CHALMERS
UNIVERSITY OF TECHNOLOGY

Regionalized Life Cycle Inventory of Power Producing Technologies and Power Grids in India

Master's thesis in the Industrial Ecology Programme

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Department of Department of Energy and Environment
Division of Environmental System Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Indian electricity production mix, power plant technological level and local production conditions vary considerably on the state level across the 29 Indian states and 7 union territories. Hence, national-level Life Cycle Inventory of Indian power producing technologies and power systems as presented in ecoinvent v3.2 may not represent well this high variability. The aim of this study is to create a consistent regionalized model of Indian power systems in order to evaluate the necessity of such regionalized inventory. Data collection covers state-specific key parameters of domestic power production and distribution, and inter-exchanges among the regional grids and with other countries in 2012-2013. Such regionalization work faces some data availability challenges. Power plant parameter data (e.g. efficiency, fuel quality, exact technology used) are mostly unavailable on plant level: if at all, relevant data are available on a state level. Moreover, local emission data are also mostly unavailable except emissions of CO_2. Emission values for other important emissions (NOx, SOx, CH_4, CO, PM) are, therefore, calculated based on assumptions and literature information. The impact assessment results show high variations among the various power grids due to different grid mixes, key parameter values and electricity losses during transmission and transformation (T&T). As an example, power from the Eastern grid shows nearly four times higher Global Warming Potential (GWP 100a, in kg CO_2-eq/kWh) scores (1.6) than the North-eastern grid (0.4) and also considerably higher than the Northern (1.1) and Southern grid (1.2). The Western grid also corresponds to relatively high GWP score (1.4). Moreover, relatively high T&T losses have been inventoried. For example, in the Eastern grid, GWP scores for high, medium, and low voltage grids are 1.7, 1.8, and 2.1, respectively, which corresponds to up to 17% technical losses along the chain from gross production. To compare, in ecoinvent v3.2, the GWP score for the national-average of Indian electricity supplied at high voltage is 1.3 which is off the both highest and lowest regional score. This confirms the need of regionalized inventories for countries with large mix and key parameter variations in order to achieve higher accuracy in life cycle studies.

Keywords: Regionalization, Life Cycle Assessment, Life Cycle Inventory, Power System, Electricity Mix, India, Energy, Environment

Preface

The idea of this thesis was born three years ago in 2013 while doing my previous master thesis titled "Life Cycle Assessment (LCA) of selected activities at University of Chittagong, Bangladesh". There was no data available on any background process in whatsoever for Bangladesh which demands a huge amount of effort and time to conduct any LCA there. The data situation is not any better in any of the South-East Asian countries hitherto. Hence, I decided to work on creating background life cycle inventory datasets whenever I get an opportunity. Moreover, being an Industrial Ecology master student, we have been discussing about energy challenges and subsequent emissions from the energy sector. Importantly, challenges of developing countries to ensure entire population access to electricity without jeopardizing the global warming problem is wickedly complex. Since India is one of the largest emerging economies, learning such information in Indian context is of particular interest to me. Moreover, as a reference database for life cycle inventory, ecoinvent Centre has particular interest to obtain the same information. And, as a university for sustainable future, Chalmers University of Technology is also keen to research on acquiring such information. Hence, this research was carried out as a Master's Thesis within the *Industrial Ecology* Programme at the Department of Energy and Environment, Chalmers University of Technology, Sweden from February to October 2016 with a collaboration with ecoinvent Centre, Zurich, Switzerland. Supervision was offered both at Chalmers from Johan Tivander and Anne-Marie Tillman and at ecoinvent Centre from Karin Treyer and Tereza Lévová.

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This master thesis period features a part of my life when I had to go through enormous emotional turmoil, uncertainties, and self-transformation – from losing a dear friend, hope to realize SDGs, visa troubles to breaking up with dear partner. Luckily, I have been blessed with love, support, and good words from many people that made it possible to finish up. Hence, I owe my gratitude to them from the bottom of my heart.

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Finally, my love to Caio, Túlio, Bruna, Raquel, and Bruno for being with me during the most stressful, uncertain, and deepest sad time of my life. I deeply care about you, my loves.

List of Abbreviations

BR	Brazil
CA	Canada
CEA	Central Electricity Authority
CH_4	Methane
CN	China
CO	Carbon monoxide
CO_2	Carbon di Oxide
GHG	Greenhouse Gas
ID	Indonesia
IEA	International Energy Agency
IMF	International Monetary Fund
IN	India
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standards
JP	Japan
Kg	Kilogram
KP	Korea
kWh	Kilo Watt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MJ	Mega Joule
MW	Mega Watt
MX	Mexico
NOx	Nitrogen Oxides
PL	Poland
PM	Particulate Matter
PT	Portugal
RO	Romania
SG	Singapore
SOx	Sulfur Oxides
TH	Thailand
TWh	Terra Watt Hour
US	United State
VOC	Volatile Organic Compound

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1. Introduction

1.1. Background

India, the third largest economy, is featured as the fastest growing major economy in 2016 by International Monetary Fund (IMF, 2016). Such rapid growth engenders a prompt increase in resource consumption, especially energy. Besides, approximately 300 million people (out of 1.25 billion) in India are still deprived of access to the electricity (Martin, 2015). This country is, thus, going through a massive nation-wide electrification effort. As a result, the installed capacity of power production grew from 1.8 GW in December, 1950 to 303 GW in April, 2016 with a projection of further rapid increase in coming years (Planning Comission, 2014), (CEA, 2016). The major share of electricity demand is supplied by the domestic power production and the rest is imported from Bhutan. The domestic power production system is characterized by a big share of coal (61%) amidst 14% hydro, 8% natural gas, 2% nuclear, 0.30% diesel oil power plants, and 14% renewable energy sources with an increasing trend of solar power based on installed capacity as on 30.04.2016 (CEA, 2016). Most of the imported electricity from Bhutan is hydro electricity.

Moreover, India is considered as the growing link in the global supply chains with a projection that this country could become a global manufacturing hub by 2025 (Das, 2009; A.T. Kearney and CSCMP, India, 2014). This implies that India is playing a sizeable role at the emissions from global trade. Particularly, electricity plays a substantial role in the overall environmental footprint of a product and/or service since majority of the industrial activities are linked to the electricity system (Curran, Mann, & Norris, 2002). Hence, local and global interest on learning environmental performance of Indian electricity system is now higher than ever. To learn such information, Life Cycle Assessment (LCA) is a widely recognized tool which models the activity chain(s) and quantifies the environmental burdens using system-wide inventory information.

However, currently, we lack in the prerequisite of calculating the life cycle impacts i.e. Life Cycle Inventory (LCI) data on Indian power systems at a resolution that can represent a large country like India. At present, LCI datasets on the national average electricity mix of India are available at the ecoinvent database v3.2, however, with minimal India-specific information (i.e. mainly adapted from global datasets) (Treyer & Bauer, 2013); similar national level datasets from the Gabi database (Thinkstep, 2016); consequential datasets for 2020 based on the production volume of 2000 and 2008 from 2.-0 LCA Consultants (Merciai, Schmidt, &

Dalgaard, 2011). Such adapted national level datasets, however, potentially suffer from both high uncertainty and lack of representativeness for mainly two reasons. Firstly, the extrapolations from global datasets may contain high uncertainty since electricity generation and transmission technology and the grid management in other countries are not exactly the same as in India. Secondly, a national average may also obscure high variability since the Indian power production volume, technology mix, power plant technological level and local production condition vary considerably across the 29 Indian states and 7 union territories.

1.2. Aim and Purpose

This study aims to prepare regionalized life cycle inventory reference datasets of electricity power production, and transmission and distribution systems in India to address the geographical variability and lack of representativeness. The purpose is to provide decision makers with the system-wide information and to equip LCA practitioners with higher resolution inventory data in order to use for a multitude of product or service chains in both Indian and global contexts.

As a reference LCI database, ecoinvent Centre supports the idea of having higher resolution data on background processes in India. In particular, since the database already provides datasets on national average electricity in India, the ecoinvent Centre is interested to have a higher resolution regionalized datasets of the same system. Hence, this study is carried out in a close collaboration with ecoinvent Centre. We have considered to be consistent with the ecoinvent methodology of modelling national power systems so that the regionalized datasets can readily be incorporated into the database.

2. Methods

Life Cycle Assessment (LCA) consists of four re-iterative steps i.e. goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (Baumann & Tillman, 2004). This study, however, focuses particularly on the preparation of the Life Cycle Inventory (LCI) data based on sound goal and scope definition.

This study sets out to improve the relevance and accuracy of LCI data about the Indian electricity system primarily by increasing the geographical resolution from national level. Hence, it is both a hypothesis that this increase will indeed improve data quality and at the same time a specification of the resulting data sets to be provided. The literature review therefore included gathering of general information on the Indian electricity network as rationale for an educated meaningful choice of geographical resolution of LCI datasets. Moreover, since ecoinvent database v3.2 already provides national level electricity datasets for India, and this study intends to submit datasets to the database, we thoroughly studied the ecoinvent methodology for creating LCI datasets of energy systems mainly from Dones, et al., 2007 (the database uses the same methodology for electricity mix of 55 other countries) and the data quality guidelines from Weidema, et al., 2013. To assess the intended improvement in data quality, the resulting datasets were finally compared to see the variability between technologies and geographies as well as compared with existing current data on national level.

We have looked at the existing literature to learn the status-quo of country-level LCI of electricity/power system. We searched related literature in the bibliographic search engines (Google Scholar, and Web of Science) and University libraries (Chalmers Library, and ETH Library) using various combinations of keywords such as ‘energy system’, ‘electricity system’, ‘life cycle inventory’, 'life cycle assessment’, ‘impacts’, and ‘emissions’ etc. We also specifically looked at the Journal of Life Cycle Assessment and Journal of Industrial Ecology because of high relevance to this kind of research. The search results found several books, workshop reports and journal articles describing LCA of Energy Systems. However, we have considered only 13 peer reviewed journal articles published between 2000 and 2016 that particularly describe electricity LCI information of 13 different countries – Brazil (BR[1]); Canada (CA); China (CN); Indonesia (ID); Japan (JP); Korea (KP); Mexico (MX); Poland (PL); Portugal (PT); Romania (RO); Singapore (SG); and Thailand (TH); and United States (US) [(Coltro, Garcia, & Queiroz, 2003); (Dubreuil, 2001); (Di, Nie, Yuan, & Zuo, 2007); (Widiyanto & Kato, 2003); (Matsuno & Betz, 2000); (Lee, Lee, & Hur, 2003); (Santoyo-Castelazo, Gujba, & Azapagic, 2011); (Lelek, Kulczycka, Lewandowska, & Zarebska, 2016); (Garcia, Marques, & Freire, 2014); (Peiu, 2007); (Tan, Wijaya, & Khoo, 2010); (Varabuntoonvit, Sadamichi, Kato, & Mungcharoen, 2008); (Kim & Dale, 2005)]. In addition, Nordic electricity producer Vattenfall’s LCI information for five Nordic countries was also considered. (Vattenfall, 2012). We have specifically looked at the goal and scope definition of the studies specially the functional unit, emission flows, and resource use were taken into

[1] The short names of the country are used according to the International Organization for Standards alpha-2 country codes (ISO, 2016).

account. **Appendix A** lists the functional units, resource use, and emission flows considered in reviewed literature.

2.1. Goal and Scope Definition

Based on the methodological learnings from the existing literature, data availability on Indian electricity system, and consultation with the experts at ecoinvent Centre on their methodology, we have set up the goal and scope of this study and prepared inventory accordingly.

Functional unit

The inventory is prepared based on 1 kWh of net electricity supplied via the distribution grid for final consumption as most of the other studies (CA, CN, JP, ID, PT, MX, RO, KP, TH, Vattenfall, ecoinvent v3.2).

Technical boundary and included processes

The technical boundary starts at the constructed power plant ready to produce electricity (that means we excluded the fuel extraction, processing, and transportation to the power plant because of time constraints and lack of data available) and ends at the power distribution grid where electricity is available for the final consumption. The activities cover domestic power production at the power plant, import from Bhutan, and transmission and distribution to the final consumer in India in 2012-13. **Figure 1** outlines the technical scope of this study. The market activity[2] contains domestic production, import from neighbouring grids (including countries), transmission and transformation infrastructure, associated emissions, and losses during transmission according to ecoinvent methodology (Treyer & Bauer, 2014).

[2] A market activity is an activity that does not transform inputs, but simply transfers the intermediate exchange from one transforming activity to another transforming activity that consumes this intermediate exchange as an input, e.g. from glycerine at the supplier to glycerine at the consumer. A market dataset collects all activities with the same reference product in a certain geographical region. (see for details: http://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-is-a-market-and-how-is-it-created.html).

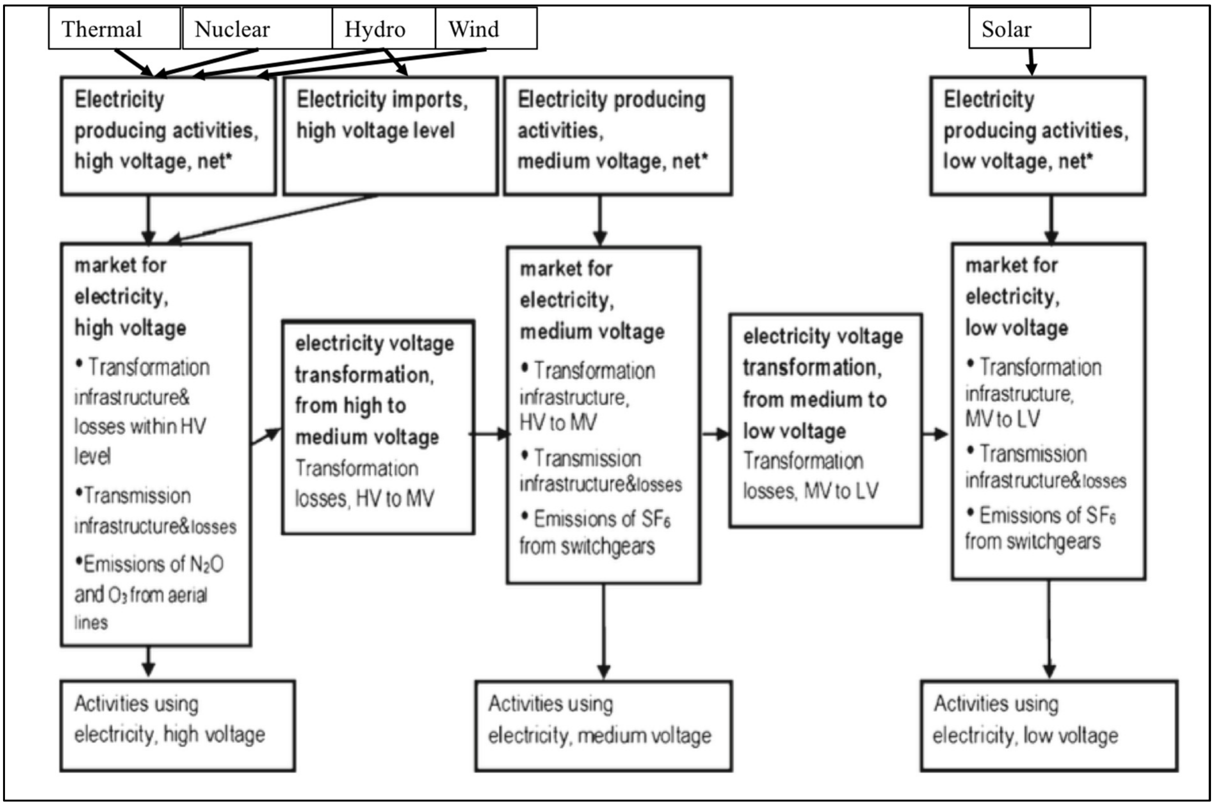

Figure 1 Structure of and links between electricity markets (high, medium, and low voltage level) in ecoinvent v3.2 (adapted from (Treyer & Bauer, 2014)).

Time boundary

The inventory is prepared as for 2012 because latest and most consistent data are available for the fiscal year 2012-13 (i.e. 01 April, 2012 to 31 March, 2013).

Geographical boundary

Due to the complexity of electricity grids production and distribution technologies and exchanges with other grids it is not a trivial choice what resolution best represents the upstream life cycle from what is actually delivered for consumption at a given location. The Indian power system comprises of three different sectors based on the ownership of the power plants i.e. central sector, owned by central government; state sector, owned by state government; and private sector, owned by private companies. Private utilities generate 31% electricity while state and central government owned utilities produce about 69% of total domestic generation (Planning Comission, 2014). Each state primarily meets the demand with own generation and additional allocation from the central sector since, constitutionally, central and state governments share responsibility for power production and distribution. Hence, the power production utilities exchange generated power among the distribution grids based on the demand. Depending on the demand and generation, regional grids also exchange among them. Moreover, India exchanges electricity with neighbouring countries.

India has a synchronized one single nationwide grid owned by POWERGRID Corporation of India Limited and managed by National Load Dispatch Centre which connects five regional grids namely Northern, Eastern, Western, North-eastern, and Southern grid from 31 December, 2013 (POWERGRID, 2016). Each grid covers several states and/or union territories as listed in **Table 1. Appendix B** lists all the geographic names with the geographic code at ecoinvent v3.2 created as part of this project.

Table 1: State/Union territory allocation among the Indian power grids (Source: (CEA, 2014))

Northern	*Eastern*	*Western*	*North-eastern*	*Southern*
Chandigarh*	Bihar	Chhattisgarh	Arunachal Pradesh	Andhra Pradesh
Delhi	Jharkhand	Dadar & Nagar Haveli*	Assam	Karnataka
Haryana	Orissa	Daman & Diu*	Manipur	Kerala
Himachal Pradesh	West Bengal	Goa	Meghalaya	Tamil Nadu
Jammu & Kashmir	Sikkim	Gujarat	Mizoram*	Puducherry
Punjab	Andaman & Nicobar*	Madhya Pradesh	Nagaland	Lakshadweep*
Rajasthan		Maharashtra	Tripura	
Uttar Pradesh				
Uttarakhand				

*excluded from inventory due to no or negligible production capacity. Listed only to show what grid they belong to when consuming electricity

Initially, we considered all 28 states (out of current 29 states[3]) and 7 Union territories in India. We have, however, taken 3 states (i.e. Chandigarh, Daman and Diu, and Dadar & Nagar Haveli) and 3 union territories (i.e. Lakshadweep, Andaman and Nicobar, and Mizoram) out of the considerations (as mentioned in **Table 1**) because those geographic units have either no production capacity at all (Daman and Diu, and Dadar & Nagar Haveli, Lakshadweep, and Andaman and Nicobar) or negligible production capacity (Chandigarh, and Mizoram) and also very small consumption. The technology specific (i.e. thermal, hydro, nuclear, wind, and solar) electricity production data are collected for state/union territory level. The produced electricity transforms into different voltage levels and feeds into the distribution grids. Several states and union territories contribute and exchange to one regional grid (as listed in **Table 1**). Hence, we aggregated the state/union territory level data into the regional grid level using weighted average of the relative production volume. Finally, for the market activities we calculated emissions per reference product (kWh of electricity at the different voltage levels (i.e. high, medium, and low) in the distribution grids available for consumption) in a regional grid level.

Selection of elementary flows

The selection of elementary flows inventoried in this study varies among the technologies and activities. See **Chapter 2.2** for a full description and motivation of choices.

Procedural and documentation requirements

The inventories are collected, documented, and reviewed according to the ecoinvent methodology using the ecoEditor[4] LCI data documentation tool. The datasets in ecoinvent database are structured as hierarchies based on geographical resolution. There is a top level global average for each ordinary transforming activity. Each step of increased resolution (regional, national, state, and so forth) inherits data from the parent level. Initially, when creating a new dataset with ecoEditor the parent geography is defined and all data is inherited, any specific knowledge about the more highly resolved level is then altered.

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[3]Indian government made a reformation of states to give birth the new state named “Telangana” after 2013 which is out of the temporal boundary (2012-13) of this study.

[4] The freeware "ecoEditor for ecoinvent version 3" is the tool to create, edit, review and upload datasets for the ecoinvent database. The primary use of the ecoEditor is to submit data to ecoinvent.

As in 2012-13, nation-wide Indian domestic power production came from thermal (hard coal, lignite, conventional natural gas, combined cycle natural gas, and diesel oil), hydro (reservoir type alpine region, run-of-river, and pumped storage), nuclear (boiling water reactor, and pressure water reactor), wind, and solar power plants. ecoinvent v3.2 already provides one national level dataset for each of the aforementioned technologies of Indian electricity mix. So we took the existing datasets in the ecoinvent database as a basis and regionalized with the Indian state/union territory specific data. New datasets were created for each technology based on the availability of that particular technology among the Indian geographies. For example, India produces electricity from hard coal in 16 states/union territories. Hence, we have created 16 datasets on "electricity production, hard coal" in India.

Appendix C lists the names of all datasets resulting from this study intended for publication (n.b. the learnings from this study contributed also to create similar datasets on Bangladesh electricity systems which are also awaiting to be published in the ecoinvent database. That work has been done as a bachelor project work at University of Chittagong, Bangladesh (Azad & Hossain, 2016).

2.2. Technology specific parameter data and emission collection

Generally, state/union territory-wise gross electricity production volume data from thermal, hydro, and nuclear power plants were extracted from the annual thermal electricity generation report of Central Electricity Authority, India (CEA, 2013). The net electricity production was then calculated by deducting auxiliary consumption from the gross production from CO_2 baseline database for the Indian Power Sector (CEA, 2014) (please see the **Table 2**) as it is done by Treyer & Bauer, 2014.

However, data on electricity generation from wind power in India is ambiguous since Statistical Yearbook, India (Statistical Yearbook, India, 2015) reports electricity generation from diesel and wind together as a single aggregated number. Instead, we used a different source. We took the total generation from wind according to the Indian energy statistics from International Energy Agency (IEA, 2016). Then, we distributed the total generation among the states according to the installed capacity data from Statistical Yearbook, India, 2015 (Statistical Yearbook, India, 2015). We have, then, distributed the total generation from wind among the three different technologies based on the turbine class i.e. 1-3 MW turbine (52.69%), <1 MW turbine (29.45%) , and >3 MW turbine (17.86%) according to the ecoinvent v3.2. However, for the technical reasons (i.e. too many datasets for a very minor share of production volume), we kept only 1-3 MW wind turbine to represent as wind power technology in India.

Table 2: Parameter data and emission factors for Indian electricity system

	hard coal	Lignite	natural gas, conventional	natural gas, combined cycle power plants	oil	hydro	nuclear	wind
Auxiliary Consumption (%)	8[a]	10[a]	1[a]	3[a]	3.5[a]	0.5[a]	10.5[a]	1[e]
Net calorific value (MJ/kg)	19.26[b]	9.55[b]	33[a*]	33[a*]	34.64[a]	-	-	-
CO_2 emission factor (kg/MJ)	0.0958[a]	0.1062[c]	0.0543[a]	0.0543[a]	0.0726[a]	-	-	-
SO_x emission factor (kg/MJ)	0.000192[c]	0.000192[c]	0.000000572[e]	0.000000572[e]	[e*]	-	-	-
NO_x emission factor (kg/MJ)	0.000189 [c]	0.000189 [c]	0.0000367[e]	0.0000367[e]	[e*]	-	-	-
CO emission factor (kg/MJ)	0.0001[c]	0.0001[c]	0.00002[e]	0.00002[e]	[e*]	-	-	-
CH_4 emission factor (kg/MJ)	0.0000008[c]	0.0000008[d]	0.000000971[e]	0.000000971[e]	[e*]	-	-	-
VOC emission factor (kg/MJ)	0.000009[c]	0.000009[c]	-	-	[e*]	-	-	-
$PM_{2.5}$ emission factor (kg/MJ)	0.000068[c]	0.000068[c]	0.000000491[e]	0.000000491[e]	[e*]	-	-	-
PM_{10} emission factor (kg/MJ)	0.000138[c]	0.000138[c]	-	-	[e*]	-	-	-

* MJ/m^3;
a = (CEA, 2014); b = (CSO, 2015); c = (Guttikunda & Jawahar, 2014); d = (Di, Nie, Yuan, & Zuo, 2007); e = ecoinvent v3.2 database; [e*] = relation_global_country (country value in relation to global dataset based on the ratio of efficiency value at ecoinvent v3.2 database)

Similar to wind power, we took the total generation from solar power according to the IEA Indian statistics (IEA, 2016) and then distributed the total generation among the states according to the installed capacity data from Statistical Yearbook, India, 2015 (Statistical Yearbook, India, 2015). We have, then, distributed the total generation from solar among two different technologies based on the panel class i.e. photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted and photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted according to the ecoinvent v3.2. However, for the same technical reason like wind power, we kept only multi-Si, panel, mounted to represent as grid-interactive solar power technology in India.

2.2.1. Thermal Power Plants

The data on fuel consumption (kg/kWh) and thermal efficiency (input of fuel required in MJ) for thermal power plants were not readily available for all the thermal technologies. However, data were available for either fuel consumption or thermal efficiency in state/union territory level. So, we have calculated efficiency and input of fuel interchangeably using net calorific value of the fuel using standard **Equations 1 and 2**. The key parameter data and corresponding source of data is documented in the **Table 2**. **Appendix D (a)** shows parameter lists for an example ecoEditor format dataset of "electricity production, hard coal. IN-KA 2015".

$$\text{input of fuel } \left(\frac{\text{MJ}}{\text{kWh}}\right) = \text{fuel consumption } \left(\frac{\text{kg}}{\text{kWh}}\right) * \text{net calorific value of fuel } \left(\frac{\text{MJ}}{\text{kg}}\right) \ldots \textbf{Equation 1}$$

efficiency = ((3.6 MJ/kWh) / (input of fuel (MJ/kWh)) ....**Equation 2**

We have selected CO_2, SOx, NOx, CO, CH_4, VOC and Particulate Matter (PM) as air pollutants to be inventoried for thermal power plants according to the 'minimum list of environmental flows for energy system' suggested by the (Curran, Mann, & Norris, 2002), and the published studies on electricity system LCA (CA, US, CN, JP, PL, ID, MX, RO, KP, SG, Vattenfall, ecoinvent v3.2) Moreover, these emission flows are amongst the main contributors to the frequently used impact categories (e.g. Global Warming Potential, Acidification, Eutrophication etc.). We have used **Equation 3** to calculate the emission of the gases.

$$\text{emission of the gas (kg)} = \text{fuel input } \left(\frac{\text{MJ}}{\text{kWh}}\right) * \text{emission factor of the gas } \ldots\ldots\ldots\ldots \textbf{Equation 3}$$

In addition, we have used the default mathematical relations in the ecoinvent v3.2 database to calculate the emission values of the other elementary flows than the aforementioned ones. By that we mean, ecoinvent v3.2 calculates emission values by multiplying input of fuel (MJ/kWh) by an emission factor which is actually a weighted average with electricity production data (Itten, Frischknecht, & Stucki, 2014) and emission values of 14 countries (AT, BE, ES, FR, IT, NL, PT, DE, CZ, HR, PL, SK, CN, US). **Appendix D (b)** shows emission flow list for an example ecoEditor format dataset of "electricity production, hard coal. IN-KA 2015". The red marked text boxes denote specifically the ones which were changed by the **Equation 3**. All other flows were calculated using the generic emission factor - the weighted average from the production data and emission values of the 14 countries.

The emission factor of the gas and corresponding reference is documented in the **Table 2**. We haven't taken desulfurization and denitrification technology into consideration in calculating the SOx and NOx emission since most of the Indian power plants do not use such technologies. Moreover, total PM emission is distributed into 3 classes such as PM<2.5, PM 2.5-10, and PM>10 in the proportion of 85%, 10%, and 5% respectively according to the ecoinvent report "Kohle" for v2.2 (Röder, Bauer, & Dones).

2.2.2. Hydro-electric power plant

Greenhouse gas (GHG) emissions and land use change are the key impacts to look at for hydro power plants. Unlike other technologies, we were able to collect India-specific data on land use for hydro-electricity. For other technologies, land use data were unavailable. So, we kept the default ecoinvent v3.2 values. We have calculated Transformation from, unspecified (m^2/kWh) and Occupation, lake, artificial (m^2*year/kWh) for the reservoir type hydro power plants using the **Equation 4** and **5**, respectively.

Transformation from $\left(\frac{\mathrm{m}^2}{\mathrm{kWh}}\right)$ = Surface area (m^2) / (production volume (kWh) * life time (year)) .... **Equation 4**

Occupation, lake, artificial $\left(\frac{m^2 * \mathrm{year}}{\mathrm{kWh}}\right)$ =Transformation from * lifetime .... **Equation 5**

The surface area data for the reservoir is collected from the power plants database called Global Energy Observatory (Global Energy Observatory, 2016) and the life time is assumed as 150 years according to the ecoinvent v3.2 (Treyer & Bauer, 2013). However, GHG emission and land use data are unavailable for pumped storage and run-of-river type hydro power plants. So, we have followed the existing emission parameters for this two technologies as-it-is at ecoinvent v3.2 (Treyer & Bauer, 2013).

2.2.3. Nuclear power plants

Radioactive wastes are the key impacts from the nuclear power plants. However, India-specific data on the nuclear wastes are unavailable. So, we have kept the emission parameters as-it-is in the ecoinvent v3.2 for nuclear power plants.

2.2.4. Wind power plants

The state-wise wind load hour data is calculated from the installed capacity and electricity generation using the **Equation 4**.

$$\text{wind load hour (hour)} = \frac{\text{gross electricity generation (kWh)}}{\text{installed capacity (kW)}} \quad \textbf{Equation 4}$$

2.2.5. Solar power

Apart from the production volume, solar yield is the key parameter to look at for solar power. However, the data were unavailable on that. So, we have kept the parameters as-it-is in the ecoinvent v3.2 for solar power.

3. Life Cycle Inventory

3.1. Electricity production volume of Indian geographic units

Production volume varies considerably across the Indian geographic units (i.e. states and union territories). **Figure 2** shows that Uttar Pradesh has the highest net production with 96 TWh which is about 11% of total production in 2012-13 followed by Gujarat and Maharashtra (90 TWh each) totalling to 31.6% altogether. Moreover, these three geographic units along with Andhra Pradesh, Chhattisgarh, and Tamil Nadu (i.e. 6 out of 28 geographic units) contribute almost 55% to total electricity production. On the other hand, 10 geographic units altogether (out of 28) such as Puducherry, Nagaland, Goa, Manipur, Meghalaya, Arunachal Pradesh, Tripura, Sikkim, Assam, and Kerala contribute only 2.1% to the total production.

In the regional grid level, Western grid contributes highest (33%) in terms of production volume followed by Northern (29%), Southern (22%) and Eastern grid (15%) (**Figure 3**). The rest comes from North-eastern grid which contributes only 1% to the national grid. Moreover, we see a large variation in the technology mixes among the regional grids despite a clear dominance of electricity from hard coal in most of the grids except North-eastern region. Eastern grid gets 94% of the electricity from hard coal and the rest is from hydro. Western, Northern, and Southern grid also get major share (76%, 60%, and 60%, respectively) of the electricity from hard coal and rest comes from a variety of technologies (lignite, hydro, natural gas, nuclear, and wind) with various shares. Unlike the other grids, North-eastern grid gets electricity from mainly natural gas (53%) and hydro (47%).

3.2. Electricity producing technological level of Indian geographic units

Key parameter values (e.g. fuel consumption, and thermal efficiency) for thermal power plants vary considerably across the geographic units. Electricity from hard coal is the major technology in Indian power system. Yet, the fuel consumption (kg hard coal/kWh) varies from 0.65 kg to 0.94 kg and thermal efficiency varies from 20% to 29%. The natural gas consumption (m^3/kWh) also varies from 0.23 kg to 0.45 kg and thermal efficiency varies from 24% to 46%. The oil consumption (kg/kWh) is pretty similar (0.22-0.23 kg) across the geographic units (only two grids) and thermal efficiency is 40%. However, state/union territory-specific data on lignite power plant are not available. Hence, we used the same value across the country assuming that technology level is similar since this technology contributes fairly a small share (<3%). We took 1.32 kg/kWh as fuel consumption and 29% as thermal efficiency for lignite power plant.

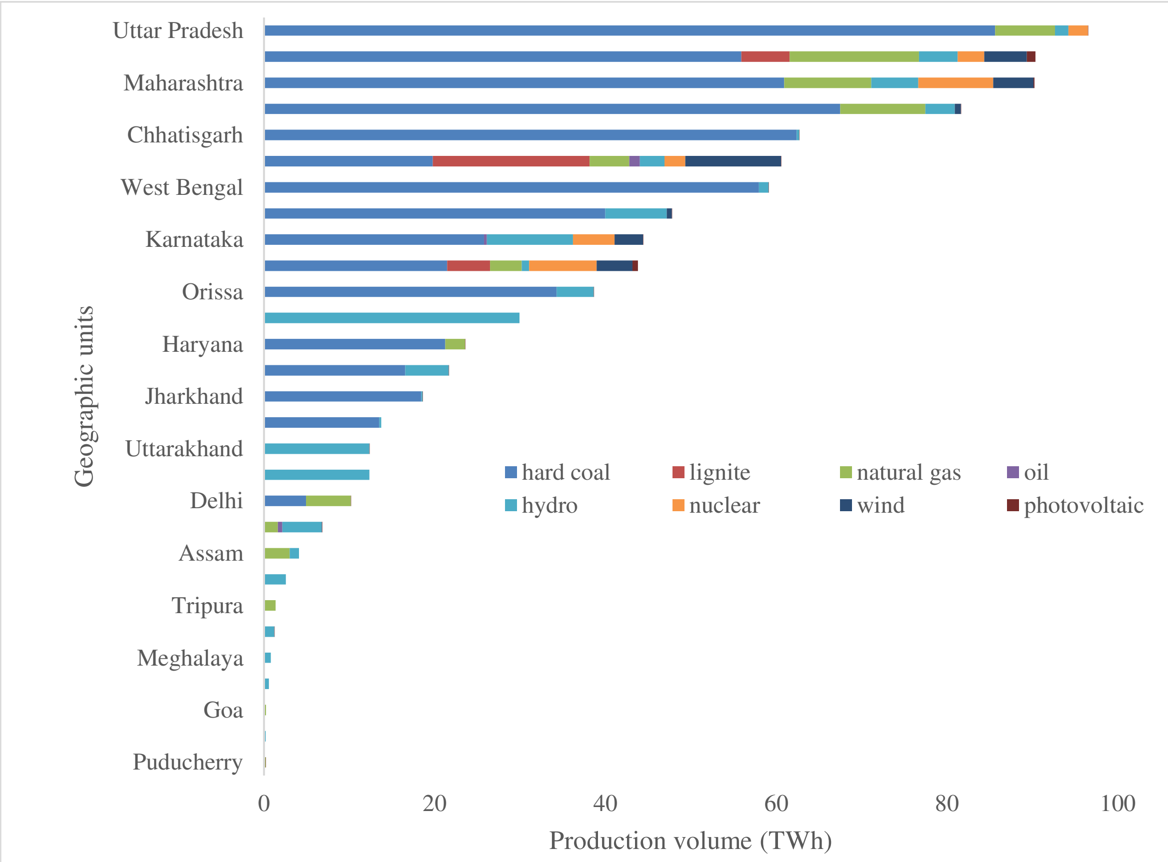

Figure 2: Production volume and technology mix of Indian Electricity among states and union territories in 2012-13

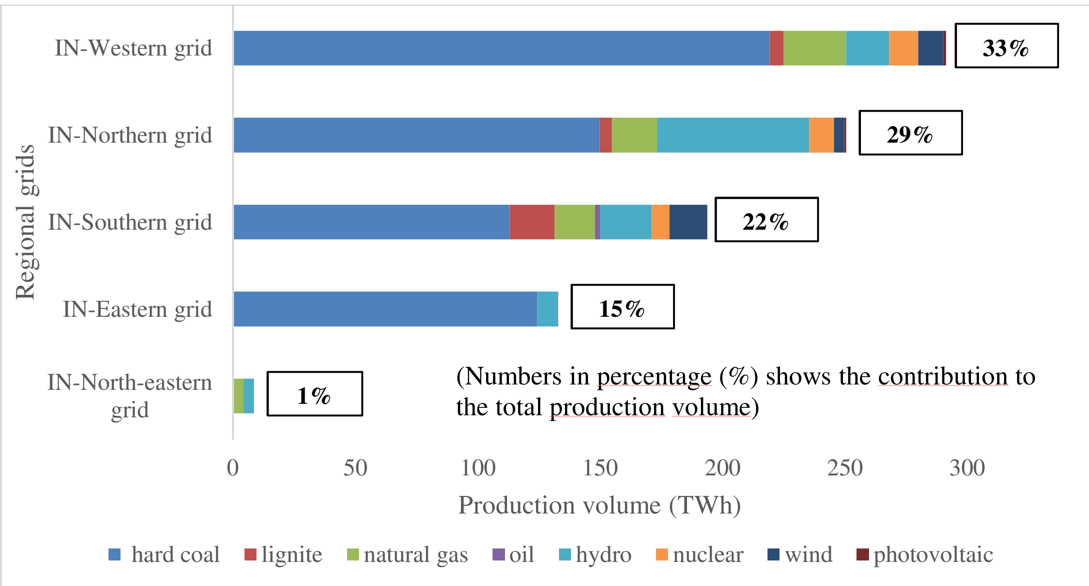

Figure 3 Production mix of the regional grids in absolute number in India in 2012-13

3.3. Resource use and air pollutants

Table 3 shows the resource consumption to produce and distribute 1 kWh of electricity at high voltage among the Indian grids in 2012-13. This also includes the exchanges among the grids and import from Bhutan. **Table 4** shows the emission of air pollutants from the electricity power plants in different grids.

Table 3: Resource use per kWh electricity produced and distributed at high voltage among the power grids in India in 2012-13

Resource use	Unit	IN-Southern grid	IN-Eastern grid	IN-Northern grid	IN-North-eastern grid	IN-Western grid
Hard coal	kg	4.94E-01	7.81E-01	5.45E-01	1.78E-01	6.45E-01
Lignite	kg	1.37E-01	4.80E-03	3.03E-02	2.30E-03	3.17E-02
Natural gas	m^3	2.29E-02	3.49E-03	1.89E-02	1.60E-01	2.29E-02
Oil	kg	1.00E-02	7.77E-03	5.64E-03	2.52E-03	6.58E-03
Water, cooling	m^3	5.35E-02	6.68E-02	5.13E-02	5.01E-02	6.11E-02
Water, turbine use	m^3	7.74E-01	1.49E+00	8.92E+00	1.03E+01	8.28E-01
Uranium	kg	7.54E-08	1.01E-07	7.52E-08	3.13E-08	2.19E-07

Table 4: Air emissions (kg) from the electricity system at high voltage in India in 2012-13

Emissions	IN-Southern grid	IN-Eastern grid	IN-Northern grid	IN-North-eastern grid	IN-Western grid
CO_2	1.13E+00	1.50E+00	1.11E+00	6.77E-01	1.31E+00
CO	1.18E-03	1.63E-03	1.17E-03	4.64E-04	1.38E-03
CH_4	4.10E-03	6.27E-03	4.45E-03	2.11E-03	5.27E-03
NOx	2.10E-03	3.15E-03	2.23E-03	9.29E-04	2.64E-03
SOx	2.82E-03	3.78E-03	2.77E-03	1.65E-03	3.27E-03
VOC	1.79E-07	1.39E-07	1.01E-07	4.65E-08	1.19E-07
PM < 2.5 um	1.82E-03	2.53E-03	1.81E-03	5.83E-04	2.13E-03
PM > 10 um	1.05E-03	1.54E-03	1.10E-03	3.66E-04	1.29E-03
PM > 2.5 um, and < 10 um	2.30E-04	3.17E-04	2.29E-04	7.96E-05	2.68E-04

4. Life Cycle Impact Assessment

We have compared the impact from regionalized inventory results with the existing national average at ecoinvent v3.2 based on the impact categories such as Climate Change (GWP100a) from IPCC 2013 (IPCC, 2007), and Human Health, Ecosystem Quality, and Resources from ReCiPe endpoint (Goedkoop, et al., 2009).

4.1. Climate Change (GWP Score)

Figure 4 shows the GWP scores (kg CO2-eq) per reference product (i.e. 1 kWh of electricity) of the production mix of the regional grids of Indian electricity system. We see a significant variation among the grids in terms of absolute score. Eastern grid scores highest (1.65) followed by Western grid (1.38) because of the higher share of fossil sources (mainly hard coal) in the technology mix. Southern, and Northern grids (1.20, and 1.12, respectively) are also among the high scores. However, North-eastern grid scores considerably low (0.43) which is 26% of the highest score among the grids. The GWP score for national weighted average is 1.30 kg CO_2-eq/kWh based on the production volume.

Figure 5 shows the GWP scores per reference product (i.e. 1 kWh of electricity) of the consumption mix of the regional grids in different voltage levels in Indian electricity system. We see that the scores get gradually higher in different voltage level because of the transformation and transmission losses. For example, in the Eastern grid, GWP score is 1.69 kg CO2-eq in high voltage level which is already slightly higher than the production mix (1.65). Similarly, the score in medium voltage is a little higher (1.74). Eventually, the score is highest at the low voltage (2.03). This describes the impact of the transformation and transmission losses along the voltage chain because the higher the losses, the higher the extra electricity required to consume 1 kWh of electricity at the end of the chain downstream. As a consequence, the emission from the total supply chain also increases.

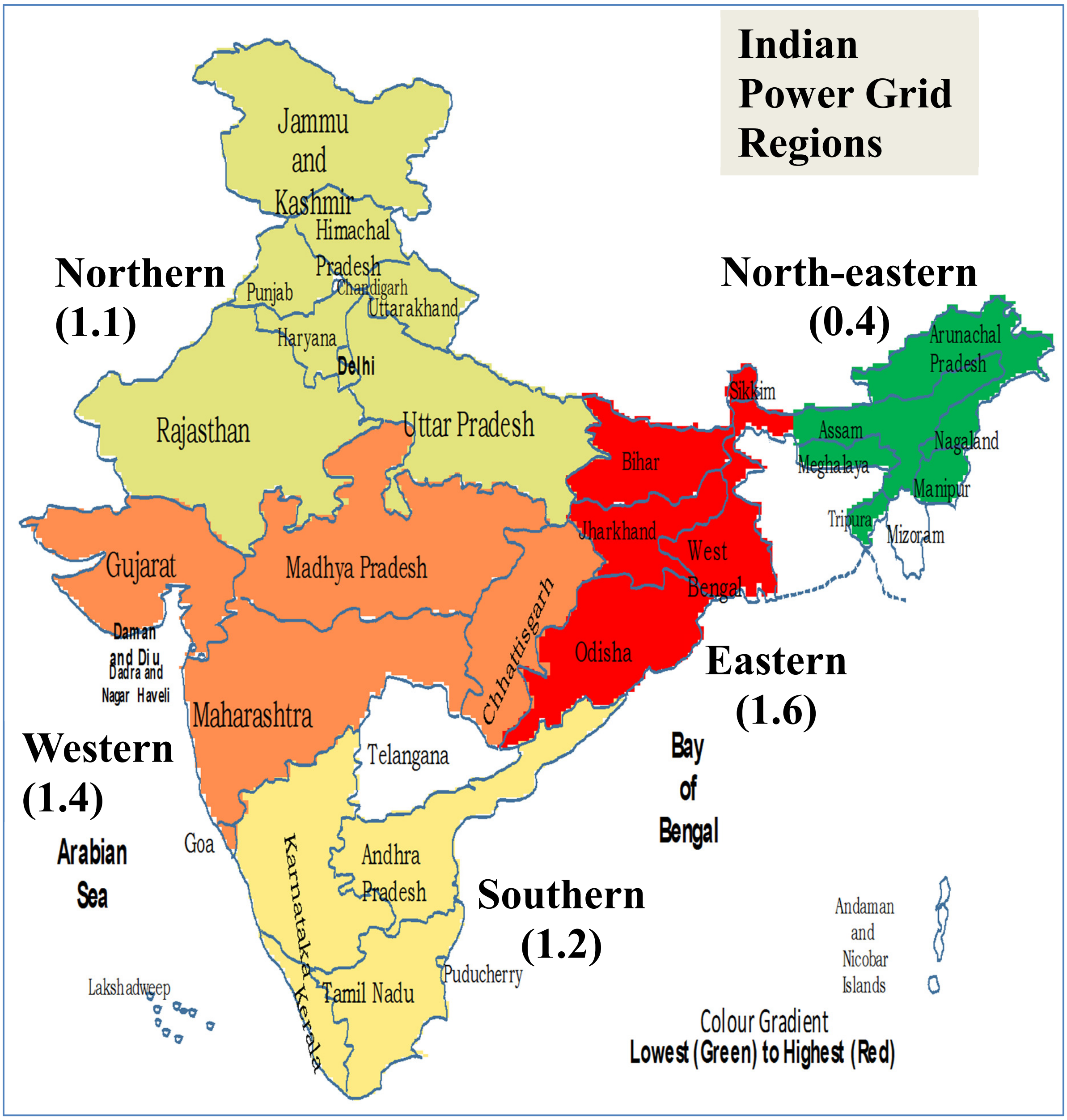

Figure 4: GWP scores (kg CO_2-eq/kWh) of different grids in Indian electricity system in 2012-13

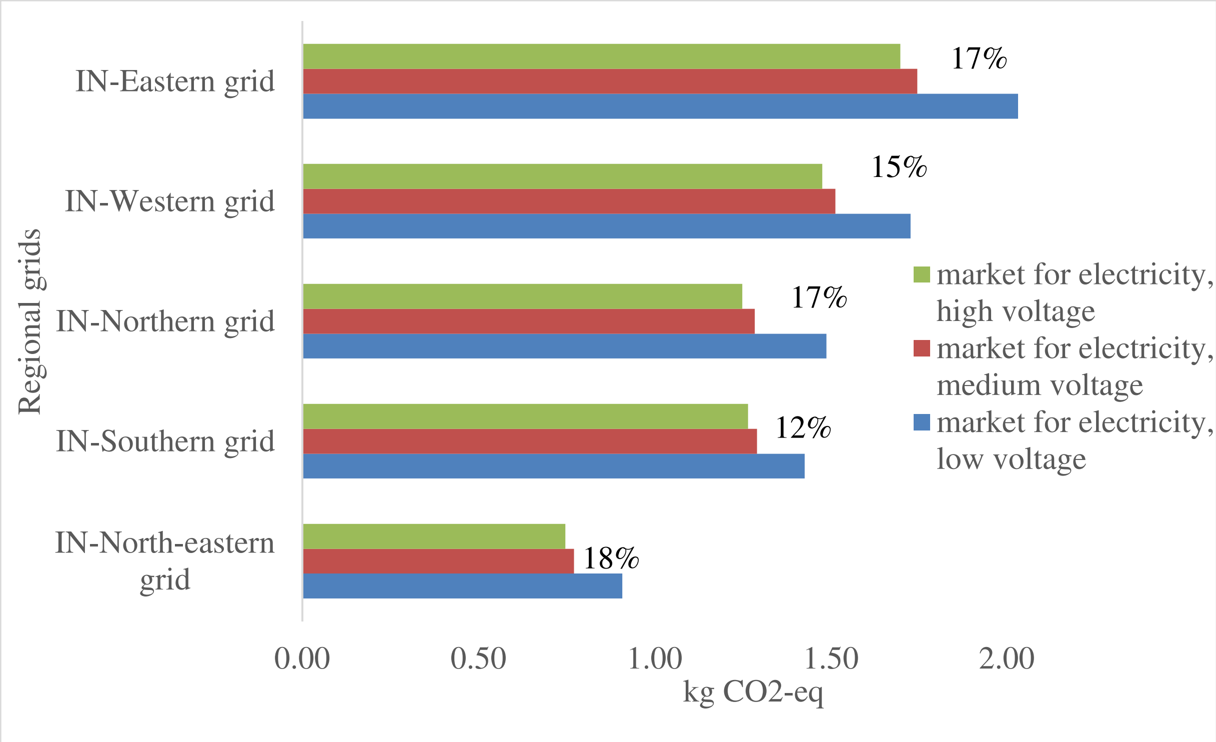

Figure 5: GWP scores (kg CO_2-eq/kWh) of the regional grids at different voltage level in Indian electricity system in 2012-13 (Number in percentage (%) shows the electricity loss along the chain)

4.2. ReCiPe Endpoint (H, A)

Figure 6 shows the performance of the Indian regional electricity grids in the order of ecosystem quality, human health and resources. This also follows the same logic of the increase on the absolute score in the voltage level in the order of high, medium and low voltage. Eastern grid scores highest followed by Western grid in ecosystem quality, human health, and resources like GWP score. However, unlike climate change, Southern grid scores higher than Northern grid in these categories. North-eastern is still the lowest scorer.

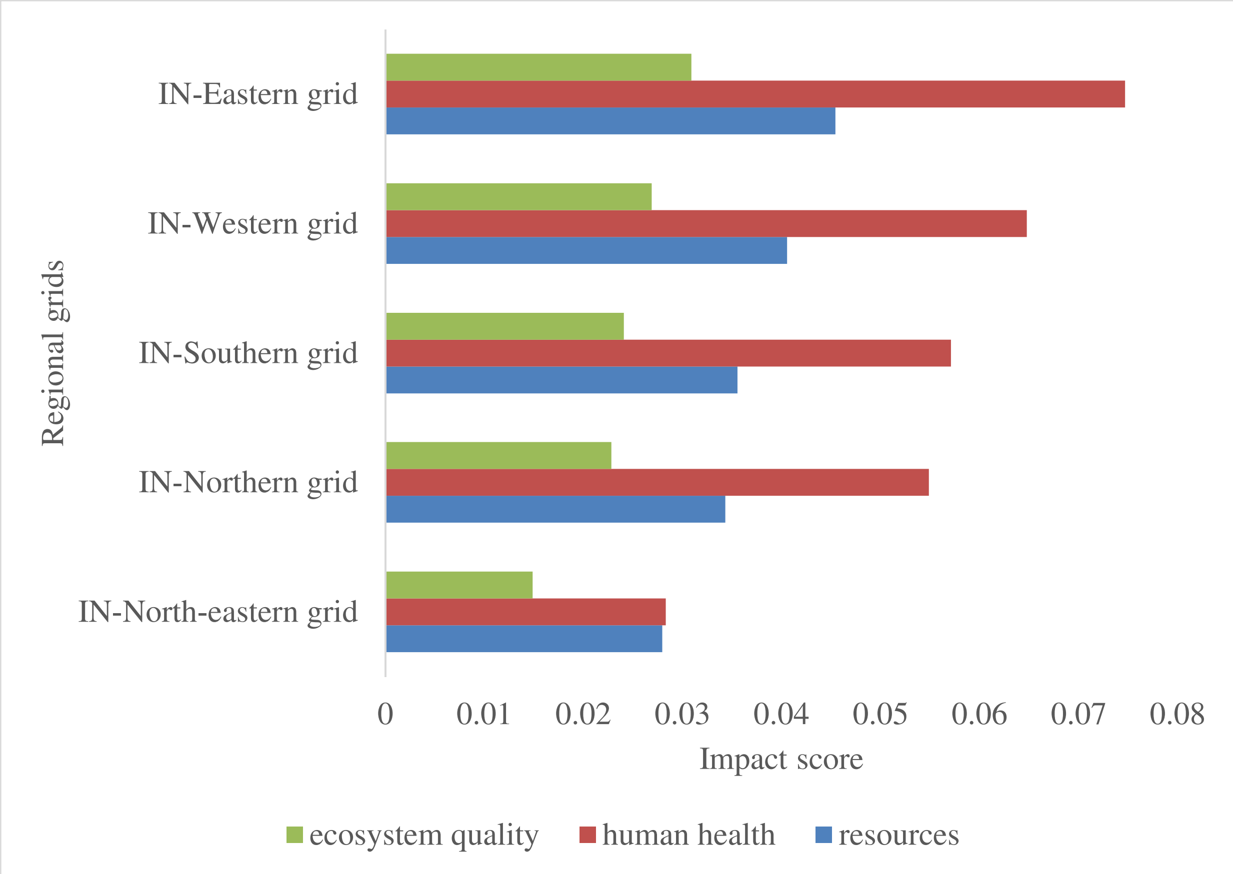

Figure 6: ReCiPe Endpoint scores among the grids of Indian Electricity System in 2012-13

5. Discussion and Conclusion

We have found a large variation in production volume, technology mix, and resulting emissions across the Indian geographic units. Now, if we take the GWP score for national weighted average (1.30 kg CO_2-eq/kWh) based on the production volume and compare with the existing national average in the ecoinvent v3.2 (1.25 kg CO_2-eq/kWh), and Gabi Database (1.38 kg CO_2-eq/kWh) we see that weighted average value is close to the existing ones. Moreover, we have also measured the GWP score by changing only production volume which results into very similar score (1.28 kg CO_2-eq/kWh). The similarity among the national average scores ascertains the validity of this study. Hence, we can also be confident about the regional values. And, the variation in regional grid values confirms that national average value contains high variability.

In the country level, electricity from hard coal is the major electricity producing technology in India. Yet, the technology level across the country varies considerably (1.5 to 2.2 kg CO_2-eq/kWh), so do the resulting emissions. This particular technology contributes highest to the per kWh emission in India because of mostly old technology and lack of de-sulphurization and de-nitrification facility. So, this technology demands immediate attention to reduce emission from Indian power system.

Moreover, Indian electricity transformation and transmission system is attributed to the one of the highest electricity losses (as high as 62% in Jammu and Kashmir; 24% as a national average) down the voltage level (Planning Comission, 2014). This is because of both technical reasons (e.g. old technology, inefficient billing management) and non-technical reasons. A major share of electricity is subjected to theft. (Itten, Frischknecht, & Stucki, 2014) estimated that technical reasons correspond to 62% of electricity losses. Non-technical reasons including theft corresponding to the remaining 38% of electricity loss. We have not considered the non-technical loss in the inventory.

This study mostly used data for state/union territory level because plant specific data were not available. Moreover, local emission data were also mostly unavailable except emissions of CO_2. Hence, we have calculated necessary parameters from other available data and eventually calculated the other emissions (e.g. NOx, SOx, CH_4, CO, PM, VOC etc.) based on the parameters. One would argue that specific power plant data would improve the resolution even further. However, it's unsure if that further resolution would really influence the decision making in LCA studies better. That would give us a mere average in state level which would not be that useful because electricity market is in grid level which consists of several states and union territories. Furthermore, data availability, time, and money constraints often act as decisive factors in regionalization.

Finally, this regionalized consistent model of Indian electricity system provides higher resolution inventory of Indian electricity system which, essentially, equips LCA practitioners with a better tool to use for LCA studies of a multitude of product and/or service chains in both Indian and global contexts. Hence, we would be able to achieve higher accuracy in life cycle studies. Moreover, this study also provides decision makers with the system-wide information on different electricity producing technologies and transmission and distribution systems which points out the emission from most important technologies (i.e. hard coal) and crucial technical and non-technical inefficiencies (e.g. theft) in grid management which eventually contributes to electricity loss and corresponding higher environmental burden.

The intention of this project has not been to analyse and provide arguments for an optimal resolution of data. The intention has primarily been to collect and derive data for concrete LCI reference datasets electricity delivered for consumption in India with improved accuracy and geographical representativeness. We conclude that this has been achieved and the relatively high assessed variability motivates using the data from this study in favour of existing national average reference data.

6. Next Steps

Within the given rather short time framework (February 2015 – September 2016) for a 30-ECTs thesis work, we have accomplished to come up with the numeric values needed to create the datasets. However, the documentation part of the LCI datasets creation is still work in progress. After the due documentation, the completed 150+ datasets will be submitted to the ecoinvent database to be published in next release.

Moreover, this work took the system boundary as starts from the constructed power plant ready to produce electricity. That means the upstream activities such as fuel extraction, transportation, and process were not included. The datasets on mentioned processes would need to be created in order to have a more complete picture of the power systems of India.

7. Publication of the Datasets

The resulting preliminary LCI data from this study are available in MS Excel spreadsheets that can be downloaded as a zip file from within the LCI dataset "Electricity production and distribution – India – Regionalized" published in the CPM LCA Database (Hossain, 2016), online: cpmdatabase.cpm.chalmers.se, Swedish Life Cycle Center. The datasets are now (as of 2016/10/24) undergoing remaining documentation and review steps according to ecoinvent data publication procedure. The data are expected to be available in the ecoinvent reference LCI database in 2017 in conjunction with a future ecoinvent database update.

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Appendices

Appendix A Functional units and emission flows considered in the literature.

	functional unit	resource use*	emission flows							
			CO_2	CH_4	SO_x	NO_x	PM	CO	VOC	Heavy Metals
BR	1000 MJ	X	X	X	X	X	X	X	X	X
CA	1 kWh		X	X	X	X	X	X	X	
US	1 MJ	X	X		X	X	X			X
CN	1 kWh	X	X	X	X	X	X	X	X	X
JP	1 kWh		X	X	X	X	X		X	X
PL	1 TJ	X	X		X	X	X	X		X
PT	1 kWh		Reults shown in midpoint impact categories (not in emission flows)							
ID	1 kWh		X	X	X	X	X	X	X	X
MX	1 kWh		X	X	X	X	X	X	X	
RO	1 kWh		X	X	X	X	X	X	X	X
KP	1 kWh	X	X	X	X	X	X	X	X	
SG	1 MWh		X	X	X	X	X	X	X	
TH	1 kWh		X	X	X	X				
Vattenfall	1 kWh	X	X	X	X	X		X		
ecoinvent v3	1 kWh	X	X	X	X	X	X	X	X	X

*We have documented only if the study had any resource use included in inventory. Inventoried resources differ a lot among studies.

Appendix B List of the newly created Indian geographies in ecoinvent database.

geography name	geography code
INDIA	**IN**
NORTHERN REGION	**IN-Northern grid**
Haryana	IN-HR
Himachal Pradesh	IN-HP
Jammu & Kashmir	IN-JK
Punjab	IN-PB
Rajasthan	IN-RJ
Uttarakhand	IN-UT
Uttar Pradesh	IN-UP
Chandigarh	IN-CH
Delhi	IN-DL
WESTERN REGION	**IN-Western grid**
Goa	IN-GA
Gujarat	IN-GJ
Daman & Diu	IN-DD

geography name	geography code
Madhya Pradesh	IN-MP
Maharashtra	IN-MH
Chhatisgarh	IN-CT
Dadar & Nagar Haveli	IN-DN
SOUTHERN REGION	**IN-Southern grid**
Andhra Pradesh	IN-AP
Karnataka	IN-KA
Kerala	IN-KL
Tamil Nadu	IN-TN
Puducherry	IN-PY
Lakshadweep	IN-LD
EASTERN REGION	**IN-Eastern grid**
West Bengal	IN-WB
Jharkhand	IN-JH
Bihar	IN-BR
Orissa	IN-OR
Sikkim	IN-SK
Andaman and Nicobar	IN-AN
NORTH-EASTERN REGION	**IN-North-eastern grid**
Arunachal Pradesh	IN-AR
Assam	IN-AS
Meghalaya	IN-ML
Tripura	IN-TR
Nagaland	IN-NL
Manipur	IN-MN
Mizoram	IN-MZ

Appendix C List of newly created regionalized datasets to be implemented in ecoinvent database.

activity name	geography
electricity production, hard coal	IN-KA
electricity production, hard coal	IN-BR
electricity production, hard coal	IN-GJ
electricity production, hard coal	IN-OR
electricity production, hard coal	IN-AP
electricity production, hard coal	IN-JH
electricity production, hard coal	IN-MH
electricity production, hard coal	IN-CT
electricity production, hard coal	IN-MP
electricity production, hard coal	IN-RJ
electricity production, hard coal	IN-HR
electricity production, hard coal	IN-PB
electricity production, hard coal	IN-DL
electricity production, hard coal	IN-TN
electricity production, hard coal	IN-UP
electricity production, hard coal	IN-WB
electricity production, hydro, pumped storage	IN-AP
electricity production, hydro, pumped storage	IN-BR
electricity production, hydro, pumped storage	IN-TN
electricity production, hydro, pumped storage	IN-MH
electricity production, hydro, pumped storage	IN-GJ
electricity production, hydro, pumped storage	IN-WB
electricity production, hydro, reservoir, alpine region	IN-KA
electricity production, hydro, reservoir, alpine region	IN-CT
electricity production, hydro, reservoir, alpine region	IN-BR
electricity production, hydro, reservoir, alpine region	IN-RJ
electricity production, hydro, reservoir, alpine region	IN-UP
electricity production, hydro, reservoir, alpine region	IN-AP
electricity production, hydro, reservoir, alpine region	IN-GJ
electricity production, hydro, reservoir, alpine region	IN-UT
electricity production, hydro, reservoir, alpine region	IN-KL
electricity production, hydro, reservoir, alpine region	IN-MP
electricity production, hydro, reservoir, alpine region	IN-HP
electricity production, hydro, reservoir, alpine region	IN-OR
electricity production, hydro, reservoir, alpine region	IN-PB
electricity production, hydro, reservoir, alpine region	IN-ML
electricity production, hydro, reservoir, alpine region	IN-TN
electricity production, hydro, reservoir, alpine region	IN-MN
electricity production, hydro, reservoir, alpine region	IN-MH
electricity production, hydro, reservoir, alpine region	IN-JH
electricity production, hydro, reservoir, alpine region	IN-NL
electricity production, hydro, reservoir, alpine region	IN-AS
electricity production, hydro, run-of-river	IN-TN

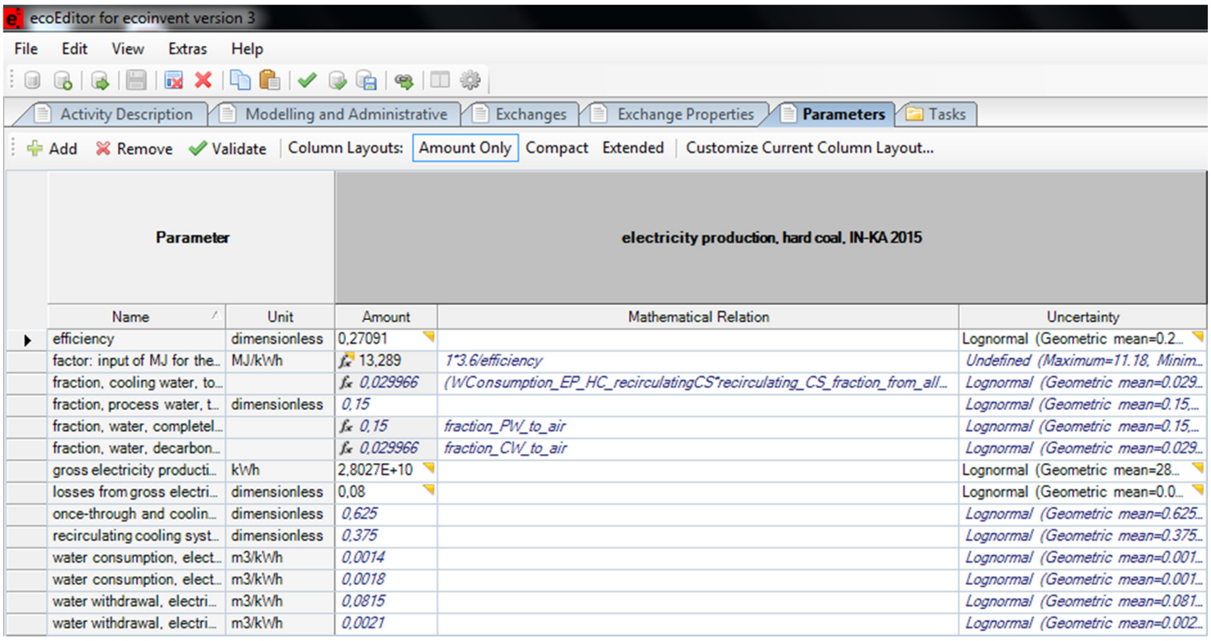
activity name	geography
electricity production, hydro, run-of-river	IN-AR
electricity production, hydro, run-of-river	IN-GJ
electricity production, hydro, run-of-river	IN-WB
electricity production, hydro, run-of-river	IN-ML
electricity production, hydro, run-of-river	IN-SK
electricity production, hydro, run-of-river	IN-AP
electricity production, hydro, run-of-river	IN-KA
electricity production, hydro, run-of-river	IN-KL
electricity production, hydro, run-of-river	IN-HP
electricity production, hydro, run-of-river	IN-RJ
electricity production, hydro, run-of-river	IN-UP
electricity production, hydro, run-of-river	IN-JK
electricity production, hydro, run-of-river	IN-MP
electricity production, hydro, run-of-river	IN-UT
electricity production, hydro, run-of-river	IN-AS
electricity production, hydro, run-of-river	IN-MH
electricity production, hydro, run-of-river	IN-PB
electricity production, lignite	IN-RJ
electricity production, lignite	IN-TN
electricity production, lignite	IN-GJ
electricity production, natural gas, combined cycle power plant	IN-KL
electricity production, natural gas, combined cycle power plant	IN-GA
electricity production, natural gas, combined cycle power plant	IN-PY
electricity production, natural gas, combined cycle power plant	IN-GJ
electricity production, natural gas, combined cycle power plant	IN-TN
electricity production, natural gas, combined cycle power plant	IN-TR
electricity production, natural gas, combined cycle power plant	IN-MH
electricity production, natural gas, combined cycle power plant	IN-AS
electricity production, natural gas, combined cycle power plant	IN-RJ
electricity production, natural gas, combined cycle power plant	IN-DL
electricity production, natural gas, combined cycle power plant	IN-HR
electricity production, natural gas, combined cycle power plant	IN-UP
electricity production, natural gas, combined cycle power plant	IN-AP
electricity production, natural gas, conventional power plant	IN-RJ
electricity production, natural gas, conventional power plant	IN-UP
electricity production, natural gas, conventional power plant	IN-DL
electricity production, natural gas, conventional power plant	IN-HR
electricity production, natural gas, conventional power plant	IN-KL
electricity production, natural gas, conventional power plant	IN-TN
electricity production, natural gas, conventional power plant	IN-GJ
electricity production, natural gas, conventional power plant	IN-PY
electricity production, natural gas, conventional power plant	IN-MH
electricity production, natural gas, conventional power plant	IN-TR
electricity production, natural gas, conventional power plant	IN-GA
electricity production, natural gas, conventional power plant	IN-AS

activity name	geography
electricity production, natural gas, conventional power plant	IN-AP
electricity production, nuclear, boiling water reactor	IN-MH
electricity production, nuclear, pressure water reactor, heavy water moderated	IN-TN
electricity production, nuclear, pressure water reactor, heavy water moderated	IN-GJ
electricity production, nuclear, pressure water reactor, heavy water moderated	IN-MH
electricity production, nuclear, pressure water reactor, heavy water moderated	IN-UP
electricity production, nuclear, pressure water reactor, heavy water moderated	IN-RJ
electricity production, nuclear, pressure water reactor, heavy water moderated	IN-KA
electricity production, oil	IN-TN
electricity production, oil	IN-AN
electricity production, oil	IN-KL
electricity production, oil	IN-KA
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-AP
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-UP
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-TN
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-WB
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-AR
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-CT
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-PY
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-HR
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-OR
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-KL
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-DL
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-MP
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-RJ
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-AN
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-LD

activity name	geography
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-PB
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-GJ
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-MH
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-KA
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-JH
electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	IN-UT
electricity production, wind, 1-3MW turbine, onshore	IN-AP
electricity production, wind, 1-3MW turbine, onshore	IN-MP
electricity production, wind, 1-3MW turbine, onshore	IN-KL
electricity production, wind, 1-3MW turbine, onshore	IN-TN
electricity production, wind, 1-3MW turbine, onshore	IN-MH
electricity production, wind, 1-3MW turbine, onshore	IN-GJ
electricity production, wind, 1-3MW turbine, onshore	IN-RJ
electricity production, wind, 1-3MW turbine, onshore	IN-KA
electricity voltage transformation from high to medium voltage	IN-Southern grid
electricity voltage transformation from high to medium voltage	IN-Western grid
electricity voltage transformation from high to medium voltage	IN-Northern grid
electricity voltage transformation from high to medium voltage	IN-North-eastern grid
electricity voltage transformation from high to medium voltage	IN-Eastern grid
electricity voltage transformation from medium to low voltage	IN-Northern grid
electricity voltage transformation from medium to low voltage	IN-Southern grid
electricity voltage transformation from medium to low voltage	IN-Eastern grid
electricity voltage transformation from medium to low voltage	IN-Western grid
electricity voltage transformation from medium to low voltage	IN-North-eastern grid
market for electricity, high voltage	IN-Western grid
market for electricity, high voltage	IN-Eastern grid
market for electricity, high voltage	IN-Northern grid
market for electricity, high voltage	IN-North-eastern grid
market for electricity, high voltage	IN-Southern grid
market for electricity, low voltage	IN-Eastern grid
market for electricity, low voltage	IN-Northern grid
market for electricity, low voltage	IN-North-eastern grid
market for electricity, low voltage	IN-Western grid
market for electricity, low voltage	IN-Southern grid
market for electricity, medium voltage	IN-North-eastern grid
market for electricity, medium voltage	IN-Northern grid
market for electricity, medium voltage	IN-Eastern grid
market for electricity, medium voltage	IN-Southern grid
market for electricity, medium voltage	IN-Western grid

Appendix D Example ecoEditor format dataset of "electricity production, hard coal. IN-KA 2015". The purpose of showing this ecoEditor template is to give reader an idea of the ecoEditor tool but not to provide accurate values and text.

a. Parameter data of the example dataset



Parameter		electricity production, hard coal, IN-KA 2015		
Name	Unit	Amount	Mathematical Relation	Uncertainty
efficiency	dimensionless	0,27091		Lognormal (Geometric mean=0.2...
factor: input of MJ for the...	MJ/kWh	13,289	1*3.6/efficiency	Undefined (Maximum=11.18, Minim...
fraction, cooling water, to...		0,029966	(WConsumption_EP_HC_recirculatingCS*recirculating_CS_fraction_from_all...	Lognormal (Geometric mean=0.029...
fraction, process water, t...	dimensionless	0,15		Lognormal (Geometric mean=0.15,...
fraction, water, completel...		0,15	fraction_PW_to_air	Lognormal (Geometric mean=0.15,...
fraction, water, decarbon...		0,029966	fraction_CW_to_air	Lognormal (Geometric mean=0.029...
gross electricity producti...	kWh	2,8027E+10		Lognormal (Geometric mean=28...
losses from gross electri...	dimensionless	0,08		Lognormal (Geometric mean=0.0...
once-through and coolin...	dimensionless	0,625		Lognormal (Geometric mean=0.625...
recirculating cooling syst...	dimensionless	0,375		Lognormal (Geometric mean=0.375...
water consumption, elect...	m3/kWh	0,0014		Lognormal (Geometric mean=0.001...
water consumption, elect...	m3/kWh	0,0018		Lognormal (Geometric mean=0.001...
water withdrawal, electri...	m3/kWh	0,0815		Lognormal (Geometric mean=0.081...
water withdrawal, electri...	m3/kWh	0,0021		Lognormal (Geometric mean=0.002...

b. Exchanges of the example dataset

Exchange					electricity production, hard coal, IN-KA 2015		
Type	Name	Unit	Compartment	Subcompartment	Amount	Mathematical Relation	Uncertainty
0 - ReferenceProduct	electricity, high voltage	kWh			1		
2 - ByProduct/Waste	residue from cooling tower	kg			7,3088E-05	factor_MJ_kWh*0.000005*1.1	Lognormal (Geometric mean...
2 - ByProduct/Waste	hard coal ash	kg			0,0994	factor_MJ_kWh*0.00748	Lognormal (Geometric mean...
4 - ToEnvironment	Radium-228	kBq	air	non-urban air or from high stacks	7,8536E-05	factor_MJ_kWh*0.00000591	Lognormal (Geometric mean...
4 - ToEnvironment	Radium-226	kBq	air	non-urban air or from high stacks	0,00024318	factor_MJ_kWh*0.0000183	Lognormal (Geometric mean...
4 - ToEnvironment	Lead	kg	air	non-urban air or from high stacks	4,9301E-07	factor_MJ_kWh*0.0000000371	Lognormal (Geometric mean...
4 - ToEnvironment	Antimony	kg	air	non-urban air or from high stacks	1,5946E-08	factor_MJ_kWh*0.0000000012	Lognormal (Geometric mean...
4 - ToEnvironment	PAH, polycyclic aromatic hydrocarbons	kg	air	non-urban air or from high stacks	9,9532E-08	factor_MJ_kWh*0.00000000749	Lognormal (Geometric mean...
4 - ToEnvironment	Hydrogen chloride	kg	air	non-urban air or from high stacks	0,00035215	factor_MJ_kWh*0.0000265	Lognormal (Geometric mean...
4 - ToEnvironment	Mercury	kg	air	non-urban air or from high stacks	3,588E-08	factor_MJ_kWh*0.0000000027	Lognormal (Geometric mean...
4 - ToEnvironment	Nitrogen oxides	kg	air	non-urban air or from high stacks	0,0025116		Lognormal (Geometric mean...
4 - ToEnvironment	Chromium	kg	air	non-urban air or from high stacks	1,0897E-07	factor_MJ_kWh*0.0000000082	Lognormal (Geometric mean...
4 - ToEnvironment	Arsenic	kg	air	non-urban air or from high stacks	1,3249E-07	factor_MJ_kWh*0.00000000997	Lognormal (Geometric mean...
4 - ToEnvironment	Acenaphthene	kg	air	non-urban air or from high stacks	5,5813E-11	factor_MJ_kWh*0.0000000000042	Lognormal (Geometric mean...
4 - ToEnvironment	Zinc	kg	air	non-urban air or from high stacks	5,5281E-07	factor_MJ_kWh*0.0000000416	Lognormal (Geometric mean...
4 - ToEnvironment	Particulates, > 10 um	kg	air	non-urban air or from high stacks	0,00013687		Lognormal (Geometric mean...
4 - ToEnvironment	Propane	kg	air	non-urban air or from high stacks	2,7508E-07	factor_MJ_kWh*0.0000000207	Lognormal (Geometric mean...
4 - ToEnvironment	Dioxins, measured as 2,3,7,8-tetrachlorodiben...	kg	air	non-urban air or from high stacks	1,4086E-13	factor_MJ_kWh*1.06E-14	Lognormal (Geometric mean...
4 - ToEnvironment	Cobalt	kg	air	non-urban air or from high stacks	4,4384E-08	factor_MJ_kWh*0.00000000334	Lognormal (Geometric mean...
4 - ToEnvironment	Hydrocarbons, aliphatic, alkanes, unspecified	kg	air	non-urban air or from high stacks	1,794E-06	factor_MJ_kWh*0.000000135	Lognormal (Geometric mean...
4 - ToEnvironment	Ethene, tetrachloro-	kg	air	non-urban air or from high stacks	4,7042E-09	factor_MJ_kWh*0.000000000354	Lognormal (Geometric mean...
4 - ToEnvironment	Uranium-234	kBq	air	non-urban air or from high stacks	2,6843E-05	factor_MJ_kWh*0.00000202	Lognormal (Geometric mean...
4 - ToEnvironment	Methane, fossil	kg	air	non-urban air or from high stacks	1,0631E-05		Lognormal (Geometric mean...
4 - ToEnvironment	Aldehydes, unspecified	kg	air	non-urban air or from high stacks	1,0405E-07	factor_MJ_kWh*0.00000000783	Lognormal (Geometric mean...
4 - ToEnvironment	Ethane, 1,1,1-trichloro-, HCFC-140	kg	air	non-urban air or from high stacks	2,1926E-09	factor_MJ_kWh*0.000000000165	Lognormal (Geometric mean...
4 - ToEnvironment	Copper	kg	air	non-urban air or from high stacks	1,091E-07	factor_MJ_kWh*0.00000000821	Lognormal (Geometric mean...
4 - ToEnvironment	Benzene	kg	air	non-urban air or from high stacks	1,8471E-06	factor_MJ_kWh*0.000000139	Lognormal (Geometric mean...
4 - ToEnvironment	Sulfate	kg	air	non-urban air or from high stacks	5,2358E-09	factor_MJ_kWh*0.000000000394	Lognormal (Geometric mean...
4 - ToEnvironment	Actinides, radioactive, unspecified	kBq	air	non-urban air or from high stacks	0,00022724	factor_MJ_kWh*0.0000171	Lognormal (Geometric mean...
4 - ToEnvironment	Dinitrogen monoxide	kg	air	non-urban air or from high stacks	1,7541E-05	factor_MJ_kWh*0.00000132	Lognormal (Geometric mean...
4 - ToEnvironment	NMVOC, non-methane volatile organic compou...	kg	air	non-urban air or from high stacks	0,0001196		Lognormal (Geometric mean...
4 - ToEnvironment	Iodine	kg	air	non-urban air or from high stacks	2,1129E-06	factor_MJ_kWh*0.000000159	Lognormal (Geometric mean...
4 - ToEnvironment	Cyanide	kg	air	non-urban air or from high stacks	2,7375E-07	factor_MJ_kWh*0.0000000206	Lognormal (Geometric mean...
4 - ToEnvironment	Particulates, > 2.5 um, and < 10um	kg	air	non-urban air or from high stacks	0,00027375		Lognormal (Geometric mean...
4 - ToEnvironment	Magnesium	kg	air	non-urban air or from high stacks	1,204E-06	factor_MJ_kWh*0.0000000906	Lognormal (Geometric mean...
4 - ToEnvironment	Ethane	kg	air	non-urban air or from high stacks	3,2292E-07	factor_MJ_kWh*0.0000000243	Lognormal (Geometric mean...
4 - ToEnvironment	Thorium-234	kBq	air	non-urban air or from high stacks	1,3687E-05	factor_MJ_kWh*0.00000103	Lognormal (Geometric mean...
4 - ToEnvironment	Xylene	kg	air	non-urban air or from high stacks	7,2556E-06	factor_MJ_kWh*0.000000546	Lognormal (Geometric mean...
4 - ToEnvironment	Benzo(a)pyrene	kg	air	non-urban air or from high stacks	5,7274E-12	factor_MJ_kWh*0.000000000000431	Lognormal (Geometric mean...
4 - ToEnvironment	Manganese	kg	air	non-urban air or from high stacks	4,7574E-07	factor_MJ_kWh*0.0000000358	Lognormal (Geometric mean...
4 - ToEnvironment	Thorium-230	kBq	air	non-urban air or from high stacks	1,3687E-05	factor_MJ_kWh*0.00000103	Lognormal (Geometric mean...
4 - ToEnvironment	Hydrocarbons, aliphatic, alkanes, cyclic	kg	air	non-urban air or from high stacks	6,3387E-08	factor_MJ_kWh*0.00000000477	Lognormal (Geometric mean...
4 - ToEnvironment	Butane	kg	air	non-urban air or from high stacks	1,4883E-07	factor_MJ_kWh*0.0000000112	Lognormal (Geometric mean...
4 - ToEnvironment	Sulfur dioxide	kg	air	non-urban air or from high stacks	0,0025514		Lognormal (Geometric mean...
4 - ToEnvironment	Thorium-232	kBq	air	non-urban air or from high stacks	6,4184E-05	factor_MJ_kWh*0.00000483	Lognormal (Geometric mean...
4 - ToEnvironment	Vanadium	kg	air	non-urban air or from high stacks	1,9667E-07	factor_MJ_kWh*0.0000000148	Lognormal (Geometric mean...
4 - ToEnvironment	Molybdenum	kg	air	non-urban air or from high stacks	1,5282E-08	factor_MJ_kWh*0.00000000115	Lognormal (Geometric mean...
4 - ToEnvironment	Propene	kg	air	non-urban air or from high stacks	1,2584E-07	factor_MJ_kWh*0.00000000947	Lognormal (Geometric mean...
4 - ToEnvironment	Polonium-210	kBq	air	non-urban air or from high stacks	0,0016345	factor_MJ_kWh*0.000123	Lognormal (Geometric mean...
4 - ToEnvironment	Uranium-238	kBq	air	non-urban air or from high stacks	0,00021129	factor_MJ_kWh*0.0000159	Lognormal (Geometric mean...
4 - ToEnvironment	Lead-210	kBq	air	non-urban air or from high stacks	0,00092091	factor_MJ_kWh*0.0000693	Lognormal (Geometric mean...
4 - ToEnvironment	Toluene	kg	air	non-urban air or from high stacks	8,837E-07	factor_MJ_kWh*0.0000000665	Lognormal (Geometric mean...
4 - ToEnvironment	Hexane	kg	air	non-urban air or from high stacks	7,3752E-09	factor_MJ_kWh*0.000000000555	Lognormal (Geometric mean...
4 - ToEnvironment	Hydrocarbons, chlorinated	kg	air	non-urban air or from high stacks	2,2192E-08	factor_MJ_kWh*0.00000000167	Lognormal (Geometric mean...
4 - ToEnvironment	Hydrocarbons, aliphatic, unsaturated	kg	air	non-urban air or from high stacks	1,701E-06	factor_MJ_kWh*0.000000128	Lognormal (Geometric mean...
4 - ToEnvironment	Methane, monochloro-, R-40	kg	air	non-urban air or from high stacks	5,8072E-08	factor_MJ_kWh*0.00000000437	Lognormal (Geometric mean...
4 - ToEnvironment	Pentane	kg	air	non-urban air or from high stacks	1,1561E-06	factor_MJ_kWh*0.000000087	Lognormal (Geometric mean...
4 - ToEnvironment	Boron	kg	air	non-urban air or from high stacks	5,0896E-06	factor_MJ_kWh*0.000000383	Lognormal (Geometric mean...
4 - ToEnvironment	Thorium-228	kBq	air	non-urban air or from high stacks	4,3853E-05	factor_MJ_kWh*0.0000033	Lognormal (Geometric mean...
4 - ToEnvironment	Methane, dichloro-, HCC-30	kg	air	non-urban air or from high stacks	3,176E-08	factor_MJ_kWh*0.00000000239	Lognormal (Geometric mean...
4 - ToEnvironment	Formaldehyde	kg	air	non-urban air or from high stacks	4,8238E-07	factor_MJ_kWh*0.0000000363	Lognormal (Geometric mean...
4 - ToEnvironment	Cadmium	kg	air	non-urban air or from high stacks	1,382E-08	factor_MJ_kWh*0.00000000104	Lognormal (Geometric mean...
4 - ToEnvironment	Carbon disulfide	kg	air	non-urban air or from high stacks	1,4219E-08	factor_MJ_kWh*0.00000000107	Lognormal (Geometric mean...
4 - ToEnvironment	Bromine	kg	air	non-urban air or from high stacks	4,1594E-06	factor_MJ_kWh*0.000000313	Lognormal (Geometric mean...
4 - ToEnvironment	Strontium	kg	air	non-urban air or from high stacks	7,8669E-07	factor_MJ_kWh*0.0000000592	Lognormal (Geometric mean...
4 - ToEnvironment	Particulates, < 2.5 um	kg	air	non-urban air or from high stacks	0,0023269		Lognormal (Geometric mean...
4 - ToEnvironment	Acrolein	kg	air	non-urban air or from high stacks	3,176E-08	factor_MJ_kWh*0.00000000239	Lognormal (Geometric mean...
4 - ToEnvironment	Chloroform	kg	air	non-urban air or from high stacks	1,0737E-08	factor_MJ_kWh*0.000000000808	Lognormal (Geometric mean...
4 - ToEnvironment	Barium	kg	air	non-urban air or from high stacks	8,6244E-07	factor_MJ_kWh*0.0000000649	Lognormal (Geometric mean...
4 - ToEnvironment	Hydrogen fluoride	kg	air	non-urban air or from high stacks	3,7607E-05	factor_MJ_kWh*0.00000283	Lognormal (Geometric mean...
4 - ToEnvironment	Chromium VI	kg	air	non-urban air or from high stacks	1,8604E-08	factor_MJ_kWh*0.0000000014	Lognormal (Geometric mean...
4 - ToEnvironment	Carbon monoxide, fossil	kg	air	non-urban air or from high stacks	0,0013289		Lognormal (Geometric mean...

4 - ToEnvironment	Radon-222	kBq	air	non-urban air or from high stacks	0,0066178	factor_MJ_kWh*0.000498	Lognormal (Geometric mean...
4 - ToEnvironment	Styrene	kg	air	non-urban air or from high stacks	2,7109E-09	factor_MJ_kWh*0.00000000204	Lognormal (Geometric mean...
4 - ToEnvironment	Radon-220	kBq	air	non-urban air or from high stacks	0,0067374	factor_MJ_kWh*0.000507	Lognormal (Geometric mean...
4 - ToEnvironment	Beryllium	kg	air	non-urban air or from high stacks	2,2989E-09	factor_MJ_kWh*0.00000000173	Lognormal (Geometric mean...
4 - ToEnvironment	Ethane, 1,2-dichloro-	kg	air	non-urban air or from high stacks	4,372E-09	factor_MJ_kWh*0.00000000329	Lognormal (Geometric mean...
4 - ToEnvironment	Benzene, ethyl-	kg	air	non-urban air or from high stacks	1,0299E-08	factor_MJ_kWh*0.00000000775	Lognormal (Geometric mean...
4 - ToEnvironment	Phenol	kg	air	non-urban air or from high stacks	1,7541E-09	factor_MJ_kWh*0.00000000132	Lognormal (Geometric mean...
4 - ToEnvironment	Carbon dioxide, fossil	kg	air	non-urban air or from high stacks	1,2731		Lognormal (Geometric mean...
4 - ToEnvironment	Potassium-40	kBq	air	non-urban air or from high stacks	0,00030564	factor_MJ_kWh*0.000023	Lognormal (Geometric mean...
4 - ToEnvironment	Protactinium-234	kBq	air	non-urban air or from high stacks	1,3687E-05	factor_MJ_kWh*0.00000103	Lognormal (Geometric mean...
4 - ToEnvironment	Water	m3	air	unspecified	0,0019128	(water_completely_softened/1000)*f...	Lognormal (Geometric mean...
4 - ToEnvironment	Water	m3	water	unspecified	0,061599	(water_completely_softened/1000)*(...	Lognormal (Geometric mean...
4 - ToEnvironment	Cumene	kg	air	non-urban air or from high stacks	5,9666E-10	factor_MJ_kWh*0.000000000449	Lognormal (Geometric mean...
4 - ToEnvironment	Furan	kg	air	non-urban air or from high stacks	5,4749E-13	factor_MJ_kWh*4.12E-14	Lognormal (Geometric mean...
4 - ToEnvironment	Selenium	kg	air	non-urban air or from high stacks	2,1926E-07	factor_MJ_kWh*0.000000165	Lognormal (Geometric mean...
4 - ToEnvironment	Nickel	kg	air	non-urban air or from high stacks	2,6577E-07	factor_MJ_kWh*0.0000002	Lognormal (Geometric mean...
4 - FromEnvironment	Water, cooling, unspecified natural origin	m3	natural resour...	in water	0,060774	((recirculating_CS_fraction_from_all...	Lognormal (Geometric mean...
5 - FromTechnosphere	hard coal	kg			0,58205	factor_MJ_kWh*0.0438	Lognormal (Geometric mean...
5 - FromTechnosphere	SOx retained, in hard coal flue gas desulfurisati...	kg			0		Uniform (Maximum=0, Minim...
5 - FromTechnosphere	water, completely softened, from decarbonised...	kg			0,079732	factor_MJ_kWh*0.006	Lognormal (Geometric mean...
5 - FromTechnosphere	NOx retained, by selective catalytic reduction	kg			0		Uniform (Maximum=0, Minim...
5 - FromTechnosphere	water, decarbonised, at user	kg			2,6577	factor_MJ_kWh*0.2	Lognormal (Geometric mean...
5 - FromTechnosphere	light fuel oil	kg			0,00022591	factor_MJ_kWh*0.000017	Lognormal (Geometric mean...
5 - FromTechnosphere	hard coal power plant	unit			*1,3333E-11*	*1/(150000*500*1000)*	*Lognormal (Geometric mean=1...*
5 - FromTechnosphere	chlorine, gaseous	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	hard coal	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	hard coal	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	hard coal	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	hard coal	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	hard coal	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	hard coal	kg			*0*		*Undefined (Maximum=0, Minim...*
5 - FromTechnosphere	transport, freight, sea, transoceanic ship	metric...			*0*		*Undefined (Maximum=0, Minim...*

c. Activity description of the example dataset

Activity	**electricity production, hard coal, IN-KA 2015**
Activity Name	*electricity production, hard coal*
Type	*UnitProcess*
Special Type	*OrdinaryTransformingActivity*
Inheritance Depth	Geography
General Comment	This dataset represents the production of high voltage electricity in an average hard coal power plant in Karnataka in 2012. 'Hard coal' includes anthracite, coking coal and other bituminous coal according to the definition of the IEA electricity information 2014. According to the India Energy Statistics 2015, hard coal is characterized as coals with a gross calorific value which is not less than 24 MJ/kg or which is less than 24 MJ/kg provided that the coal has a vitrinite mean random reflectance greater than or equal to 0.6 percent.
Included Activities Start	*From the constructed hard coal power plant ready to produce electricity.* *From reception of hard coal and operating materials at power plant gate.*
Included Activities End	This activity ends with 1kWh of high voltage electricity produced at the power plant and arrived at the busbar. This dataset includes: - all operation and maintenance activities and materials of the power plants. - Use of fuel oil for startup - Particle removal (dedusting of the flue gas) - Cooling: It is assumed that all plants use wet cooling with a cooling tower. No cooling tower is included in this dataset (will be implemented in future versions) - Loss of feed water This dataset doesn't include - raw materials extraction, decommissioning and waste treatment as these activities are already included in the infrastructure datasets - transformation of the electricity produced - The disposal of non-recycled ashes is modelled separately.
Synonym	*coking coal, anthracite, other bituminous coal*
Tags	*hard coal power, fossil fuels, coal power*
Energy Values	*Undefined*
Allocation Comment	
Dataset Icon Url	
Dataset Icon	
Classifications	
System : Value	*ISIC rev.4 ecoinvent: 3510:Electric power generation, transmission and distribution*
Geography	
Shortname	IN-KA
Comment	
Technology	
Technology Level	*Modern*
Comment	*POWER PLANT:*
TimePeriod	
Start Of Period	*1980-01-01*
End of Period	*2015-12-31*
Data Valid For Entire Period	☑
Comment	*The Annual Production Volume is valid for the year 2012.*
MacroEconomicScenario	
Value	*Business-as-Usual*