Supporting Information for

Greening Industrial Production through Waste Recovery: “Comprehensive Utilization of Resources” in China

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1. General information

This document contains detailed data sources and assumptions for life cycle inventories (LCIs) of representative instances of waste reuse in Jiangsu, China. They are used for life cycle assessment (LCA) to measure environmental impacts of waste reuse to produce products as relative to the average production processes of the same products in Jiangsu, China. The functional unit for comparison varies across cases: if using waste does not change product function or quality, the functional unit is a unit of products produced; otherwise, the functional unit is a minimum bundle of services that can be provided by either the original product or the product produced from waste.

The LCIs are based on multiple data sources. First, we conducted interviews with 24 representative firms that were certified for comprehensive utilization of resources in Jiangsu to acquire their production and emission inventories, and when possible their previous inventories when waste were not used as inputs. This information was not necessarily used directly to build LCIs, but informed how alternative LCIs of using and not using waste in production shall be built for comparison. Second, we relied on environmental impact assessment, cleaner production audit or project evaluation reports for individual firms, product standards, industrial standards, statistical yearbooks, as well as academic literature to build industrial average inventories for production and pollution emissions. Third, when information above was not available, materials and energy balances were used to calculate the substitution of waste for original fuel or materials. Fourth, the LCI database Ecoinvent database 3.1[1] were used, mainly for baseline inventories of some products when lacking alternative data sources for China, and for background LCIs that would not contribute much to the final results.

The next section explains how LCIs of electricity and industrial heat specifically in Jiangsu, 2011 are built, which are used by various LCIs of waste reuse. The LCIs of waste reuse are organized according to the products or services provided. To classify the firms consistently, we refer to both the International Standard Industrial Classification (ISIC) and the Chinese Standard Industrial Classification (CSIC), particularly at the two-digit level to avoid differences at the three or four-digit levels of the two classification systems.

2. Energy infrastructure in Jiangsu province

Given the wide use of electricity and heat in most production processes in this research and the variation in efficiency and environmental impact of producing them, we construct LCIs for electricity and heat specifically for Jiangsu. They are used for the other inventories introduced in the following sections, and the upstream inventories that contribute to more than 1% of the environmental impacts.

2.1 Electricity

The entire Jiangsu province locates in the East Grid, one of the six regional power grids in China. To build the LCI of electricity in the East Grid, we consider mix of energy sources in power generation, efficiency and emission inventories of coal-fired power plants. Because the grid includes five provincial equivalent jurisdictions – Jiangsu, Shanghai, Anhui, Zhejiang, and Fujian, data are drawn from aggregate and plant-level statistics in the five provinces in 2011.

The amount of electricity generation from different energy sources in 2011 is collected from multiple data sources: the amount of nuclear, hydropower, and wind power generation in each province is from the China Electric Power Yearbook (CEPY) 2012;[2] total electricity generation from coal, oil, and natural gas fired power plants in each province is from the provincial energy balance table in the China Energy Statistical Yearbook (CESY) 2012,[3] where the total amount of generation reported in the table is divided into the three energy sources according to consumption of different fuel types in the energy balance tables, heating value and conversion efficiency in electricity generation; electricity generated from all the other energy sources can be calculated by combining the statistics in the CEPY and the CESY 2012, but is much less than 0.1% of the total electricity generation and thus ignored; import, export, and loss of electricity is based on the energy balance tables in the CESY 2012.

Because more than 80% of the electricity generation in the East Grid is from coal-fired power plants, their efficiency and emission inventory is updated. The amount of coal used to produce a unit of electricity is calculated according to the energy balance tables in the CESY 2012. Emission of carbon dioxide is based on the emission factor of operating margin in the East Grid in 2011, calculated by the National Development and Reform Commission.[4] Emissions of sulfur dioxide, nitrogen dioxides, and particulate matters are calculated following methods and statistics of Cai and colleagues[5] and Henriksson and colleagues,[6] as well as new observations of more than 1,200 power plants in the five provinces 2011:[7, 8] emissions are calculated as a result of pollution contents of the coal used, emission coefficient of the pollution contents in electricity generation, as well as the removal efficiency of pollution control devices installed at all the power plants in the five provinces. Other emission factors are directly from Henriksson and colleagues.[6] Electricity generated from other sources only consists of less than 20% of total electricity in the East Grid, and their inventories are directly from the Ecoinvent database 3.1.

2.2 Heat

According to the energy balance table of Jiangsu in CESY 2012, coal accounts for more than 99.5% of all energy sources used in heat generation in terms of heating value. Therefore, we assume that industrial use of heat, which is about two thirds of total provincial heat consumption, all come from coal-fired boilers. This is consistent with our interview feedback. The conversion efficiency of heat is based on the ratio between coal consumption and heat production in the energy balance table. Emission factors are according to the boiler emission standard of air pollutants published in 2014[9] and Jiangsu's specific greenhouse gases emission factors based on the fuel type and the greenhouse gas protocol for China.[10]

3. Wood products

47 firms certified for CUR in Jiangsu in 2011 produced engineered wood products. They belong to the two-digit sector manufacture of wood and of products of wood and cork, which is C20 in CSIC and C16 in ISIC. Except one manufacturer of wood-plastic composite, all the other firms used forest and agricultural residues as 100% of their material inputs in production. These residues included small wood branches and twigs, scrap from wood logging, lumbering, and manufacturing, straw and hull of agricultural products. The products were either medium-density fiberboard (MDF) or particle board.

3.1 Medium-density fiberboard from forest and agricultural residues

There were 22 firms producing MDF from residues. To estimate their production inventories, we rely on our interview with engineers from one of the 22 firms, three project evaluation reports, and one environmental impact assessment report (table 1). They represent five different MDF producers using forest residues located in regions similar to Jiangsu province, where central heating in winter is typically not necessary and not part of firms' total energy consumption. The energy sources include coal, electricity, and reuse of scrap and dust from firms' own manufacturing processes. Three of the firms do not use coal – one can cover all the fuel use by burning its own residues from manufacturing processes, and the other two purchase additional agricultural and forest residues for fuel. The quantities of residues purchased for fuel are converted to coal, because regular MDF producers may also use residues as fuel without being qualified for CUR. The average is considered as the inventory for the 22 certified producers in Jiangsu.

Table 1. Residues used and energy composition per m^3 of MDF products.

	Residue (kg/m^3)	Coal (kg/m^3)	Self reuse (kg/m^3)	Electricity (kWh/m^3)
Interview 1	1658	98	34	237
Report 2	1500	71	144	131
Report 3	1250	135*	135	178
Report 4	1800	0	156	225
Report 5	1910	79*	266	273
Average	1624	76	147	209

* Purchase of straw and wood waste for fuel is converted to coal of the same heating value.

The baseline inventory of MDF manufacture without use of forest residues is based on the national cleaner production standard for MDF.[11] There are three levels in the standard – internationally advanced, nationally advanced, and nationally basic – and we rely on the average of the first two levels for southern China without central heating demand. More advanced levels are used to match with the firm-level reports we use, which represent new plant and equipment. While the standard only specifies total energy consumption levels, we assume a ratio of between heating value consumed in heat boilers and that from electricity-consuming devices to be 5:1, the same as the average of the five firms in table 1. So the baseline electricity consumption is 325 kWh/m^3. We further assume that all the processing waste is reused as fuel, according to the required 100% recycling rate in the standard. The quantity of processing waste is calculated as the difference between dry input density (860 kg/m^3) and final product density (750 kg/m^3) in the standard, as 110 kg/m^3. The coal consumption is then 203 kg/m^3. The emission inventories for burning coal and wood waste are based on inventories for coal-fired boiler and wood-fired boiler in this document, respectively. Because the standard does not specify limits for regular pollution emissions, it is assumed that there is no other difference in pollution emissions in production processes, except from burning coal and wood waste and upstream electricity generation. The CUR firms benefit both from using the residues burden-free without most of the energy consumption in lumbering and wood chipping, and from having more scraps and dust from manufacturing processes available for fuel.

3.2 Particle board from forest and agricultural residues

There were 24 firms producing particle board from forest and agriculture residues. We follow the estimation strategy for MDF producers and collect reports of environmental impact assessment or project evaluation for four particle board producers in areas similar to Jiangsu. The average is used to represent the energy composition for the 24 firms certified for CUR in Jiangsu.

Table 2. Residues used and energy composition per m^3 of particle board products.

	Residue (kg/m^3)	Coal (kg/m^3)	Self reuse (kg/m^3)	Electricity (kWh/m^3)
Report 1	945	105	0	27
Report 2	1030	6*	64	28
Report 3	1157	10*	114	200
Report 4	1189	53*	57	162
Average	1080	44	59	104

* Purchase of straw and wood waste for fuel is converted to coal of the same heating value.

Similarly to MDF, the baseline inventory for particle board is based on the national cleaner production standard for particle board,[12] specifically the average of internationally advanced and nationally advanced levels. Total energy consumption in the standard is disaggregated into 55 kg/m^3 processing residues, 65 kg/m^3 coal, and 128 kWh/m^3 electricity. The emission inventories for burning coal and wood waste are based on inventories for coal-fired boiler and wood-fired boiler in this document, respectively. Differences in emissions other than coal and wood burning and electricity generation are not considered.

4. Biodiesel

Four firms produced biodiesel and belonged to the sector of manufacture of coke and refined petroleum products, which is a two-digit sector, C25 in CSIC and C19 in ISIC. The firms relied mainly on food refuse and used cooking oil as feedstock, which accounted for 83% to almost 100% of their total materials input.

The common process in production of biodiesel is transesterification,[13] which causes most of the environmental impacts in a life cycle of four processes: waste collection, delivery, pretreatment, and transesterifcation.[14] Both alkali-catalyzed process and acid-catalyzed process have been used in China. To reflect current technologies used, we rely on our interviews and project evaluation reports of Chinese firms to build a production inventory (table 3). Because some firms also collected food refuse, part of which was used to produce biogas for heat and electricity generation, their steam and sometimes electricity were partly or fully self-supplied. Other business activities – for example production of protein and fertilizers – based on food refuse and associate inputs are not considered. Collection and delivery of waste cooking oil and food to production sites are excluded from estimation following previous research,[15] as they are also necessary processes in alternative situations for treatment and disposal. The reported heating value of biodiesel ranges from 37.27 to 42.65 MJ/kg,[13, 15-18] and the average of 40.55 MJ/kg is used, in comparison to 42.65 MJ/kg regular diesel to determine the ratio of substitution in use. The low content of sulfur in biodiesel is taken into account by using low-sulfur diesel production from the Ecoinvent database 3.1 as the baseline comparison.

Table 3. Inputs per ton of biodiesel production.

	CH_3OH (kg)	NaOH (kg)	H_2SO_4 (kg)	Electricity (kWh)	Coal (kg)
Report 1	33.3	2.52	0.65	0	0
Report 2	120	1.6	0.1	37.3	66
Report 3	134	10.4	43.4	32	116
Average	95.8	4.83	14.7	34.7	60.7

5. Chemicals and chemical products

26 firms certified for CUR used waste gas, wastewater, and solid waste to produce various kinds of chemical products. They belonged to the two-digit sector of manufacture of chemicals and chemical products, C26 in CSIC and C20 in ISIC. The popular products were basic chemicals from chemical waste gas, including liquid carbon dioxide and sulfur.

5.1 Liquid carbon dioxide from chemical waste gas

Five firms produced liquid carbon dioxide as food additives from chemical waste gas of ammonia production, which contained small amounts of hydrogen sulfide and light hydrocarbon. Waste gas usually goes through desulfurization, catalytic oxidation, and is finally dried and condensed. Because the amount of pollutant in waste gas is usually low and not necessarily treated, the production of liquid CO_2 is assumed to avoid both regular production of liquid CO_2 and pollution emissions from ammonia production. The production inventory for CO_2 (table 4) and chemical composition of waste gas from ammonia production (table 5) are based on one Chinese firm's environmental impact assessment report, to get more specific information. Baseline inventory of liquid CO_2

production is from the Ecoinvent database 3.1 updated with Jiangsu's electricity and heat inventories.

Table 4. Inputs and emissions of producing one ton liquid carbon dioxide from waste gas.

Inputs				Emissions	
Charcoal (g)	Al_2O_3 (g)	Electricity (kWh)	Water (kg)	H_2S (g)	Ammonia (g)
160	240	180	390	1.2	10

Table 5. Chemical composition in input waste gas.

CO_2	O_2	CH_4	C_2H_2	H_2S
97.8%	2%	0.1%	0.1%	0.004%

5.2 Sulfur from chemical waste gas

Chemical waste gas with high concentration of hydrogen sulfide has to be treated for pollution control. There were four firms certified with CUR producing sulfur fully based on waste gas from chemical and petrochemical plants. Because removal of sulfur content is necessary in alternative situations, sulfur is assumed to be produced burden free in CUR. The baseline for comparison is assumed to consist of the same level of pollution control for waste gas and sulfur production from regular processes, according to the Ecoinvent database 3.1 with Jiangsu's electricity and heat inventories.

6. Man-made fibers

Seven firms were certified for CUR by using waste chemical fibers to produce recycled ones. They belonged to the sector of man-made fibers, which is a two-digit sector C28 in CSIC, and a three-digit sector C203 within the two-digit sector of C20 in ISIC. The major products from CUR were polyester fibers, which is the type of fibers that is mostly produced in China and the world.

Table 6. Inputs and emissions of producing one ton recycled polyester stable fibers.

Inputs			Emissions to water			Emissions to air			
Ethylene glycol (kg)	Electricity (kWh)	Water (m^3)	Water (m^3)	COD (g)	NH_3-N (g)	TSP (g)	Ethylene glycol (g)	CH_2CHO (g)	NMVOC (g)
6.5	285	1.2	0.30	18	4.8	125	6.14	7.8	10

As five of the seven firms produced polyester stable fibers, the alternative production inventories for the fibers are constructed for comparison. According to the national standards,[19, 20] both primary and recycled polyester stable fibers have their advantages in quality: recycled ones are required to have higher strength, but can have larger variation in quality compared to primary ones. Therefore, the two are compared directly without any discounting for differences in use. The inventory for producing recycled fibers is based on the mandatory constraint for the industry,[21] combined with a production inventory of firms for detailed energy composition and emissions (table 6). The inventory for primary fiber production is based on the national cleaner production standard,[22] where the basic level is used, in accordance with the mandatory constraint for the recycled.

7. Rubber and plastics products

Twelve firms were certified for CUR by producing recycled rubber and plastics products. They belonged to the two-digit sector of manufacture of rubber and plastics product, C29 in CSIC and C22 in ISIC. The major products included retreated tire and recycled plastics.

7.1 Tires from used tires

Used tires can be retreaded and reused, which preserves most of the materials in a tire. The retreaded tires are reported to last 75-100% of the lifetime of equivalent new tires,[23] or with a proportion of 1: 0.8: 0.7 for three tire lives used by some industries.[24] To make the retreaded tires comparable to new ones, we assume that tires are retreaded twice, with 80% and 70% of the original lifetime respectively; an average retreaded tire then can replace 75% of an equivalent new tire. While some research stresses that the energy efficiency of retreaded tires in use stage may be greatly compromised,[23] the conclusion is mainly based on the US case of old generations of retreaded versus new generations of new tires. Considering the relatively new generations of recycled tires in China, the loss in efficiency in use stage is ignored.

Based on our interviews, the retreaded tires production certified for CUR mainly retreaded radial tires for bus and heavy duty trucks. The production inventory is based on interviews with a representative firm (table 7), where coal is used in heat boilers for steam generation. The baseline inventory for producing a new heavy truck tire is from Boustani et al.,[23] and updated with Chinese data from the national cleaner production standard.[25] While the emissions from producing retreaded tires are likely smaller than producing new tires, they may vary according to the detailed characteristics of firms, and are assumed the same for two types of tires.

Table 7. Inputs for producing one retreaded heavy truck tire.

Natural rubber (kg)	Synthetic rubber (kg)	Carbon black (kg)	Chemical oil (kg)	Electricity (kWh)	Coal (kg)
6	6	6	2	5.8	16.5

7.2 Plastics from used plastics

Because of high specificity in production, only three recycled plastics producers were certified for CUR, and they each produced different products. To evaluate the benefits of waste reuse, we interviewed one firm producing polyethylene (PE) packaging films.

The literature of life cycle assessment for plastics packaging materials shows that recycling is always the most beneficial approach to deal with waste materials.[26, 27] However, as the literature mainly focuses on containers, we rely on our interview results and environmental impact assessment report of another firm. Because the extrusion process for producing PE films is the same for primary and recycled feedstock, the comparison is made for granulated PE produced from petroleum and from waste PE films. The production inventory is in table 8. The inventory for granulated PE produced from petroleum is from the Ecoinvent database 3.1, because the production is similar across different places.

Table 8. Inputs and emissions for producing one ton of granulated PE.

	Electricity (kWh)	Water (m^3)	TSP (g)	NMVOC (g)
Interview 1	30	0.143	N/A	8
Report 2	30	0.138	1.5	5
Average	30	0.141	1.5	6.5

8. Construction materials

Table 9. List of construction materials and their use of waste.

	Total	Fly ash	Coal refuse	Other mine tailings	River sediments	FGD gypsum
Concrete products	**238**	**192**	**2**	**120**	**9**	**9**
Autoclaved aerated concrete blocks	47	39	0	7	3	9
Perforated concrete bricks	63	49	0	51	0	0
Concrete hollow bricks	40	33	1	19	2	0
Other concrete bricks and blocks	58	41	1	15	1	0
Concrete	30	30	0	28	3	0
Binder products	**152**	**141**	**35**	**28**	**3**	**39**
Cement	111	107	35	23	3	36
Mortar	41	34	0	5	0	3
Other brick and block products	**287**	**231**	**70**	**4**	**195**	**0**
Fired bricks	262	206	70	1	193	0
Unfired fly ash bricks and blocks	25	25	0	3	2	0
Wallboard and gypsum	**28**	**7**	**0**	**0**	**0**	**16**
Other products	30	26	1	4	0	0

Note: There were other wastes used but not listed in the table, including furnace slags, sludge, construction waste, etc.

Construction materials belong to the sector of manufacture of non-metallic mineral products, which is C30 in CSIC and C23 in ISIC. It is the largest industrial sector for certified CUR activities in Jiangsu. There were 735 CUR instances that produced construction materials in Jiangsu 2011, where several firms involved in multiple instances as they produced more than one product from CUR. Main products include concrete and concrete products, cement, mortar, fired and unfired bricks and blocks, gypsum products, etc. Reuse materials include fly ash, coal and other mine tailings, sediments and sludge, and wastes from power plants, construction, refinery and other sectors.

9.1 Autoclaved aerated concrete (ACC) blocks with fly ash

ACC blocks are produced differently from other concrete products. Two major components of raw materials for producing ACC blocks are calcareous (CaO-rich) materials such as cement and lime, and siliceous (SiO_2-rich) materials such as sand. The desirable Ca/Si ratio is 0.8 to 1.0.[28] Being rich with both SiO_2 and CaO, fly ash is the major waste used in ACC blocks production in Jiangsu. There were 47 producers of ACC blocks certified for CUR in 2011, most of which used fly ash. Because the amount of different waste used was usually aggregated and reported as a single number, we rely on 28 producers that used fly ash exclusively to know the exact amount of fly ash used in each of the processes.

Fly ash is primarily used as a siliceous component in AAC production, a replacement to sand, and accounts for up to 80% of the dry ingredient weight [29, 30]. As confirmed by the literature[29, 31] and our interviews in Jiangsu, using fly ash does not change the production process and usually improves product performance compared to using sand. Even when undesirable fly ash with high carbon and ammonium salt content is used, product quality still reaches standards for sand-based AAC products.[30] Therefore, we assume no difference in production and product durability with changes in input composition by using fly ash.

The baseline input composition for AAC blocks production without fly ash is from the Ecoinvent database 3.1: per kg AAC block requires 0.912 kg of dry input in total, including 0.104 kg quicklime, 0.260 kg Portland cement, 0.504 kg sand, and 0.044 kg other materials. With the use of fly ash, the composition of fly ash, quicklime, cement, and sand in the dry input is about 66-72%, 17-21%, 6-12%, and 0% respectively, based on six independent project evaluation reports online and our interviews. Therefore, it is assumed with fly ash, sand is always fully replaced, cement is partially replaced, and quicklime is usually increasingly used. Fly ash was used as 68-85% of total dry inputs in CUR firms, while the producer with the highest percentage use of fly ash maintained a composition of fly ash, quicklime, and cement as 0.72:0.2:0.08, among the fix inveotries.

Therefore, for producers with more than 72% fly ash use, we assume that the rest of fly ash, after replacing all the sand, replaces both quicklime and cement but does not change the relative ratio of 0.2:0.08 of the two. Only several producers used fly ash less than 72% of total inputs, and their inputs ratio is assumed to be a combination of different inputs composition identified from the reports.

9.2 Other concrete products with fly ash

Except AAC blocks, other concrete products are produced in similar ways. They are mainly made of cement, aggregate, and water in varying ratios according to the requirement of products' strength. Fly ash is still the most common waste used in these products. Among the 38 producers that used fly ash exclusively, fly ash accounted from 30% to 75% of the dry weight of the total inputs. The literature shows that fly ash improves the quality of different concrete products.[32, 33]

According to interviews with CUR firms, online project evaluation reports and national standards of using fly ash in concrete and concrete blocks,[34, 35] we assume that fly ash can replace up to 20% of cement. Besides replacing cement, the rest of fly ash works as fine aggregate and replaces silica sand of the same weight, i.e. sand that has been dried with less than 1% of water content, according to the requirement of less than 1% water content in the national standard of fly ash used in concrete.[34, 36] The standard also specifies the water consumption of fly ash concrete to be less than 95%, 105%, and 115% of that of concrete without fly ash, for three categories of fly ash respectively. But the category of fly ash with highest water demand is less used in concrete, and the average concrete water consumption of 87 samples of fly ash in Shanghai is even less than that of concrete without fly ash.[37] Based on the two facts, we assume that fly ash does not change water demand, without knowledge of detailed fly ash used by each producer. The baseline inventory for producing concrete products when fly ash is not used, is based on the Ecoinvent database 3.1, updated with Jiangsu's specific electricity and heat inventories.

9.3 Other concrete products with quarrying and mining residue

Producers of concrete products also widely used quarrying and mining residues. These mining residues were the sole waste input for 27 producers, and accounted for 32-91% of their total inputs. It is confirmed that concrete with mining tailings is not compromised in physical and mechanical characteristics,[38] and concrete with quarry dust has improved quality.[39]

According to our interviews with concrete bricks and blocks producers using mining residues, small stones, scrap and dust from quarrying and mining can be directly used as coarse and fine aggregates for producing concrete and concrete products, including perforated concrete bricks, concrete hollow blocks, solid concrete bricks, and concrete paving bricks. Therefore, residues are assumed to be substitutes of the same weight for gravel and sand from quarry operation, where the baseline inventory with no waste reuse is based on the Ecoinvent database 3.1, updated with Jiangsu specific electricity and heat inventories.

9.4 Cement with fly ash

Fly ash cement is relatively a mature product and has been produced for decades. Almost all cement producers certified for CUR used fly ash. Among them, 11 producers used fly ash exclusively without other waste, and the ratio of fly ash in their inputs ranged from 31% to 42%.

Three inventories for cement production are used – one with no fly ash as the baseline, one with 23.1% of fly ash and 76.9% conventional input, and one with 45.5% fly ash and 54.5% conventional input. They are all based on the Ecoinvent database 3.1 and Jiangsu specific electricity and heat inventories. The updated baseline energy consumption from clinker production is 3.2 GJ per ton of clicker, very close to the national average of 115 kg coal equivalent.[40] Each cement firm is assumed to produce different composition of the two types of fly ash cement – one with higher content of fly ash and one with lower content, so that the overall use of fly ash in total inputs matches the firm's actual reuse rate. The inventories generated by this combination process have been confirmed by two cement engineers we interviewed.

9.5 Mortar with fly ash

Fly ash was also the major waste for mortar producers certified for CUR. There were 29 of the certified producers that used fly ash exclusively, accounting for 30-70% of their total inputs.

While the national standard dedicated to the use of fly ash in mortar has not been updated for decades,[41] the standard for fine aggregate used in concrete and mortar[42] suggests the same requirement for both concrete and mortar. In addition, the literature shows that mortar with various levels of fly ash to partially replace cement has even improved quality.[43] Therefore, we follow the standards for use of fly ash in concrete,[34, 36] and assume similarly that fly ash first replaces up to 20% of cement and then replaces silica sand, with the baseline inventory of mortar production from the Ecoinvent database 3.1, updated with Jiangsu specific electricity and heat inventories.

9.6 Fired bricks with fly ash

While fly ash and sediments from rivers and lakes were two main waste sources that make producers of fired bricks certified for CUR, they were more often used together or in combination with coal reuse and other waste. To know the accurate amount of each waste used and calculate benefits, however, we have to rely on firms used only one type of wastes. There were only three firms that used fly ash exclusively, which was 31%, 69% and 99% of their total inputs, respectively.

The literature shows that the quality and durability of bricks with low and high volume of fly ash are not sacrificed, or even improved,[44, 45] and the heavy metal contents are well encapsulated without any release beyond permissible limits set by the regulations.[46] Similarly, the cleaner production requirements[47] and our interviews suggest that the production process does not become more polluted. Rather, fly ash not only replaces clay but also reduces use of coal, as it contains unburned carbon with heating value. The amount of unburned carbon in fly ash varies, and can be measured by the loss on ignition value.[48] We assume that unburned carbon is 3.14% of fly ash by weight, according to the loss on ignition of 3.37% and water content of 0.23%, averaged over 87 samples of fly ash around Shanghai.[37] With the heating value of 32.808 MJ/kg for carbon, one kg of fly ash is assumed to have heating value of 1030 kJ, and replaces coal of 0.049 kg. Considering the average density standard of 1,100 kg/m^3,[49] the cleaner production requirement of less than 1,196 kg/m^3 of raw materials used,[47] and the loss on ignition of 3.37%, one kg of fly ash is assumed to replace 1.05 kg of clay. Other production inventories are built according to the national cleaner production requirements for fired bricks and greenhouse gases protocol for fuels.[10, 47, 50]

9.7 Fired bricks with river and lake sediments

River and lake sediments were used as the only waste by 12 certified producers of fired perforated bricks, and accounted for 68-85% of their total inputs. The literature shows that fired bricks with low,[51] high,[52] and exclusive[53] use of river sediments at varying production scales have much better thermal-insulation function and acceptable physical strength. When using sediments from polluted rivers with heavy metals, leaching is well below the regulatory limits.[51, 52]

River and lake silt contains combustible organic components. Although news suggest that sediments from some lakes are comparable to lignite in heating values, the value can vary substantially across areas. We rely on production inventories from our interviews and online[54] that use sediments from Yangtze River and Tai Lake, the two major water bodies in Jiangsu province. Sediments usually have high water content, and are naturally dried, and also have high percentage loss on ignition. One kg of sediments usually produce 0.64 kg in the bricks, after drying and firing, and replace 0.70 kg clay. One ton of brick products, when fully using sediments, require about 18 kg less coal equivalent. Therefore, one kg of sediments before drying can replace 0.016 kg coal. Other production inventories are built according to the national cleaner production requirements and greenhouse gas protocol mentioned above.[10, 47, 50]

9.8 Fired bricks with coal mine refuse

Although less extensively used than fly ash and sediments, coal mine refuse was the most popular one as the single waste input in brick production. 25 certified CUR producers used coal refuse exclusively, as 30-100% of their inputs.

The benefit of using coal refuse is that it has enough heating value and does not require any additional energy sources for firing. Our interview respondents suggested that producers usually chose coal refuse with lower heating value to use more refuse in their inputs; when the heating value was high, however, other materials had to be added. However, there is also sulfur content in the coal refuse, and with more use of coal refuse, more SO_2 would be released. According to one version of the cleaner production requirements under review,[47] the level of SO_2 emission is set as 850 mg/m^3 products produced when using coal refuse, and 400 mg/m^3 otherwise. Therefore, we assume SO_2 emission varies linearly from 400 to 850 mg/m^3 products production when using 4% to 100% of coal gangue. Because coal refuse is the single energy source, the weight loss is assumed to be fixed at 45 kg/m^3 products produced, according to the heating value of carbon, while the unburned weight is assumed to be in the final weight of products. Like above, products' density is considered as 1,100 kg/m^3.[49] Other production inventories are built according to the national cleaner production requirements and greenhouse gas protocol.[47, 50 10]

9.9 Fly ash bricks and blocks

Besides fired bricks, fly ash and other waste were also used for unfired bricks and blocks through curing and autoclaving. There were 14 producers that used fly ash exclusively, as 31-72% of their total inputs. Tests show that such bricks and blocks, produced from different methods and with different percentages of fly ash, have comparable strength and durability as fired bricks.[55-58]

Fly ash bricks and blocks are substitutes for fired ones. Two types benefits of fly ash bricks and blocks are considered: first, brick production from curing and autoclaving requires less energy than firing; second, more fly ash used means less use of sand or other primary resource. Producing one m^3 fly ash bricks is assumed to consume 183 kg steam, 12.2 kWh electricity, and 1470 kg material inputs, based on the average of four production inventories we found online. It is also assumed that fly ash replaces sand of the same weight. In comparison, the energy consumption for fired bricks is based on the national standard of 50 kg coal equivalent and 25 kWh electricity.[47, 50] Emission factors follow the assumption used above in 9.6-9.8.

9.10 Wallboard and gypsum from flue-gas desulfurization gypsum

Flue gas desulfurization has been increasingly mandated at power plants and other SO_2 emitting process. Among the SO_2 removing methods, wet scrubbing using limestone and lime is a popular one. A by-product from the process is flue-gas desulfurization (FGD) gypsum, which well replaces regular gypsum in producing wallboard and other applications. There were 10 producers of FGD gypsum and 8 producers of wallboards that used FGD gypsum that were certified for CUR. To avoid double counting, only production of FGD gypsum was considered in calculating the overall benefits.

Because desulfurization is necessary for power plants, it is assumed that FGD gypsum is produced burden free. Therefore, the benefits of producing FGD gypsum are assumed to be the avoided production of gypsum mineral from quarry operation. The inventory is based on the Ecoinvent database 3.1, updated with Jiangsu specific electricity and heat inventories.

9. Metals

Ten firms were certified for CUR by recycling ferrous, precious, and other non-ferrous metals from waste chemicals, electronics, batteries and slags. They belonged to the two-digit sector manufacture of basic metals (C24) in ISIC, and two separate sectors for ferrous metals (C31) and non-ferrous (C32) in CSIC.

To reflect the benefits of different recycling activities, we select representative processes from the ten firms: copper production from electronic waste, lead production from scrap batteries, as well as recovery of palladium, platinum, and rhodium from used catalyst. The inventories of both primary production and recycling for the five metals are based on the Ecoinvent database 3.1, where the recycling processes are updated with Jiangsu's specific electricity and heat inventories.

10. Heat

Seven firms were certified for CUR by supplying steam and hot water from waste sources – waste heat and residues from forest and agriculture. They belonged to the utility sector, D44 in CSIC and D35 in ISIC.

10.1 Heat from waste heat

There were five firms that sell steam or hot water generated from waste heat. Because the industrial waste heat was collected and used burden free, it is assumed that the benefits are simply avoided steam or heat water generation from regular heat boilers. The inventory for regular heat generation has been specified in section 2.2 and used here, which is mainly based on coal. The reported amount of steam or hot water generation by each CUR firm is converted to heating value to be consistent with the output of heat boilers.

10.2 Heat from forest and agricultural residues

Two firms produced heat or biofuel for heat boilers as products from forest and agricultural residues. We collect the inputs and emissions information of producing one MJ of steam from one of the firms, based on the typical heat boilers it uses (table 10). For comparison, the baseline inventory is similarly from the coal-fired heat boilers in section 2.2.

Table 10. Inputs and emissions of producing one MJ steam from wood residues.

Inputs		Emissions		
Electricity (kWh)	Water (kg)	TSP (mg)	SO_2 (mg)	NO_x (mg)
0.00635	0.4356	33.7	47.2	166

References

1. Weidema, B. P. B., Ch.; Hischier, R.; Mutel, Ch.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O.; Wernet, G, , The ecoinvent database: Overview and methodology, Data quality guideline for the ecoinvent database version 3. In 2013.
2. CEPY Editting Committee, *China Electric Power Yearbook*. China Electric Power Press: 2012.
3. National Bureau of Statistics, *China Energy Statistical Yearbook 2012*. China Statistics Press: 2012.
4. National Development and Reform Commission, 2013 Baseline Emission Factors for Regional Power Grids in China. In 2013.
5. Cai, W.; Wang, C.; Jin, Z.; Chen, J., Quantifying baseline emission factors of air pollutants in China’s regional power grids. *Environmental science & technology* **2013,** *47*, (8), 3590-3597.

6. Henriksson, P. J. G.; Zhang, W.; Guinée, J. B., Updated unit process data for coal-based energy in China including parameters for overall dispersions. *The International Journal of Life Cycle Assessment* **2015,** *20*, (2), 185-195.
7. Ministry of Environmental Protection, List of Desulphurization Facilities in Operation in Coal-Fired Units 2011. In Beijing, 2012.
8. Ministry of Environmental Protection, List of Denitrification Facilities in Operation in Coal-Fired Units 2011. In Beijing, 2012.
9. Ministry of Environmental Protection of China; General Administration of Quality Supervision Inspection and Quarantine of China, Emission standard of air pollutants for boiler. In 2014.
10. World Resources Institute, Greenhouse Gas Protocol Tool for Energy Consumption in China (Version 2.1). In 2013.
11. State Environmental Protection Administration of China, Cleaner production standard - Wood based panel industry (Medium density fiberboard). In China Environmental Science Press: Beijing, 2006; Vol. HJ/T315-2006.
12. China, M. o. E. P. o., Cleaner Production Standard - Wood based panel industry (Particle board). In under review.
13. Yaakob, Z.; Mohammad, M.; Alherbawi, M.; Alam, Z.; Sopian, K., Overview of the production of biodiesel from Waste cooking oil. *Renewable and Sustainable Energy Reviews* **2013,** *18*, 184-193.
14. Talens Peiró, L.; Lombardi, L.; Villalba Méndez, G.; Gabarrell i Durany, X., Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of the production of biodiesel from used cooking oil (UCO). *Energy* **2010,** *35*, (2), 889-893.
15. Elsayed, M.; Matthews, R.; Mortimer, N., *Carbon and energy balances for a range of biofuels options*. Resources Research Unit, Sheffield Hallam Univ.: 2003.
16. Enweremadu, C.; Mbarawa, M., Technical aspects of production and analysis of biodiesel from used cooking oil—A review. *Renewable and Sustainable Energy Reviews* **2009,** *13*, (9), 2205-2224.
17. Kulkarni, M. G.; Dalai, A. K., Waste cooking oil an economical source for biodiesel: a review. *Industrial & engineering chemistry research* **2006,** *45*, (9), 2901-2913.
18. Tsai, W.-T.; Lin, C.-C.; Yeh, C.-W., An analysis of biodiesel fuel from waste edible oil in Taiwan. *Renewable and Sustainable Energy Reviews* **2007,** *11*, (5), 838-857.
19. Ministry of Industry and Information Technology of China, Recycled polyester stable fiber. In China Standard Press: Beijing, 2014; Vol. FZ/T 52010-2014.
20. General Administration of Quality Supervision Inspection and Quarantine of China; Standardization Administration of China, Polyester stable fibre. In China Standard Press: Beijing, 2008; Vol. GB/T 14464-2008.
21. Ministry of Industry and Information Technology of China, Constraint standard for recycled chemical fibers (polyester). In 2015.
22. Protection, M. o. E., Cleaner production standard: Chemical fibre industry (polyester fibre). In China Environmental Science Press: Beijing, 2008; Vol. HJ/T 429-2008.
23. Avid Boustani, S. S., Timothy Gutowski, Steven Graves *Tire Remanufacturing and Energy Savings*; MIT Environmentally Benign Manufacturing Laboratory: 2010.

24. Ferrer, G., The economics of tire remanufacturing. *Resources, conservation and recycling* **1997,** *19*, (4), 221-255.
25. National Development and Reform Commission, Cleaner production assessment indicator system for tire industry (for trial implementation). In 2012.
26. Arena, U.; Mastellone, M.; Perugini, F., Life Cycle assessment of a plastic packaging recycling system. *The International Journal of Life Cycle Assessment* **2003,** *8*, (2), 92-98.
27. Perugini, F.; Mastellone, M. L.; Arena, U., A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. *Environmental Progress* **2005,** *24*, (2), 137-154.
28. Alexanderson, J., Relations between structure and mechanical properties of autoclaved aerated concrete. *Cement and Concrete Research* **1979,** *9*, (4), 507-514.
29. Narayanan, N.; Ramamurthy, K., Structure and properties of aerated concrete: a review. *Cement and Concrete Composites* **2000,** *22*, (5), 321-329.
30. Dilmore, R. M.; Neufeld, R. D., Autoclaved Aerated Concrete Produced with Low NOx Burner/Selective Catalytic Reduction Fly Ash. *Journal of energy engineering* **2001,** *127*, (2), 37-50.
31. Hu, W.; Neufeld, R. D.; Vallejo, L. E.; Kelly, C.; Latona, M., Strength properties of autoclaved cellular concrete with high volume fly ash. *Journal of energy engineering* **1997,** *123*, (2), 44-54.
32. Topçu, İ. B.; Canbaz, M., Effect of different fibers on the mechanical properties of concrete containing fly ash. *Construction and Building Materials* **2007,** *21*, (7), 1486-1491.
33. Pei-wei, G.; Xiao-lin, L.; Hui, L.; Xiaoyan, L.; Jie, H., Effects of fly ash on the properties of environmentally friendly dam concrete. *Fuel* **2007,** *86*, (7–8), 1208-1211.
34. Ministry of Housing and Urban-Rural Development of China; General Administration of Quality Supervision Inspection and Quarantine of China, Technical code for application of fly ash concrete. In China Planning Press: Beijing, 2014.
35. China, N. D. a. R. C. o., Small hollow block of fly ash concrete. In China Building Materials Press: Beijing, 2008.
36. General Administration of Quality Supervision Inspection and Quarantine of China; Standardization Administration of China, Fly ash used for cement and concrete. In China Standard Press: Beijing, 2005.
37. Commission, S. C. a. T., Practice code for application of fly ash concrete. In Shanghai, 2006.
38. Thomas, B. S.; Damare, A.; Gupta, R. C., Strength and durability characteristics of copper tailing concrete. *Construction and Building Materials* **2013,** *48*, 894-900.
39. Lohani, T., Optimum utilization of quarry dust as partial replacement of sand in concrete. *International Journal of Applied Science and Engineering Research* **2012**.
40. China, M. o. I. a. I. T. o., Cement Industry "12th Five Year" Development Plan. In 2011.
41. Ministry of Urban-Rural Development and Environmental Protection, Technical code for application of fly ash in concrete and mortar. In Beijing, 1987.

42. General Administration of Quality Supervision Inspection and Quarantine of China; Standardization Administration of China, Recycled fine aggregate for concrete and mortar. In China Standard Press: Beijing, 2010.
43. Agarwal, S. K.; Gulati, D., Utilization of industrial wastes and unprocessed micro-fillers for making cost effective mortars. *Construction and Building Materials* **2006,** *20*, (10), 999-1004.
44. Cultrone, G.; Sebastián, E., Fly ash addition in clayey materials to improve the quality of solid bricks. *Construction and Building Materials* **2009,** *23*, (2), 1178-1184.
45. Lingling, X.; Wei, G.; Tao, W.; Nanru, Y., Study on fired bricks with replacing clay by fly ash in high volume ratio. *Construction and Building Materials* **2005,** *19*, (3), 243-247.
46. Koseoglu, K.; Polat, M.; Polat, H., Encapsulating fly ash and acidic process waste water in brick structure. *Journal of Hazardous Materials* **2010,** *176*, (1–3), 957-964.
47. Ministry of Industry and Information Technology of China, The technical requirements for cleaning production of fired brick and tiles enterprises. In under review.
48. Koukouzas, N.; Ketikidis, C.; Itskos, G.; Spiliotis, X.; Karayannis, V.; Papapolymerou, G., Synthesis of CFB-Coal Fly Ash Clay Bricks and Their Characterisation. *Waste Biomass Valor* **2011,** *2*, (1), 87-94.
49. General Administration of Quality Supervision Inspection and Quarantine of China; Standardization Administration of China, Fired perforated brick and block. In China Standard Press: Beijing, 2011.
50. General Administration of Quality Supervision Inspection and Quarantine of China; Standardization Administration of China, The norm of energy consumption for unit product of sintering wall and roof materials. In 2014.
51. Samara, M.; Lafhaj, Z.; Chapiseau, C., Valorization of stabilized river sediments in fired clay bricks: Factory scale experiment. *Journal of Hazardous Materials* **2009,** *163*, (2–3), 701-710.
52. Xu, Y.; Yan, C.; Xu, B.; Ruan, X.; Wei, Z., The use of urban river sediments as a primary raw material in the production of highly insulating brick. *Ceramics International* **2014,** *40*, (6), 8833-8840.
53. Mezencevova, A.; Yeboah, N. N.; Burns, S. E.; Kahn, L. F.; Kurtis, K. E., Utilization of Savannah Harbor river sediment as the primary raw material in production of fired brick. *Journal of Environmental Management* **2012,** *113*, 128-136.
54. Zhang, X.; Zhu, X.; Zhu, A.; Zhuang, W., Study of Fired Perforated Brick with Yangtze River Sediments. In Office, J. W. M. I., Ed. 2012.
55. Cicek, T.; Tanrıverdi, M., Lime based steam autoclaved fly ash bricks. *Construction and Building Materials* **2007,** *21*, (6), 1295-1300.
56. Kumar, S., A perspective study on fly ash–lime–gypsum bricks and hollow blocks for low cost housing development. *Construction and Building Materials* **2002,** *16*, (8), 519-525.
57. Shakir, A. A.; Naganathan, S.; Mustapha, K. N., Properties of bricks made using fly ash, quarry dust and billet scale. *Construction and Building Materials* **2013,** *41*, 131-138.

58. Zhang, Z.; Qian, J.; You, C.; Hu, C., Use of circulating fluidized bed combustion fly ash and slag in autoclaved brick. *Construction and Building Materials* **2012,** *35*, 109-116.