3 countries with wind power were determined based on data for individual turbines installed in August 2011 (TheWindPower 2011). Details on the installed capacities in each class per geography are provided in Table vii in the ESM. One of the most important factors in the LCA of wind power is the location-specific yield or capacity factor, i.e. the annual wind load hours (Dolan and Heath 2012; Caduff et al. 2012; Jungbluth et al. 2005). These are provided in

Table 4 Key direct emission factors in conventional natural gas power plants without CHP

	CO ₂ [g/kWh]	NO _x [g/kWh]		CO ₂ [g/kWh]	NO _x [g/kWh]
ASCC	635	1.626	IT	539	0.614
AT	572	0.312	JP	517	0.330
AU	620	0.426	KR	583	<i>0.400</i>
BE	491	0.439	LU	823	0.735
BG	650	0.580	MRO	645	0.483
BR	531	0.400	MX	583	0.400
CA-AB	583	<i>0.400</i>	MY	583	<i>0.400</i>
CA-BC	583	<i>0.400</i>	NL	552	0.493
CA-MB	583	<i>0.400</i>	NO	486	0.434
CA-NB	583	<i>0.400</i>	NPCC	533	0.147
CA-NS	583	<i>0.400</i>	PE	583	<i>0.400</i>
CA-NT	583	<i>0.400</i>	PL	650	0.580
CA-ON	583	<i>0.400</i>	PT	531	0.474
CA-SK	583	<i>0.400</i>	RFC	553	0.253
CL	583	<i>0.400</i>	RO	650	0.580
CN	650	0.580	RS	650	0.580
CZ	650	0.580	SA	801	0.551
DE	461	0.294	SE	486	0.434
DK	486	0.434	SERC	518	0.295
ES	433	0.387	SI	531	0.474
FI	486	0.434	SK	650	0.580
FR	398	0.356	SPP	515	0.442
FRCC	729	0.570	TH	583	<i>0.400</i>
GB	464	0.415	TR	583	<i>0.400</i>
GR	531	0.474	TRE	518	0.235
HR	531	0.474	TW	583	<i>0.400</i>
HU	650	0.580	TZ	583	<i>0.400</i>
ID	583	<i>0.400</i>	UA	641	0.440
IE	531	0.474	WECC	527	0.249
IN	583	<i>0.400</i>	GLO	583	0.400
IR	583	<i>0.400</i>			

Data from regions with grey shading belong to the newly implemented countries in v3. Values in italic are inherited from the GLO parent. Maximum and minimum values are in bold. Source: ecoinvent v3

Table 6 for the onshore turbines in the individual geographies as implemented in ecoinvent v3 for the year 2008 according to (WWEA 2011; Itten et al. 2012; IEA and OECD 2010a). A loss of 1 % between gross and net electricity production is assumed based on Itten et al. (2012) and expert judgement.

3.7 Photovoltaic

The inventories for electricity production with photovoltaics are based on Jungbluth et al. (2012) and represent grid-connected 3 kW_p systems combining different types of panels or laminates installed on facades, slanted roofs or flat roofs resulting in 17 types of installations (see Table viii in the

ESM). Additionally, there is a 570 kW_p open ground PV plant in ecoinvent v3. The 3 kW_p systems can be extrapolated to installations with higher capacities without requiring significant changes in the inventories. For the new v3 countries, datasets for all the 17 types were established and adapted to local annual yields based on literature sources with local conditions (see Table 7). For all other countries, only the two building-integrated modules with the highest worldwide shares in installed capacity and the open ground module were taken into account in a simplified approach as contributing to the country-specific electricity production, i.e. the total electricity generated by photovoltaic was split among these two and the open ground system. The

Table 5 Key direct emission factors in conventional natural gas power plants with CHP and in combined cycle natural gas power plants with and without CHP. These technologies have only been modeled for the newly implemented countries in v3

	Heat and power co-generation, natural gas, conventional power plant, 100 MW electrical		Electricity production, natural gas, combined cycle power plant		Heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical	
	CO ₂ [g/kWh]	NO _x [g/kWh]	CO ₂ [g/kWh]	NO _x [g/kWh]	CO ₂ [g/kWh]	NO _x [g/kWh]
AU	687	0.472	384	0.184	520	0.248
CA-AB	915	0.629	363	0.173	—	—
CA-BC	915	0.629	363	0.173	—	—
CA-MB	915	0.629	363	0.173	—	—
CA-NB	915	0.629	363	0.173	—	—
CA-NS	915	0.629	363	0.173	—	—
CA-NT	915	0.629	363	0.173	—	—
CA-ON	915	0.629	363	0.173	—	—
CA-SK	915	0.629	363	0.173	—	—
ID	—	—	363	0.173	—	—
IN	—	—	363	0.173	—	—
IR	—	—	363	0.173	—	—
KR	687	0.472	363	0.173	520	0.248
MX	—	—	363	0.173	—	—
MY	—	—	363	0.173	—	—
PE	—	—	363	0.173	—	—
Québec	915	0.629	—	—	—	—
RU	769	0.528	—	—	520	0.248
SA	—	—	363	0.173	—	—
TH	—	—	363	0.173	—	—
TR	915	0.629	363	0.173	601	0.287
TW	—	—	363	0.173	—	—
UA	785	0.539	—	—	—	—
GLO	687	0.472	363	0.173	520	0.248

Values in italic are inherited from the GLO parent. Source: ecoinvent v3

technology shares of these three are valid for 2008 and estimated according to Jungbluth et al. (2012) and IEA and PVPS (2010):

- A 3-kW_p slanted-roof installation, single-Si, panel, mounted representing about 16 % of the worldwide installed capacity
- A 3-kW_p slanted-roof installation, multi-Si, panel, mounted representing about 20 % of the worldwide installed capacity
- A 570-kW_p open ground installation, multi-Si representing about 35 % of the worldwide installed capacity

The share of open ground installations in the different countries was calculated based on (IEA and PVPS 2010), assuming that all centralized capacity is in the form of open ground. Shares are very high in Spain (98 %), Portugal (95 %) and South Korea

(84 %), while all other countries do not have open ground photovoltaic installations at all or only on a low level.

The location specific irradiation and the resulting annual yield of photovoltaic plants is one of the decisive factors for LCA results of photovoltaics (Kim et al. 2012; Hsu et al. 2012; Jungbluth et al. 2012). Table 7 shows the country-specific figures as implemented in ecoinvent v3 along with the specific data sources of the yields. The global yield is a weighted average of all countries in v3.

3.8 Other renewables

Hydropower is modelled with run-of-river plants, pumped storage plants and reservoir plants (in alpine, non-alpine and tropical regions). All children are unadapted copies of their parents—i.e. GLO activities, which are copies of the Swiss v2 datasets from Bauer et al. (2007). Bauer et al. (2007) modelled

Table 6 Wind power: installed capacity (WWEA 2011), gross electricity production ((Itten et al. 2012) for new ecoinvent v3 countries with grey shading and (IEA and OECD 2010a) for all other countries) and calculated wind load hours in the ecoinvent v3 countries

	Total installed capacity [MW]	Gross electricity production [GWh/a]	Wind load hours (2008) [h/a]
AT	995	2,014	2,024
AU	1,494	3,941	2,638
BE	384	637	1,661
BG	158	122	775
BR	339	637	1,882
CH	14	19	1,377
CL	20	38	1,891
CN	12,210	13,079	1,071
CZ	150	245	1,633
DE	23,903	40,574	1,697
DK	3,163	6,928	2,190
ES	16,740	32,203	1,924
FI	143	261	1,825
FR	3,404	5,689	1,671
GB	3,195	7,097	2,221
GR	990	2,242	2,265
HR	18	40	2,198
HU	127	205	1,614
IE	1,027	2,410	2,347
IN	9,587	13,740	1,433
IR	82	196	2,390
IT	3,736	4,861	1,301
JP	1,880	2,623	1,395
KR	278	436	1,568
LU	35	61	1,728
MX	85	269	3,165
NL	2,235	4,260	1,906
NO	429	917	2,138
PE	0.7	1	1,429
PL	472	837	1,773
PT	2,862	5,757	2,012
RO	7	5	714
RU	17	5	303
SE	1,067	1,996	1,871
SK	6	7	1,167
TR	333	847	2,540
TW	358	589	1,645
UA	90	45	500
US*	25,237	55,696	2,207
ZA	22	32	1,468
Canadian provinces with wind power installed			
CA-AB	439	769	1,664

Table 6 (continued)

CA-MB	104	349	3,187
CA-NS	53	190	3,432
CA-ON	414	530	1,218
CA-PE	44	43	930
CA-SK	171	623	3,453
CA-YK	0.8	0.4	512
Québec	376	1,490	3,787
GLO	121,188	218,454	1,803

Maximum and minimum values are in bold

^a Due to lack of more detailed information, average data for USA have been used for all US regions

direct emissions of GHG (dinitrogen monoxide (N₂O), methane (CH₄) and CO₂) from reservoir lakes according to their location, i.e. GHG emissions from lakes in tropical regions are substantially higher than in higher latitudes. Three datasets for heat and power co-generation with *wood* are available. Two are for a thermal capacity of 6,400 kW with different levels of emission control⁵, one is for a capacity of 1,400 kW thermal and only used for the Swiss geography. Electricity from *bio-gas* is modelled as a by-product from the treatment of the biogas, which is a by-product of treatment of liquid manure, and the treatment of sewage sludge. Electricity production with *geothermal* technology is new in ecoinvent v3. The inventories represent an enhanced geothermal system (EGS) with binary cycle, also known as Hot-Dry-Rock system, as planned for installation and operation in Basel (Switzerland). The v3 datasets are based on the inventory data for current technology in Bauer et al. (2008). Electricity as by-product of *waste incineration* is modelled in the dataset “treatment of municipal solid waste, incineration”. The global dataset is a copy of the v2 dataset for Switzerland (Doka 2007).

4 Discussion of results

4.1 Hard coal and lignite

Emissions of SO₂, NO_x and particles depend on the coal quality as well as on installation rate and efficiency of flue gas treatment. No desulphurization units are installed in hard coal power plants in Chile, China, Peru, Portugal and Russia (IEA 2012). Particulates are in most of the countries removed by electrostatic precipitators, but with substantially differing efficiencies. According to IEA (2012), 25 countries do not have any denitrification installations in their hard coal power plants. The information content and level of completeness of IEA (2012) depends on the country the power plants are located: data are much more complete for countries with

higher economic development like South Korea than for less developed ones like Peru and Tanzania; as a consequence, the uncertainties of these exchanges are affected accordingly (i.e. much higher), which is documented in the datasets.

As a result of the country-specific differences in flue gas cleaning, the emission factors of hard coal plants show high country-specific variations: SO₂ emissions in Mexico (max) are 28.6 times higher than in Austria (min). For NO_x, the range is smaller (Chile, nine times higher than Austria). In contrast, the PM emissions are spread over a large range, with some extreme max/min factors of 200 (Malaysia), 280 (Tanzania) and 1,240 (Chile) compared to Korea (min). Also for lignite, the factors between maximum and minimum emission values are in the same range as for hard coal. For SO₂, the country-specific maximum (Bosnia and Herzegovina) is 40 times higher than the minimum value (Germany). For NO_x, the factor amounts to 5.9 (Russia and Ukraine compared to Germany), whereas the PM_{2.5} emissions spread over a huge range (factor 1915 for India compared to Canada).

The calculated particle emission factors as well as (to a smaller extent) SO₂ and NO_x emissions are very sensitive to the share and efficiency of installed particle filters, desulphurization and denitrification devices. Since this information was not consistently provided by IEA (2012) for all single power plants, the uncertainties of some emission factors are high.

Electric efficiencies determining CO₂ emissions were calculated from IEA/OECD statistics (IEA and OECD 2010a, b). These statistics provide fuel-, country- and technology-specific information on the amount of fuel used and the amount of electricity produced. The uncertainties are low for OECD countries, whereas the mentioned data are only provided for the general category “coal” for non-OECD countries, including hard coal, lignite, peat and industrial gases. Extrapolations had therefore to be made and uncertainties are higher, as documented in the datasets (values in italics in Tables 1 and 2).

The direct CO₂ emissions of hard coal plants vary between 0.81 kg/kWh for DK, FI, NO, SE with comparatively high power plant efficiencies (0.35) and 1.45 kg/kWh in Russia, which has the lowest efficiency (0.238, but as this is an extrapolated value it is associated with a higher uncertainty). CO₂

⁵ Multicyclone emission control for particle removal or further emission controls installed, e.g. selective noncatalytic reduction filter.

Table 7 Country-specific annual yields and installed capacities for the year 2008 in v3 countries with electricity from photovoltaics. Maximum and minimum values are in bold

	Photovoltaic yield [kWh/kW _p a]	Source	Installed capacity 2008 [MW _p]	Source
AU	1,407	IEA (2006)	105	IEA (2010)
AT	945	IEA (2008)	32	IEA (2010)
BE	788	IEA (2006)	71	CONUEE (2009); Sopian et al. (2005)
CA ^a	1,100	IEA (2008)	33	IEA (2010)
CH	950	IEA (2008)	48	IEA (2010)
CN	1,042	McKinsey (2008)	14	Hawkins et al. (2012)
CZ	890	McKinsey (2008)	55	CONUEE (2009); Sopian et al. (2005)
DE	950	IEA (2008)	6,000	IEA (2010)
DK	850	IEA (2008)	3	IEA (2010)
ES	1,300	IEA (2008)	3,463	IEA (2010)
FI	826	McKinsey (2008)	6	CONUEE (2009); Sopian et al. (2005)
FR	1,000	IEA (2008)	180	IEA (2010)
GB	750	IEA (2008)	23	IEA (2010)
GR	1,220	McKinsey (2008)	19	CONUEE (2009); Sopian et al. (2005)
HU	1,080	McKinsey (2008)	1	CONUEE (2009); Sopian et al. (2005)
IN	1,800	JRC (2011)	102 ^b	Hawkins et al. (2012)
IT	1,260	McKinsey (2008)	458	IEA (2010)
JP	1,051	IEA (2008)	2,144	IEA (2010)
KR	1,002	IEA (2006)	358	IEA (2010)
LU	882	McKinsey (2008)	25	CONUEE (2009); Sopian et al. (2005)
MX	1,369	IEA (2008)	22	IEA (2010)
MY	1,100	Euroserver (2011)	9	IEA (2010)
NL	821	IEA (2008)	57	IEA (2010)
PT	1,370	McKinsey (2008)	68	IEA (2010)
SE	850	IEA (2008)	8	IEA (2010)
SI	963	McKinsey (2008)	2	CONUEE (2009); Sopian et al. (2005)
TH	1,650	Wakabayashi (2010)	35	IEA (2010)
TW	1,125	Estimation based on global avg. irradiation	4	IEA (2010)
US ^c	1,338	IEA (2008)	1,169	IEA (2010)
ZA	1,620	McKinsey (2008)	20	
GLO	1,110	Calculated as average of locals	14,559	Sum of locals

^a Due to lack of more detailed information, average data for CA have been used for all Canadian provinces.

^b Value for 2009

^c Due to lack of more detailed information, average data for US have been used for all US regions.

emissions are in general higher for lignite power plants, where they vary between 1.08 kg/kWh (Poland) and 1.71 kg/kWh (Russia). Russia holds again the lowest efficiency value, but with a high uncertainty.

Both efficiencies and emission parameters for lignite and hard coal power plants (within the fuel categories, Tables 1 and 2) show a high correlation with country-specific levels of economic development: positive correlation for efficiencies, negative for emission factors.

The wide range of efficiencies and emission parameters of hard coal power plants in the US regions of the NERC (Table 1) demonstrates the importance of partitioning of large

countries into smaller regional geographical units: power plant efficiencies as well as CO₂ emissions vary by a factor of 1.4 (max/min); SO₂, NO_x and PM_{2.5} emissions by factors of 4.5, 5.5 and 2.5, respectively.

4.2 Natural gas

Key direct emission factors for CO₂ and NO_x are listed in Table 4 (conventional natural gas power plants without CHP) and Table 5 (conventional natural gas power plants with CHP and combined cycle power plants with and without CHP). Due to the lack of detail in the available statistical information,

shares of combined cycle plants as well as CHP rates are associated with high uncertainties, which need to be taken into account when comparing natural gas power generation activities in different countries. In general, the combined cycle natural gas power plants without CHP have the lowest CO₂ and NO_x emissions (0.363 and 0.173 kg/kWh, respectively). Conventional power plants in general show higher emissions due to lower (electrical) efficiencies for technical reasons (up to 0.915 and 1.626 kg/kWh, respectively). Plants with CHP have lower electrical efficiencies due to the co-generation process, i.e. heat available after combustion of the energy carrier is partially used for the production of heat instead of electricity. For the conventional power plants without CHP, the highest and lowest NO_x emissions can be found in the US regions ASCC and TRE, respectively. However, electricity generation activities using natural gas as fuel (conventional natural gas power plants) already present in ecoinvent v2 have not been updated and subdivided into the four different plant types available for the new v3 countries, even if in countries such as, e.g. the USA, combined cycle power plants have recently been installed. This limitation means that the current inventory data partially do not reflect the latest developments in specific regions and certain modern technologies are not available in some countries, which might lead to an overestimation of environmental burdens from power generation for these electricity markets, as discussed in detail by Treyer and Bauer (2013).

4.3 Other non-renewables

Electricity generation activities with oil power plants have not been updated, i.e. the data content basically corresponds to the inventory data in v2 with country-specific power plant efficiencies for the new v3 countries. The resulting data quality can be regarded as sufficient, since only very few (if any) new oil power plants have recently been installed in v2 countries and power plant efficiencies are one of the key factors determining the environmental burdens caused by such plants in the new v3 geographical regions.

Also in case of nuclear power, the data quality can be regarded as sufficient despite of the largely missing update of inventory data: nuclear reactors usually have a lifetime of 40 years or more, the technological development with an influence on LCI data during the last two decades has been minor, and country-specific efficiencies of the reactors could be implemented.

4.4 Renewables

Annual wind load hours of wind turbines and annual yields of photovoltaic plants are key factors for the environmental life cycle burdens of wind and solar power, which are the technologies with the most substantially updated and extended

inventory data compared to ecoinvent v2. Average geography-specific onshore wind load hours vary by a factor of 10 (max/min). The number of wind load hours seems to be suspiciously low in a few countries such as Russia or Ukraine; unfortunately, the figures could not be verified using alternative sources. The best onshore wind conditions are prevailing in some Canadian provinces and Mexico. The variations within Canada, i.e. the differences between the single Canadian provinces in terms of wind load hours as shown in Table 4 (max/min factor of 7.4) again highlights the importance of splitting large countries into regional electricity markets. Average load hours of offshore wind turbines could not be quantified separately, i.e. these are equal to the onshore load hours of the geographical regions.

Annual average photovoltaic yields vary by a factor 2.4, primarily as a consequence of location-specific solar irradiation. Northern countries like UK or Belgium show the lowest yields, while photovoltaic installations are most productive in India, Thailand and South Africa.

Geothermal power generation is represented by inventory data reflecting only one specific type of deep geothermal technology, so-called EGS. These inventory data are based on a case study for a specific site in Switzerland (Basel) and will be extended in near future. Including shallow geothermal plants will be important for future ecoinvent versions in order to account for the different conditions when using geothermal energy.

The other renewable power generation technologies—hydro reservoir and run-of-river plants as well as wood- and biogas-fuelled CHP units—have not been updated and reflect the data content of the v2 inventories. Uncertainty factors due to geographical extrapolations for the new v3 countries have been correspondingly increased. Inventory data corresponding to v2 data content does not necessarily mean that these data are outdated: while more modern wood power plant technologies will likely emit less pollutants, hydropower plants are infrastructures with lifetimes around 100 years and, therefore, the inventory data also valid for such periods.

5 Conclusions and recommendations

Inventories for average technology-specific electricity production in all important economies worldwide have been created with geography-specific technology datasets and are available in the ecoinvent v3 database. The technology portfolio contains almost all options available today for power generation with fossil, renewable and nuclear power plants: conventional power plants for hard coal, lignite, peat and fuel oil combustion; small-scale CHP as well as large-scale conventional and combined cycle plants, both with and without CHP, for natural gas; electricity from treatment activities of industrial gases, municipal waste and biogas; BWR and PWR as nuclear

plants; reservoir, run-of-river and pumped storage hydropower; 17 different types of solar photovoltaic cells and installations on roofs, facades and open ground; offshore and onshore wind turbines, the latter represented by three size categories; an enhanced geothermal system representing deep geothermal power; and wood-fuelled CHP generation.

Compared to version 2 of the ecoinvent database, the power generation technology inventories are now available for additional 18 countries with Canada and the USA partitioned into 13 and 10 regions, respectively. In total, inventories for 71 geographical regions are available and all countries with a share of more than 1 % in global power generation—plus a few less important ones—are covered. The technology update of wind and solar power and the new inventories for geothermal power ensure an up-to-date representation of the quickly developing renewable sector.

The large country- and region-specific differences in key parameters for LCA results of power generation technologies—emission factors and efficiencies of fossil power plants, annual yields of wind power and photovoltaics, etc.—clearly demonstrates the significance and benefit of the availability of inventories for electricity production on a country- and region-specific level. Together with the new inventories of electricity markets (Treyer and Bauer 2013), the improved coverage of power generation on a country- and region-specific level representing 83 % of global electricity production in 2008 will increase the quality of and reduce uncertainties in LCA studies worldwide and contribute to a more accurate estimation of environmental burdens from global production chains. The geographical expansion of power generation inventories can also be regarded as one more important step towards internationalization of the ecoinvent database. Furthermore, transparency and flexibility of the inventory datasets could be increased due to use of parameters, variables and mathematical relations as well as implementation of parent–child relationships between global and local activities. The uncertainties of inventory data or key parameters such as efficiency values still vary substantially between the geographical regions. In general, newly collected data for the new v3 countries are of a good quality. However, e.g. the IEA statistics show differences between OECD with more detailed data and non-OECD countries. Even if many emission values are copied or inherited, the emission data and other parameters like power plant efficiencies and annual yields, which have according to common LCA experience most influence on LCIA results, are implemented in a country-specific way for most geographical regions.

Future work on LCI of electricity production in ecoinvent should focus on including new technologies such as solar thermal, wave and tidal power as well as on improving and refining of the currently available local data and the associated fuel chains; additionally, certain technologies currently missing

in some of the geographical regions such as natural gas combined cycle plants in the US regions need to be integrated in the database. Partitioning of additional large countries like China, India and Australia, and availability of power generation LCI data on a more regional scale would further improve the database. The international LCA community is encouraged to supply their LCI data on power generation to ecoinvent in order to further improve the content of the database.

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