A life-cycle model of Chinese grid power and its application to the life cycle impact assessment of primary aluminium

Abstract:

Primary aluminum production is energy intensive due to the large amount of electrical power consumed in the unit process “electrolysis”. In the life cycle analysis of primary aluminium, environmental impact can therefore be heavily affected by indirect greenhouse gas emissions (among other impacts) from the consumption of thermally generated power.

This study outlines the development of a life-cycle model of Chinese grid power at national level, further developed into regional and provincial levels to better assess the cradle-to-gate life cycle impacts of primary aluminium production in China. The results suggest that the contribution to the impact category of global warming potential by electrical energy consumption in the electrolysis process in China is on average around 13 kg CO_2-eq per kg of aluminium.

1. Introduction

The *International Aluminium Institute* (IAI) regularly publishes life cycle inventory data from primary aluminium production, as well as environmental impact data based on such Life Cycle Inventories (LCIs[1]). The last decade has seen a significant increase in the global share of thermal (in particular coal) power consumed in the production of primary aluminium, driven predominantly by the strong growth in production in China. This in turn has had a significant impact on the environmental impact of aluminium production.

It should be noted that aluminium power mixes in different countries and regions can differ significantly from the national or regional grid mix, due to self- generated or contractual arrangements. For instance, the share of coal and hydropower supplying power to the aluminium industry in China is 90% and 10% respectively, compared to a China national grid mix of 70% and 20%. The calculation of impacts from power consumption for aluminium should always therefore reflect an industry grid mix. The

[1] 2015 Life Cycle Inventory Data and Environmental Metrics (2017) -- http://www.world-aluminium.org/publications/tagged/life%20cycle/

IAI has collected and published such data for over 30 years[2].

Even taking these issues into account, however, the use of third party published background data[3] for China power production, applied to a 90% coal fired grid, has produced environmental impact numbers (represented by GWP) in excess of those expected. These expected numbers are based on a consideration of the fact that most aluminium production in China is now occurring in regions with very new (and therefore more efficient) power generating capacity and with a quality of feedstock that is higher than other coal-fired regions of the globe.

IAI therefore commissioned IKE to develop an up-to-date life cycle model of Chinese grid power at the provincial level, which allows an aluminium-specific production weighted provincial impact to be developed. While the study looks at power mixes per province and as we have seen the aluminium industry has power mixes that are industry specific, the provincial data was felt to be a relatively good proxy for the industrial grid, given that the major aluminium producing provinces (Shandong, Xinjiang, Henan, Inner Mongolia) tend to have relatively homogenous power sources. Thus, the study is a provincial model that takes account of both technology and power mix, which can be applied to provincial aluminium production, albeit using a china national average energy efficiency[4] to generate a weighted impact number for use in regional and global life cycle impact assessments of primary aluminium.

2. Methodology

A national power grid model was firstly created. Its structure lays the foundation for further development of a regional and provincial power model.

Thermal power and hydropower accounted for 75% (including coal-fired power of 70%) and 19%, respectively, of total electrical power generation in China in 2014, although the aluminium-specific mix in China was 90% coal and 10% hydropower. The model therefore focuses on grid power generation from thermal energy and hydro power plants. The functional unit as well as the reference flow is defined as 1kWh of grid electricity transmitted to end users, excluding electricity use phase.

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2 Primary Aluminium Smelting Power Consumption (2015) – http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/#map

3 ecoinvent 3.3 -- https://www.ecoinvent.org/database/ecoinvent-33/ecoinvent-33.html

4 Primary Aluminium Smelting Energy Intensity (2015) – http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/#data

Target representativeness

1) Technological representativeness: the life-cycle model and data is mainly[5] based on statistics, which represents national averages of thermal power and hydropower generation.
2) Geographic representativeness: 31 provincial, six regional, and one national average data sets are provided separately, with their own shares of power mix.
3) Time representativeness: 2014.

System boundary

The Chinese electrical power system is composed of three main processes: thermal power generation, hydropower generation, and grid power mixing and transmission. Each process contains several unit processes as shown in Table 1.

Table 1. Processes included in the system boundary

main process	thermal power generation	hydropower generation	grid power mixing and transmission
unit process	coal extraction, coal washing, coal transportation, thermal power generation	Hydropower station construction, hydropower generation	power grid construction, grid power mixing and transmission

Chinese electrical power statistics of 2014 shows the power generation from nuclear, wind, and solar and other sources account for 2%, 3%, and less than 0.35%, respectively, for the total electricity generation. In this model, these power is covered by data sourced from ELCD and ecoinvent.

Impact categories

Considered impact categories include global warming, acidification, eutrophication, photo-oxidant formation, ozone depletion, and primary energy.

Cut-off rules

1) In the collection of unit-process data, an intermediate flow that accounts for 1% or less of the total inputs is cut off; the total cut-off intermediate flows, however, should be no more than 5% of the total inputs.
2) Machinery, minor infrastructure[6], and labour input are left out in the life-cycle model.
3) Any pollutant flow that accounts for more than 1% of the total environmental

[5] 85% data is from industry statistics and annual publications; the remaining data is from literature research.

[6] Infrastructure of grid and dams are included.

emissions is included in the LCI results.

Data quality assessment

1) Completeness of foreground data sets is checked via mass balance and comparison with similar data sets.
2) An intermediate flow that accounts for more than 5% for any impact category as well as its upstream process from background database is highlighted for scrutiny.
3) Background data are obtained from the Chinese Core Life Cycle Database (CLCD-China). For missing background data, proxy data from ELCD or ecoinvent database are applied and their representativeness are assessed.

3. Life cycle model of Chinese grid power on national level

Coal fired power generation is divided into two groups: raw coal (including processes of coal mining and transport), and washed coal (including processes of coal mining, washing, and transport). This division is reflected in the Life-cycle flowchart of grid power in China (Figure 1), which has enhanced accuracy level when analysing thermal power generation.

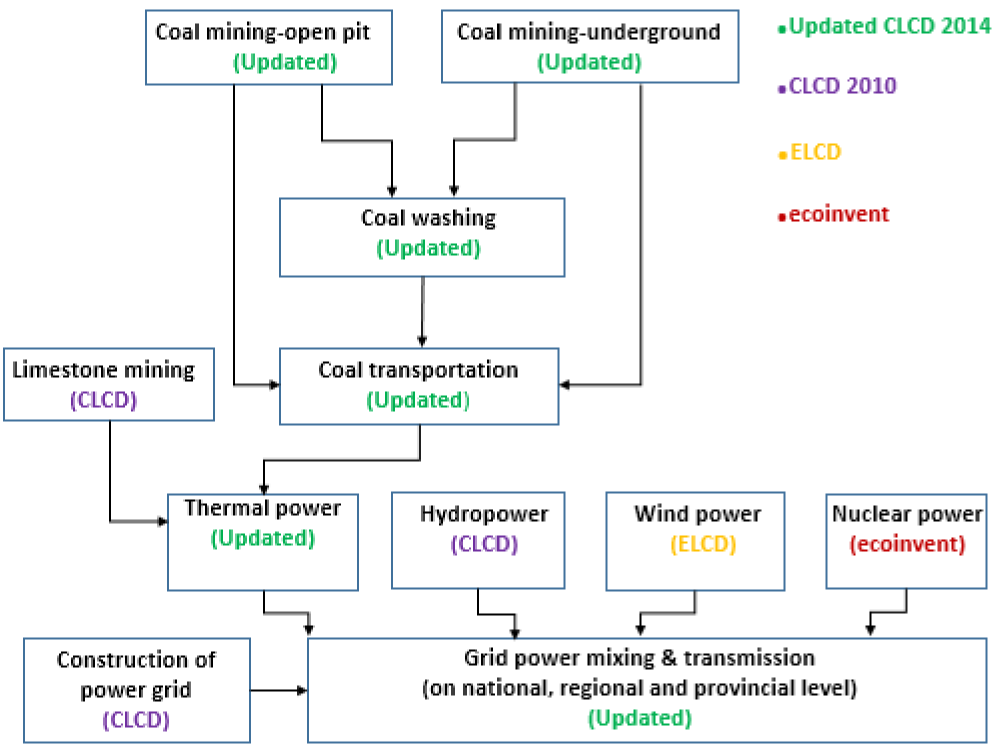


Figure 1. Life-cycle flowchart of grid power in China (national level)

The power mix is based on the proportion of thermal power, hydropower, wind power and nuclear power. And the distribution loss rate in power transmission is defined as the power lost in transmission and distribution divided by the total amount of supplied power.

Table 2. Inputs of 1kWH thermal power generation on national level

Name	Amount	Unit	Data source
raw coal	493.417	g	China Energy Statistical Yearbook 2015 Raw coal contributes >97% among all fuels.
gangue	8.632	g	
other washed Coal	6.908	g	
LNG	0.476	g	
petroleum coke	0.310	g	
refinery gas	0.176	g	
coke	0.135	g	
fuel oil	0.096	g	
cleaned coal	0.087	g	
diesel	0.070	g	
blast furnace gas	0.039	m^3	
crude oil	0.024	g	
natural Gas	0.006	m^3	
coke oven gas	0.005	m^3	
converter gas	0.003	m^3	
petrol	$1.1*10^{-4}$	G	
LPG	$5*10^{-5}$	g	
other gases	$3*10^{-5}$	m^3	
kerosene	$3*10^{-5}$	g	
limestone	0.022	kg	China Electric Power Yearbook 2015
water	1.600	kg	

Inputs to produce 1kWh thermal power are listed in Table 2. They are the national average numbers published in the referenced statistical yearbooks. Table 3 shows the national average outputs from 1kWh thermal power generation.

Table 3. Outputs of 1kWH thermal power generation on national level

Name	Amount	Unit	Data source
CO_2 (fossil source)	1.050	kg	2006 IPCC Guidelines for National Greenhouse Gas Inventories
CO	0.136	g	
N_2O	0.016	g	
CH_4 (fossil source)	0.011	g	
non-methane VOC	0.077	g	
CO_2 (from desulfuration by limestone)	9.640	g	Guidelines for Accounting and Reporting GHGs: China's Power Generation Enterprises (Trial)
SO_2	1.470	g	China Electric Power Yearbook 2015
NO_X	1.470	g	
PM2.5	0.230	g	
fly ash	0.146	g	
gypsum	0.020	g	
wastewater	0.180	kg	
exhaust gas	4.680	m^3	Handbook of Coefficient of Pollution Discharge from Industrial Sources (2010)
COD	$2.48*10^{-3}$	g	
slag	14.500	g	
Hg (water)	$3.82*10^{-5}$	g	estimated from coal-fired power plants in China during the 12th Five-Year (2011-2015)
Hg (atmosphere)	$2.83*10^{-5}$	g	
Hg (soil)	$2.47*10^{-5}$	g	
Se	$2.54*10^{-4}$	g	estimated from coal-fired power plants in China in 2007
As	$1.78*10^{-4}$	g	
HCl	0.296	g	Bituminous and Subbituminous Coal Combustion, US EPA
HF	0.037	G	

The national grid power mix, as well as power loss rates in transmission, are listed in Table 4.

Table 4. Grid power mixing on national level

Name	Amount	Unit	Data source
Thermal power	0.758	kWh	2015 Power Statistics, China Electricity Council
Hydropower	0.187	kWh	
Nuclear power	0.024	kWh	
Wind power	0.028	kWh	
Transmission loss: 6%			

Sensitivity study shows grid power mixing on national level contributes the most to GWP, thermal power generation is the main contributor, which accounts for over 99%.

Table 5. Sensitivity of inventory to global warming (GW)

In unit process	Inventory	GW (%)
Grid power transmission on national level (to user)	Grid power mixing on national level	99.6
Grid power mixing on national level	thermal power	99.3
Thermal power generation on national level	CO_2 (Fossil resources)	93.8
Thermal power generation on national level	raw coal (after mining)	3.9
Raw coal (after transportation)	raw coal	1.6
Raw coal (after mining)	raw coal	1.5
Coal mining (underground)	national average grid power	1.1
Raw coal (after transportation)	water carriage	1.0
Raw coal (after transportation)	road transport	1.0

Raw coal transported has a relatively significant impact on GWP, as shown in Figure 2. This suggests the importance of having data on raw coal transport at sub-national levels.

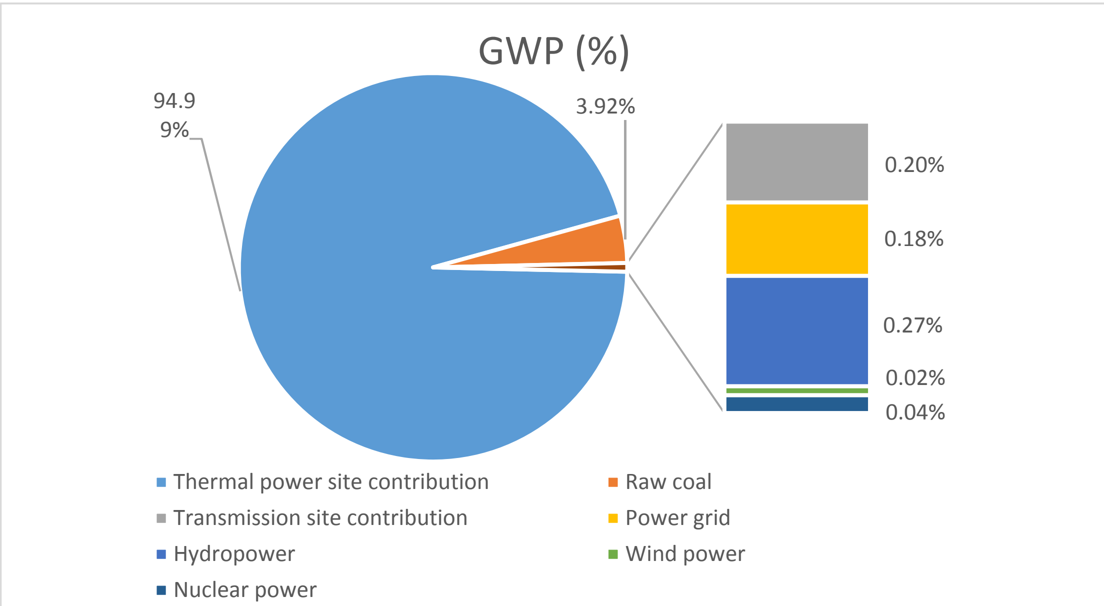


Figure 2. Process Cumulative Contribution of GWP

4. Life cycle model of Chinese grid power on provincial levels

The life cycle model of provincial power grid is similar to the national model in structure. The only difference is that inter-province power transmission is added into the provincial model.

Figure 3. Inter-provincial transmission of China

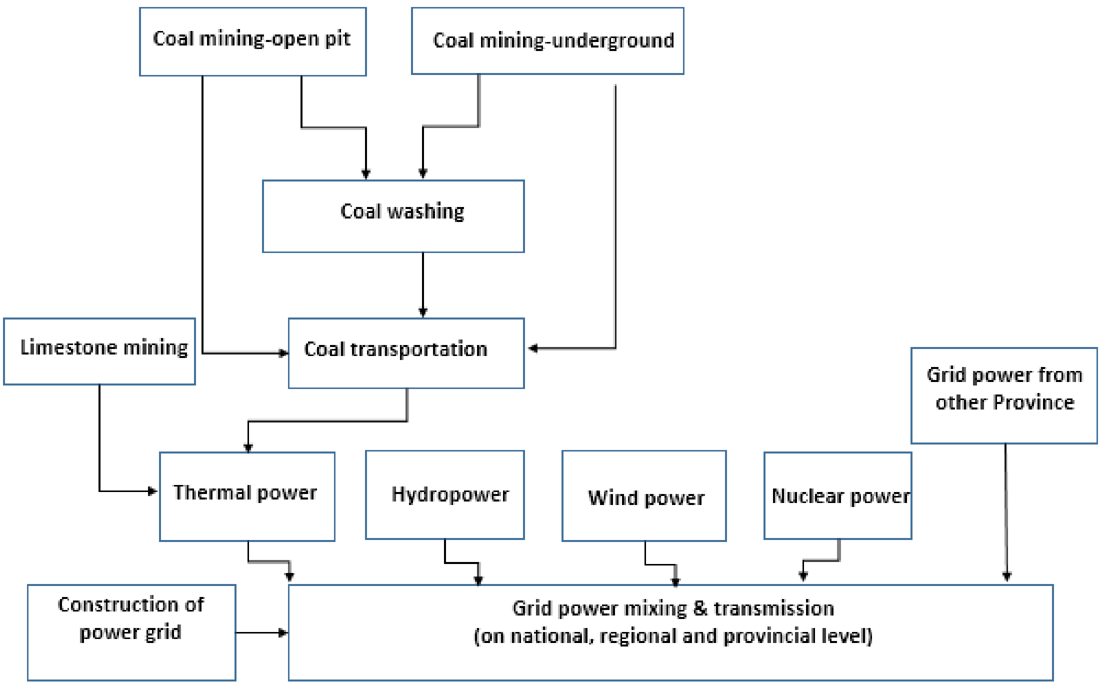


Figure 4. Life-cycle flowchart of grid power in China (provincial level)

As aforementioned, raw coal transported has a material impact on GWP results. Thus, raw coal transport of each province/region is modelled separately.

Table 6 and 7 demonstrate an example of comparing the power mix between two provinces. The differences contained here will affect their following life cycle impact assessment (LCIA).

Table 6. Grid power mixing on provincial level (Henan Province)

Name	Amount	Unit	Data source
Thermal power	0.957	kWh	China Energy Statistical Yearbook 2015
Hydropower	0.0348	kWh	
Wind power	0.00248	kWh	Wind power industry monitoring-State Statistical Bureau 2014
Transmission loss: 7%			

Table 7. Grid power mixing on provincial level (Shandong Province)

Name	Amount	Unit	Data source
thermal power	0.89	kWh	China Energy Statistical Yearbook 2015
hydropower	0.0013	kWh	
wind power	0.0247	kWh	Wind power industry monitoring-State Statistical Bureau 2014
grid power from Ningxia Province	0.071	kWh	China Electric Power Yearbook 2015
Transmission loss: 7%			

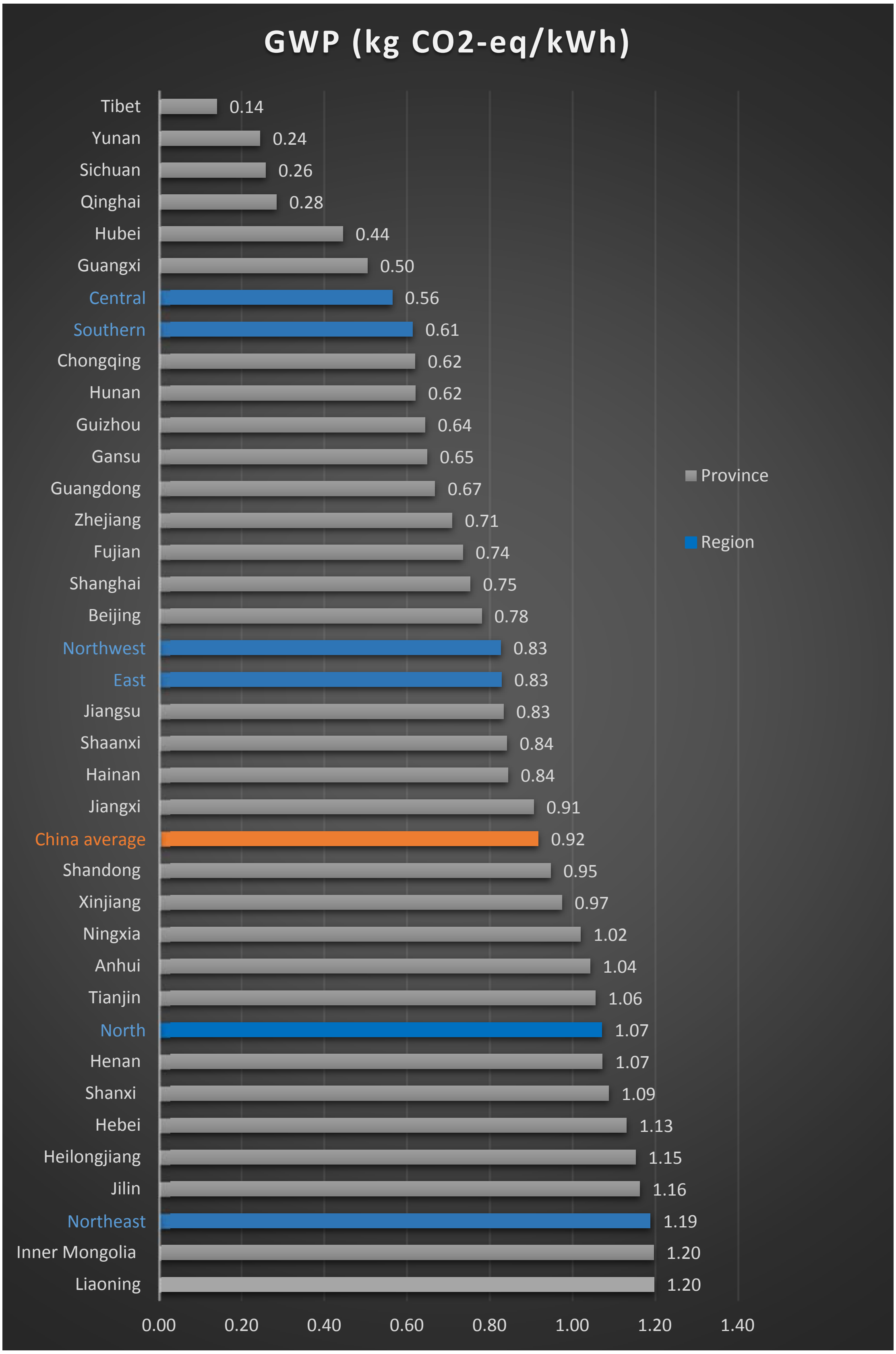
5. Results

The life cycle models outlined above were built and analyzed in eBalance and eFootprint, life cycle assessment (LCA) software developed by IKE. Results of the carbon footprint of 1 kWh grid power on provincial, regional, and national levels is summarised in Figure 5 and reveals a wide spectrum of results, from 0.14 kg CO_2-eq/kWh to 1.20 kg CO_2-eq/kWh, based on GWP factors of IPCC2013.

Aluminium production is not present in all provinces in China and is unevenly distributed among those provinces that do have such production. The primary aluminum smelting energy intensity in China in 2015 was 13.6 kWh/kg Al[7].Using this national average energy intensity and the carbon footprint results generated from the China power grid model, Table 8 shows average CO_2e emissions intensity from electricity consumption in different provinces in China.

[7] http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/#data

Figure 5. Carbon footprint (global warming) of 1kWh Chinese grid power 2014 on national, regional and provincial levels (Hongkong, Macao and Taiwan are not included).



By following the formula below, the national average CO_2e emission from electrolysis is calculated as 11.7 kg CO_2e per kg aluminium.

$$China\ CO2e\ emission\ intensity\ from\ electrolysis = \frac{\sum (Provincial\ CO2e\ emission\ intensity\ from\ electrolysis * Provicianl\ production)}{China\ Total\ Production}$$

Table 8. CO_2e emissions intensity of electrolysis at provincial level in China using grid mix

Province	2015 Primary Aluminium Production (t)	% Production	kg CO_2e/kWh	kg CO_2e per kg aluminium
Shandong	8,063,879	26%	0.95	12.9
Xinjiang	5,864,454	19%	0.97	13.2
Henan	3,259,330	10%	1.07	14.6
Inner Mongolia	2,596,390	8%	1.20	16.2
Gansu	2,303,846	7%	0.65	8.8
Qinghai	2,185,198	7%	0.28	3.9
Yunnan	1,200,307	4%	0.24	3.3
Ningxia	1,200,111	4%	1.02	13.8
Guizhou	855,242	3%	0.64	8.7
Shanxi	660,257	2%	1.09	14.8
Shaanxi	639,128	2%	0.84	11.4
Chongqing	612,283	2%	0.62	8.4
Guangxi	575,629	2%	0.50	6.8
Liaoning	465,267	1%	1.20	16.2
Sichuan	350,089	1%	0.26	3.5
Hunan	329,991	1%	0.62	8.4
Fujian	135,365	0%	0.74	10.0
Hubei	104,167	0%	0.44	6.0
Hebei	12,126	0%	1.13	15.3
China	**31,413,060**	**100%**	**0.92**	**11.7**

*Provincial production data source: Antaike

However, such an analysis does not take into account that aluminium production in a given province does not necessarily align to the grid, but rather uses captive or directly purchased power. Hence the aluminium industry power mix in China is 90% coal fired, as opposed to the China grid average of around 70%.

Applying a weighting to aluminium produced in coal intensive provinces equivalent to 100% coal fired, gives a revised carbon footprint for those smelters, as shown below:

Table 9. CO_2e emissions intensity of electrolysis at provincial level in China - grid mix vs aluminium industry power mix

Region	Grid Mix		Al Industry Power Mix	
	% thermal power (grid)	kg CO_2e per kg aluminium	% thermal power (Al ind'y)	kg CO_2e per kg aluminium
Shandong	95%	12.9	100%	13.3
Xinjiang	84%	13.2	100%	14.5
Henan	96%	14.6	100%	14.2
Inner Mongolia	88%	16.2	100%	18.3
Gansu	59%	8.8	100%	14.1
Qinghai	22%	3.9	22%	3.9
Yunnan	15%	3.3	15%	3.3
Ningxia	90%	13.8	100%	14.8
Guizhou	60%	8.7	60%	8.7
Shanxi	96%	14.8	100%	14.4
Shaanxi	92%	11.4	100%	12.4
Chongqing	48%	8.4	48%	8.4
Guangxi	49%	6.8	49%	6.8
Liaoning	68%	16.2	68%	16.2
Sichuan	19%	3.5	19%	3.5
Hunan	59%	8.4	59%	8.4
Fujian	68%	10.0	68%	10.0
Hubei	40%	6.0	40%	6.0
Hebei	91%	15.3	100%	15.0
China	**77%**	**11.7**	**90%**	**12.6**

6. Discussion

ecoinvent is one of the most widely used life cycle database among LCA practitioners. In ecoinvent v3.3, the database also provides LCIs as well LCIA of China grid power at provincial level.

Table 9. CO_2e emissions intensity of electrolysis at provincial level in China from ecoinvent v3.3

Province/Region	**GWP (kg CO_2e/kWh), using grid mix**	**GWP (kg CO_2e/kWh), using Al industry power mix**
Shandong	1.39	1.40
Xinjiang	1.23	1.46
Henan	1.41	1.46
Inner Mongolia	1.82	1.99
Gansu	0.84	1.40
Qinghai	0.31	0.33
Yunnan	0.53	0.58
Ningxia	1.50	1.55
Guizhou	0.91	0.99
Shanxi	1.50	1.53
Shaanxi	1.26	1.34
Chongqing	0.96	1.04
Guangxi	0.77	0.84
Liaoning	1.47	1.59
Sichuan	0.40	0.43
Hunan	0.89	0.97
Fujian	0.88	0.95
Hubei	0.52	0.56
Hebei	1.42	1.48
China	1.15	1.31
GWP for electricity used in electrolysis (kg CO2e/ kg Al)	**16.3**	**17.7**

Repeating the calculation, by using ecoinvent's GWPs in Table 9, the national average CO_2e emission intensity from electrolysis is 17.7 kg CO_2e/kg Al, which is different from the 12.6 kg CO_2e/kg Al produced by the IKE model.

Most data contained in the IKE model is sourced from 2015 annual industry statistics publication in China. Provincial grid data contained in ecoinvent 3.3 is mainly sourced from Sachbilanzen von Energiesystemen. Final report No. 6 ecoinvent data v2.0

(2007). Some datasets, which are linked to the LCIA of China electricity generation in ecoinvent, have not been updated for over 10 years. For example, the methane emissions factor from underground coal mining is dated 1990 (reference: Rui S. et al. (1994) Coal Industry: Sustainable Development and the Environment. Coal Industry Publishing House, Beijing). Its value is 16.9 kg CH_4/t coal; IKE's latest value is 1.84 kg CH_4/t coal. China has substantially improved its CH_4 management over the last 25 years. Such a reduction from the coal supply chain can have a significant impact on the GWP result from power generation.

Gabi is another mainstream life cycle database. The IAI commissioned Thinkstep to create an aluminium producing model in Gabi in 2012. This model is a cradle-to-gate analysis of electrolytic aluminium system, which includes bauxite mining, alumina production, carbon anode production, aluminium electrolysis, ingot casting, raw materials transport, electricity generation, and aluminium dross processing. It also includes the production of ancillary materials and fuels required for primary aluminium production. The IAI uses this model to develop impact category results from its LCI data gathered from the global aluminium industry.

Inclusion of a 2015 China primary aluminum smelting energy intensity of 13.6 kWh/kg Al into the GaBi model results in a China national average CO_2e emissions from electrolysis of 13.2 kg CO_2e per kg aluminium. This result is close to the IKE modeled result, but unlike ecoinvent data, the GaBi data is available only at national, rather than provincial level and is less transparent in its sources. Furthermore, GaBi does not offer its background data along with the model.

7. Conclusions

For the development of a robust cradle to gate LCA of the global primary aluminium production process (and in order to understand changes to impacts over time), it is critical to have a China energy model that can be interrogated at the provincial level.

A national power grid model for China does not reflect the power mix of the Chinese aluminium industry. Two thirds of primary aluminium produced in China comes from thermal power dominated regions, including the newly developed provinces of Xinjiang and Inner Mongolia, but the power mix of Chinese aluminium is 90% coal.

Secondly, aluminium production in China is developing under different conditions in different regions with different growth rates. A model at provincial level can reflect different impacts of different power mix, as well as their changing weight over time.

The IKE model developed in this study, using 2014 as reference year, is the most transparent provincialised model for Chinese power grid available. Data used in this model will continue to be updated in future to reflect the changes in the Chinese power generation sector and data uncertainty will be analyzed. The differential of aluminium production development by province should also be revisited to ensure impacts that affect the China weighted average result are included in the analysis.

Further information on provincial LCIs is available on request (Linlin Wu wu@world-aluminium.org).

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