Energy and material footprints of construction materials to inform resource and energy efficiency policy in India

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Dedication

I want to dedicate this thesis to my parents Victor León and Patricia Méndez, and to my grandmother Lidiette Rivera.

Abstract

Manufacturing of construction materials constitutes one of the most natural resource and energy intensive human activities. In industrialized countries, the construction sector represents around 50% of the whole flow of materials (Wiedmann et al., 2015). India is demanding a large volume of construction materials while the economy grows and the country becomes more industrialized and urbanized. Policies that promote resource and energy efficiency of construction materials could help lower the environmental impact of construction. However, it is essential to have metrics that allow for tracking the performance of policies.

A bottom-up methodology with an existing industrial dataset for India was used to estimate the material and energy footprint of manufacturing three of the most important construction materials: cement, steel and aluminum. The study provides additional quantitative metrics regarding energy, materials, and labor intensity.

This approach could benefit other developing countries that lack top-down input/output models. The analysis shows evidence of waste reutilization and electricity cogeneration at construction materials factories in India.

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Chapter 1: Introduction

1.1. Synopsis

This study develops and implements a new bottom-up methodology to estimate the direct and indirect material and energy requirements (i.e. footprints) for manufacturing three of the most resource intensive construction materials in India: cement, steel, and aluminum. The data, the analysis methods, and the results are relevant to both energy and resource efficiency policies such as circular economy policies. The bottom-up methodology is evaluated by estimating the bottom up energy intensity metrics and comparing them with national and international datasets/benchmarks.

1.2. Why are construction materials important?

Construction materials tend to be highly resource and energy intensive. Globally, construction minerals, metals, and wood together represent more than half of the total global material resource extraction (OECD, 2015). In the US, in terms of bulk mass of materials moving through the economy, construction materials contribute around 50% of the total (Wiedmann et al., 2015). Construction materials are also a large source of greenhouse gas emissions. Production of cement and steel alone is responsible for almost 16% of the global annual anthropogenic CO_2e emissions worldwide (Allwood, 2010). Therefore, there is a high interest in tracking metrics related to construction products and materials, for both climate and natural resources policy.

The United Nations has developed a list of Sustainable Development Goals that include responsible consumption and production, climate action, and affordable and clean energy (UNEP, 2015). Construction industries play an important role in meeting these goals. In fact, in a recent summary to the COP Paris, the UNEP IRP (International Resource Panel) emphasized that achieving climate targets is not feasible without paying attention to materials and resource efficiency. (IRP, *n.d.*).

There is increased interest by the public and private sectors, in minimizing energy use and GHG emissions from the life cycle of buildings and infrastructure. The life cycle of buildings account for almost 40% of the GHG emissions worldwide. This includes the energy and emissions related to manufacturing of construction materials. Five specific materials dominate in terms of energy usage: steel, cement, paper, plastics, and aluminum (Gutowski et al., 2013).

An analysis of the building sector in China reveals that the manufacturing of materials accounts for approximately 40% of a building life cycle emissions (Cong et al., 2013). This emphasizes the importance of reducing the materials and energy/GHG impact of buildings by using a life cycle based approach emphasizing the production of construction materials.

Life cycle approaches have been increasingly used in developing footprints. It is important to remark the distinction between an LCA of manufacturing construction materials (like the one intended in this study) and an LCA for a building or structure (Ortiz et al., 2009). These are two different units of analysis. The LCA of manufacturing construction materials are the material and energy flows involved in producing construction materials. This study estimates a “cradle-to-gate” footprint, which goes from the extraction of raw materials to the factory gate, before the construction materials are transported for sale.

A full life cycle approach considers all the stages of an economic activity: from “cradle to grave”. The full life cycle of a building for example, is taking into consideration the extraction of raw materials from nature, the manufacturing of new materials, the energy/resource from the building’s construction and during its useful life, and the demolition of the building.

A footprint refers to the system-wide impacts of an economic activity or a product in terms of energy, GHG, materials or other environmental parameters. Footprints include direct as well as indirect material, energy and pollution flows associated with a unit of analysis. Environmental footprints have been defined for different units of analysis such as: production (a specific product i.e. a TV or a toaster), consumption (i.e. households), or of regions, like cities or nations using different perspectives, such as a *Community-Wide Infrastructure* footprint (Chavez and Ramaswami, 2013). The types of footprint can also be classified by the types of environmental impacts (i.e. energy, GHG, water, land, ecosystems, pollution).

This thesis focuses on a production-based footprint of construction materials, looking at energy and materials. These types of footprints are very scarce in developing nations.

1.2.1. Construction materials in emerging economies and co-benefits of resource efficiency.

Emerging economies such as India are requiring large quantities of construction materials for new buildings, due to accelerated development and rapid urbanization (Seto et al., 2014; Ghosh and Kanijilal, 2014). This raises concerns from a sustainability stand-point, given that, as mentioned before, construction materials are very resource and energy/GHG intensive.

China is an example of an emerging economy that has experienced an accelerated demand of materials for construction and because of this, higher risks to environmental sustainability and human health (Chang et al., 2010; Li et al, 2010).

Currently, China faces many problems with increased air pollution by particulate matter (PM) which in part is generated by manufacturing of materials like cement (Lei et al., 2011). China is currently the most CO_2e emitting country in the world (IEA, 2015). The cement industry by itself accounts for approximately one eighth of China's national CO_2

emissions (Lei et al., 2011). The Chinese government has already launched strategies to decrease the impact of construction which includes promoting a circular economy. Huang et al., (2013) estimated that with a series of actions that include recycling and extending the lifetime of buildings, the impact of construction in China will be reduced considerably.

India is also undergoing important socio-economic transitions that could compromise environmental sustainability. The Gross Domestic Product of India is forecasted to continue growing steadily in the next decade (OECD, 2017), which could improve the standards of living of many people and at the same time, put large pressures on natural resources. Wiedmann et al., (2015) found that for a 10% increase in GDP a country increases its material and energy flows by around 6%. This is concerning when considering that India is the second most populated country in the world.

India is also experiencing a high rate of urbanization (Ahmad et al., 2015; Chauvin et al., 2017). Urbanization is linked to more construction and thus, to a higher demand of construction materials. For example, a material flow analysis of the city of Taipei shows an increased use of natural resources with urbanization in the decades since the 1980s due to new buildings and infrastructure (Huang and Hsu, 2003). One of the recurrent problems linked with new construction is the generation of waste (Huang et al., 2013). There are opportunities to recycle construction waste which could improve the sustainability of the construction industry (Yilmaz and Degirmenci, 2009; Pappu et al., 2007; Bravo el al., 2015)

Resource efficiency can help reduce the negative environmental impacts of the construction industry. Reusing iron and steel can avoid the LCA impact of mining iron ores (Yellishetty et al., 2011; Brimacombe et al., 2001). Cement manufacturing inputs can in many cases be replaced with more sustainable alternatives. For example, the rubber of tires and fly ash are two materials that can be used as inputs in making cement and concrete (Kumaran et al., 2008; Yilmaz and Degirmenci, 2009). All these contribute to resource efficiency.

There are important co-benefits associated with resource efficiency. More resource-efficient processes could lead to important environmental improvements, reductions in greenhouse gas emissions (Gutowski et al., 2013) and increase in the health and livability of communities.

Immediate concerns like improving air quality can be addressed by decreasing the burning of fossil fuels, which generate most of India’s power (EIA, 2016). In India, there are important local air pollution concerns. Khamaparia and Chatterje (2013) found that air quality was impaired near cement plants in Chhattisgarh, representing a risk for human health and agriculture. Some of the air pollution was generated by burning coal. Therefore, energy efficiency and shifts to new ways of producing construction materials could help to decrease pollution. This is important as the production of cement in India is forecasted to continue growing in the decade of the 2020s (Morrow et al., 2013).

1.3. Material and energy efficiency policies

Policy could promote more energy and material efficiency in the construction industry. Examples of policies for resource efficiency include economic instruments, regulation, information-based approaches, voluntary approaches, and subsidies (OECD, 2015). Policy solutions that emphasize the “3Rs”, reduce, reuse, and recycle of resources could help to decouple economic growth from negative environmental impacts (OECD, 2015).

The purpose of policies is to influence action that has been found to improve resource efficiency, for example: promoting more sustainable practices in construction materials manufacturing like: waste heat recovery (Zhang et al., 2013), increasing the use of alternative fuels (Aranda Usón el al., 2013), reducing the amount of raw material by cutting waste and increasing recycling (Augiseau and Barles, 2016) and extending the use life of materials by ensuring the quality and durability of products.

A series of abatement opportunities for the steel and cement industries have been proposed as viable energy and material efficiency solutions. These include energy efficiency measures, implementing new technologies, recycling of raw materials, and using alternative fuels (Morrow et al., 2013; McKinsey and Company, 2009). For cement manufacturing, a frequent recommendation is blending cement with less energy intensive recycled materials such as fly ash, blast furnace slag or construction demolition waste (Galbenis et al., 2006; Benhelal et al., 2013).

1.3.1. Policies in India

In India, one of the main energy efficiency policies recently implemented is called Performance Achieve Trade (*PAT*), a market-based approach that rewards energy savings in highly energy intensive industries. There are eight sectors that are covered by the Performance Achieve and Trade Policy, which are: cement, iron and steel, thermal power plants, pulp and paper, chlor-alkali, aluminum, and textiles (Dasgupta et al., 2016). These industries are directly or indirectly related to construction. Under the PAT policy, industries are required to audit their energy use by a certified auditor. This helps to establish a baseline from which the industries can make improvements. These improvements are rewarded with Energy Saving Certificates which are tradable.

There is also evidence that in India voluntary compliance by industries is having a positive outcome in reducing energy consumption and CO_2 emissions. Prasad and Mishra (2017) found that in a sample of 76 steel factories in India, 33% were complying with the standard ISO-14001, which requires measurements of environmental performances. Their regression analysis suggested a positive relationship between the voluntary compliance with ISO-14001 and better environmental performance.

One solution to make construction materials more sustainable is by substituting waste for virgin materials. Waste reutilization in India and most of Asia is common because there are lower costs associated with using waste relative to using virgin materials (Pariatamby and Fauziah, 2014). Bain et al., (2010) reported a high degree of recovery (almost 99.5%) from waste residuals generated in a business cluster in Mysore, India. From those residuals, 81% were reused by the same companies that generated them. These results suggest that the commercial/industrial sector has already realized some of the economic benefits of becoming more resource efficient.

1.3.2. Circular economy policy in China and Europe

A sustainable solution that is being discussed in India, is applying the principles of "circular economy" to industries that manufacture construction materials (EMF, 2016). The concept of circular economy refers to a model of economic development that keeps creating value from waste, which is opposed to the linear models where resources are extracted from nature and end their life cycle either disposed or incinerated. China for example, has progressed in their pursuit for a more circular economy, including this as one of their national development goals (Mathews and Tan, 2011). The Circular Economy Promotion Law in China proposes more than 200 national standards as well as actions to raise the country's resource efficiency (Briengezu and O'Brien, 2017). Similarly, countries in Europe have stablished strategies that promote circular economy. By looking at the life cycle of products, policy makers can identify stages of a material's life cycle and target that specific stage. For example, on the extraction of raw materials countries have created strategies that seek reducing the use of primary raw materials, but also reducing the impact of extracting these new raw materials. A different set of policies that look at the design of product have as an objecting extending the lifespan of products and integrating environmental aspects in a product’s design.

Singhal and Kampur (2002) proposed the development of planned industrial states as a strategy to maximize industrial ecology and reduce certain environmental harms in India. Analyzing the demand of materials from each industry could help identify potential synergies, which reinforces the need for metrics.

1.4. Need for methodologies adapted to developing countries

Sustainable production used to be tracked in nations only by using direct energy and resource use. This has shifted to indirect flows and footprint measures, recognizing the trade and supply chains are responsible for a large amount of overall resource use.

Matthews et al., (2000) in a report to the World Resource Institute highlighted that standard economic indicators at the time provided incomplete information of the environmental impact of economic activities. Hence, they proposed new metrics that provide a better understanding of the material and energy flows related to an economic activity. In their report, they analyzed the MEF of economic activities in developed countries. When “hidden” flows (what I refer to as “indirect” flows) are included in the analysis a much greater resource use was observed, providing more comprehensive metrics.

There are scattered footprints for a few industries in India. Having constant and updated benchmarks is a great tool for policy making because it allows tracking the performance of policies. Hence, this study creates baseline footprints for the year 2014 that includes direct and indirect material and energy intensity, which informs policies surrounding construction materials.

1.5. Objective of this study

The objective of this study is to develop material and energy intensity metrics for the manufacturing of a few key construction materials, cement, steel, and aluminum in the context of India. The purpose of these metrics is to inform existing and proposed policies to promote resource efficiency.

The analysis focuses on three main metrics related to the manufacturing of construction materials: Energy intensity (including primary energy and electricity), materials intensity, and labor intensity. The materials included in the analysis are Portland cement, steel, and aluminum. These materials were selected because they correspond some of the most energy-intensive materials in construction and in the whole industrial sector (Gutowski et al., 2013). The analysis includes an estimation of the indirect resource intensity from the main inputs of each of these materials.

Energy intensity is an estimation of the approximate amount of energy required to produce one unit of output. Obtaining this value for a material makes it possible to perform international comparisons and set benchmarks for energy efficiency measures. This study is to makes comparisons of the energy intensity calculated for Indian factories with other countries. Once there is an assessment of energy intensity, industries and policy makers can investigate the reasons for one country to having higher or lower intensities, and these could help identify opportunities. However, the main purpose of estimating the direct energy intensity in this study is to test the reliability of the data set.

The analysis of material intensity corresponds to the amount of a given material that goes into making one unit of the selected construction commodity. One of the questions to answer with this analysis is: to what extent is waste being utilized in the production of new construction materials? Reused materials are generally less resource intensive than virgin materials; hence evidence of waste reutilization can be an indicator of progress towards resource efficiency.

Chapter 2 provides a detailed explanation of the methodology used for analyzing the footprint of the commodities included. The chapter describes the Annual Survey of Industries, which is the dataset used for this analysis. This study uses factory-level data on inputs and outputs to construct a baseline footprint.

Chapter 3, 4, and 5 show the results of the study. Chapter 6 discusses the results observed in the study and provides some potential limitations that emerge from the methods and assumptions made. Finally, Chapter 7 describes, some conclusion made from this study.

Chapter 2: Data and Methodology

The current approach to assess material and energy footprint of construction materials is innovative way to analyze an existing dataset from India, the Annual Survey of Industries. It relies on input/output data from factories in India to make a bottom-up estimate of the material and energy footprint of manufacturing construction materials. The methodology is corroborated by benchmarking the results with similar national and international metrics.

This study also provides metrics on waste reutilization. Doing energy and materials with attention to recycling is a new approach for India.

2.1. Existing Life Cycle Inventories

In the United States, the National Renewable Energy Laboratory (NREL) created a database of inter-industry material and energy demands for an extensive list of commodities: The Life Cycle Inventory Database provides an inventory of the material and energy flows associated with the different steps in the production of a product which facilitates making Life Cycle analysis for the US economy. “EcoInvent” is an example of a similar “life cycle inventory” in Europe. However, many developing countries including India, lack these types of resources. It is important to find methods that could help to estimate footprints taking into consideration the data available in developing countries.

2.2. Annual Survey of Industries

The methodology of this study relied on the Annual Survey of Industries (ASI) which is a survey administered by the Central Statistics Office of the Indian Minister of Statistic and Program Implementation. The ASI is the main source of industrial data for India.

The survey is mandatory for all industrial plants in India registered under section 2(m)(i) and 2(m)(ii) of India’s Factories Act, 1948, which means that it includes all industries in the six least populated states of India, and all factories in all other states that have more than one hundred workers. It contains data on individual industrial units for all of India catalogued at the state level. The unit of analysis is the factory. The reference period of the survey was from April 1st, 2012 to March 31st, 2013. Factories are classified under industries based on their main activity. The data available through the survey ranges from the commodities manufactured, energy and material inputs of each factory, to labor related statistics.

The ASI reports the 10 biggest inputs to a factory. The commodities in the dataset are classified using the NPCMS (National Product Classification for Manufacturing Sector). These inputs are reported by their total amount (ex. Metric tons or kg) and by purchase value in rupees.

The dataset contains a total of 50,561 factories from 686 different industries. There are 5,700 different commodities reported as either inputs or outputs of the factories. Energy is reported with all the other commodities as type of fuel or electricity. Raw materials, processed materials inputs, and waste materials inputs reuse are also identified along with the labor and sale value of the products.

There are previous studies that have utilized data from the ASI in different ways. However, using the data for energy and material footprinting has not been done before; this constitutes an innovative approach for analyzing the data from the survey.

Mukherjee (2008) compared the direct energy efficiency of manufacturing sectors across states using the ASI for the years 1998-99 to 2003-04. Mukherjee study looks at the energy intensity of whole industries and not to specific commodities. The model relied on economy inputs and outputs rather than amount of materials or energy.

Dasgupta and Roy (2015) made a comprehensive analysis of the energy demand behavior of manufacturing industries in India using the ASI. They estimated the average annual growth in the manufacturing sector (in terms of capital, labor, direct energy and materials) of industries that are included in the Performance Achieve Trade (PAT) policy. They found that technological progress and changes in the retail price of energy have contributed to an increase in the energy productivity of industries. Other authors have also used the ASI data to answer policy questions surrounding the electricity supply and its effect on the industrial sector (Allcott et al., 2016).

The ASI has been used to answer questions related to labor (Hsieh and Klenow, 2014), economic growth and allocation of government resources (Asher and Novosad, 2017), productivity growth (Bollard et al., 2012), spatial development of India (Desmet et al., 2015) among other topics relevant to the industrial sector in India.

2.3. Construction materials analyzed

The commodities analyzed in this study were selected using two criteria: 1) the materials are used for construction and 2) they constitute some of the most energy and material intensive materials in the construction sector (Gutowski et al., 2013). A key challenge is that many industries make more than one type of commodity, because if factories manufacture more than one product, the inputs of the factory have to be allocated to the different products. Therefore, a key aspect of the methodology is that only factories that had one output commodity were selected for analysis and this reduces the sample size significantly, as shown below.

Table 2.3.A: List of commodities included in the analysis.

Commodity	**Number of factories analyzed**
Ordinary Portland Cement	39

Cement Clinkers (*only direct*)	12
Non-alloy Steel	50
Aluminum in Ingots	14

The metrics estimated include: direct primary energy intensity, electric intensity, material intensity (with an estimate of percent waste reutilized), and direct labor intensity (mostly for benchmark purposes).

2.3. Direct primary energy intensity and electric intensity

Direct primary energy intensity refers to calculating the primary energy input per unit of output for the industrial process of interest, in this case manufacturing of construction materials; this does not include energy used upstream or downstream of the factory such as energy embodied in input materials.

The ASI provides the necessary information to make energy intensity estimation because it reports the amounts of fuels and electricity used by a factory. Given that these energy inputs are provided in different units and types (ex. kg of natural gas), conversion factors must be applied to obtain the primary energy amount.

Equation A: To estimate the direct primary energy intensity of a commodity.

$$D = \frac{\sum[F_x * H_x] + [P]}{Total\ Ouput\ of\ Factory}$$

D = Direct primary energy intensity (GJ/output)

F_x = Amount of a fuel input X

H_x = Heat value of the fuel input X (GJ/unit)

P = Primary energy equivalent of electricity input (GJ)

<u>Equation B</u>: To estimate the primary energy equivalent of direct electricity input of a commodity.

$$P = \frac{[T * C]}{E}$$

P = Primary energy equivalent of electricity input (GJ)

T = Total Electricity Input to Factory (kWh)

C = Conversion Factor of kWh to Gigajoules (0.0036 GJ/kWh)

E = Assumed Efficiency of Thermal Plants in India

These are the most common input energy sources reported in the dataset:

1. *Electricity:* ASI reports both purchased and own-generated electricity consumed by the factory in kWh. To calculate the primary energy intensity, electricity has to be converted to a primary energy unit. The efficiency rate of thermal plants in India was assumed to be 33% based on a report by (Bhawan and Puram, 2014). This means that three times as much energy is required to generate the end use electricity. The assumed calorific value of direct electricity was assumed to be

0.0036 GJ/kWh.

2. *Coal:* Coal is the largest industrial fuel used in India (EIA, 2016). Coal is reported by ASI in metric tons consumed. The survey asks factories to report separately coal that is used for energy and coal that goes into the composition of the manufactured commodity. The assumed calorific value of coal is 30 GJ/t.
3. *Natural Gas:* Natural gas was reported in kilograms. The calorific value of natural gas used was 0.0532 GJ/kg.

2.4. Materials intensity

Material intensity refers to the estimated amount of materials that goes into making a unit of a different product. The ASI provides a list of the top ten inputs and the associated outputs of factories in India, which facilitates this analysis.

For instance, it is possible to know the amount of limestone that was consumed by a factory that makes cement. These input commodities were categorized into broad categories for the analysis as described below to be consistent with the MFA accounting literature.

1. *Coal/Petrochemicals**:*** This category contains most chemicals, synthetic chemicals and coal that are not used for generation of heat.
2. *Metals:* Any material composed mostly of metallic element(s). This includes metal

ores.

3. *Non-Metallic Minerals:* Any commodity that comes mostly from minerals that are non-metallic, for instance, sand or gravel.
4. *Biomass Food:* Any food commodities.
5. *Biomass Fiber:* Any commodities that come from plants or animals but are not considered food, for example, wood.
6. *Waste Reutilized:* Some commodities were directly reported as waste. Others were classified into waste based on their description. For example, scrap iron can be assumed to be a waste material that is used for recycling even if by its composition, it is a metal.

2.5. Energy and materials footprints of manufacturing construction materials

The resource intensity of materials based on direct inputs and outputs to factories only captures part of the energy and materials that go into making a commodity. To obtain a. full systems LCA of resources and energy used to make products, it is necessary to estimate the “inputs to make inputs”.

The approach of tracking multiple rounds of inputs eventually leads to the *Leontief Matrix* which is an estimation of the *total requirements* of a sector of the economy from other sectors of the economy (Waugh, 1950). This matrix allows making estimations of the flows of materials and energy among industries in an economy.

Multiple rounds of inputs might have to be estimated until the only inputs are natural resources. For construction materials, this meant doing two rounds of calculations. There were only a few materials that constitute most of the bulk input of making construction materials, for example, the limestone that goes into making cement. Most of them were natural resources. Only virgin materials are included in the indirect analysis. Materials categorized as “waste reutilized” were not included because they are being recycled.

The tracking of upstream inputs (in the second round) was conducted for the largest material/energy streams that represent the top 90% of total inputs (in the first round).

2.6. Direct labor intensity

The labor intensity of the analyzed commodities was estimated from the reported average number of workers of each factory. This metric was calculated as another benchmark for the data.

The ASI requires that each factory reports the average number of employees working at the factory during the reference year. The relation between the outputs of factories and the average number of employees was estimated for each of the commodities.

Chapter 3: Cement

3.1. What is cement?

Cement is a binder powder used in construction that is made primarily from limestone and other materials such as silica, clay, chalk, and gypsum. Cement is one of the ingredients used to make concrete. Concrete is the name given to the solid material that is obtained from mixing and letting cement set with other materials such as stone, gravel or sand and water. The most common type of cement used around the world is Ordinary Portland Cement (OPC) (Sonebi et al., 2016).

3.2. How is cement made?

The process of making cement starts with the extraction of raw materials, mostly limestone that is found in natural deposits. Limestone is mined and crushed into smaller pieces that are taken to cement plants. At the cement plant, the limestone is mixed with other materials in smaller proportions (clay, silica among others) and heated to high temperatures, which leads to the chemical reaction that forms Portland Cement Clinkers. Clinkers are marble sized stones that are later pulverized along with gypsum to obtain the OPC dust. After that, OPC can be sold for construction. Some manufacturers blend the OPC with other supplementary materials; in such cases the final product is referred to as blended cement. Figure 3.2.A shows a diagram summarizing the cement manufacturing process.

Figure 3.2.A: Diagram of the basic steps involved in manufacturing OPC.

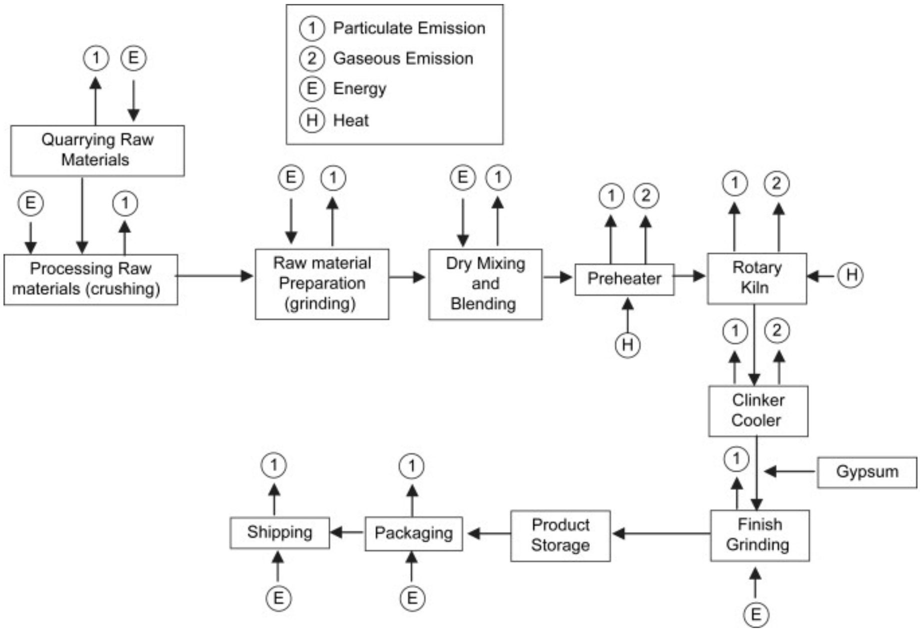


Figure from Hutzinger and Eatmon (2008)

3.3. Methodology overview

The energy and material intensity of manufacturing Ordinary Portland Cement (OPC) was estimated from a sample of 42 factories. The same analysis was done for cement clinkers with a sample of 12 factories.

OPC is different from blended cement. Some manufacturers mix OPC with other materials once it is finished which, in many circumstances, does not affect the quality of the product when sold. The output reported by factories in the sample was OPC (not blended cement). However, there was evidence from the inputs reported that some of the factories in the sample were blending their cement with other materials, which makes it blended cement. To account for this, the weight of some inputs that affect the purity of OPC had to be subtracted from the estimated total output of cement. This guarantees that the product being analyzed is pure OPC.

The OPC factories included in the sample were selected based on two criteria:

1) They were only producing OPC as their output and hence there are not issues with the allocation of inputs into multiple products.
2) They did not report cement clinkers as one of their inputs, which means that the energy consumption reported should capture the procedure of making the cement clinker, but excludes the quarrying of raw materials.

Similarly, for the cement clinker analysis, factories were selected when they only had clinkers as an output. Factories that reported using clinkers as an input to make clinkers (as an output) were also removed from the sample.

3.4. Summary of the analysis

Table 3.4.A: Summary of the inputs of materials, energy, and labor for the total output of Ordinary Portland Cement from the factories in the sample.

Product: Ordinary Portland Cement n = 39 Total Quantity Manufactured = 37,254,484 t		**Amount per 1000 metric tons**
Output	Economic Value (Sale Price) (US Dollars)	73,955
Material and Energy Inputs	Coal/Petrochemical (t)	36 (direct) + *91 (indirect)*
	Metal (t)	24 (direct)
	Non-Metallic Mineral (t)	1,323 (direct) + *4,401 (indirect)*
	Energy - Electricity (tons of coal equivalent)	*25 (indirect)*
	Energy - Coal (t)	185 (direct) + 590 (indirect)
	Waste Reutilized (t)	154 (direct)
Labor Input	Average Number of Employees	0.6

Table 3.4.B: Summary of the inputs of materials, energy and labor for the total output of cement clinkers from the factories in the sample.

Product: Cement Clinkers n = 12 Total Quantity Manufactured = 2,763,956 t		**Amount per 1000 metric tons produced**
Output	Economic Output (US Dollars)	51,528
Material and Energy Inputs	Coal/Petrochemical (t)	8
	Metal (t)	28
	Non-Metallic Mineral (t)	1,340
	Energy - Electricity (tons of coal equivalent)	32
	Energy - Coal (t)	116

	Waste Reutilized (t)	42

3.5. Electric intensity of manufacturing cement

The obtained average electricity intensity per metric ton of OPC was 98.04 kWh/t.

In the case of cement clinker, the electricity intensity was 88.38 kWh/t of clinker.

Some cement plants in India generate their own electricity to supplement the electricity purchased from the grid. From the sample of 39 OPC plants, 17 were generating their own electricity and all of them were consuming electricity from the grid. From those plants generating electricity, their own generation accounted for an average of 28% (s = 3%) of the total electricity demand of the factory.

Jankovic et al., (2004) reported the approximate electrical energy consumption in cement production to be 110 kWh/t of OPC. Taylor et al., (2006) reported the electricity directly used to manufacture cement in India to be approximately 90 kWh/t in 2001.

3.6. Direct primary energy of manufacturing cement

The primary energy intensity obtained was 6.62 GJ/t of OPC.

Table 3.6.A. Compares the obtained direct energy intensity of OPC with the one obtained for other countries as reported in the literature.

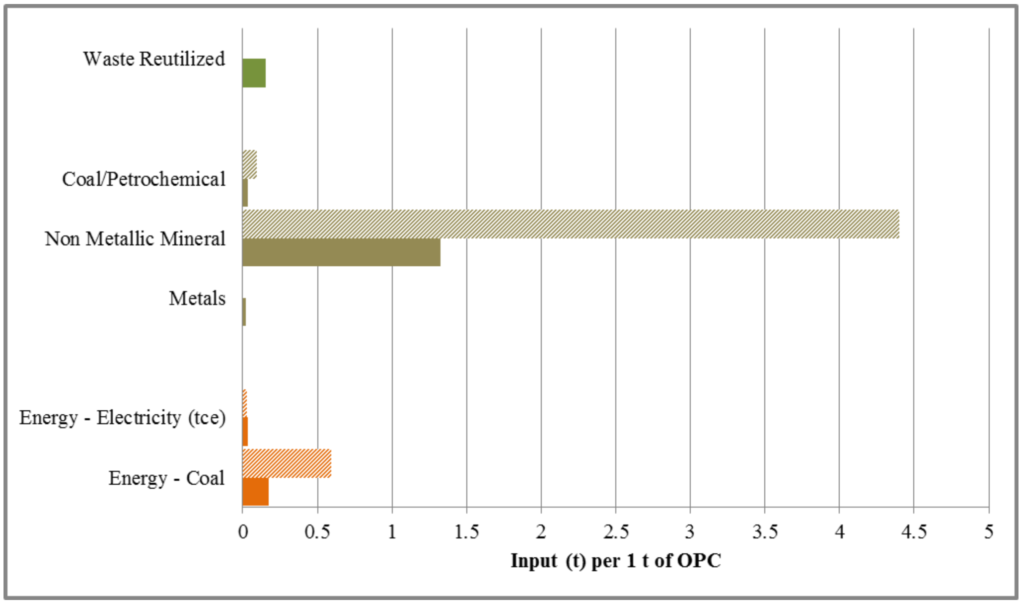
Country	**Year**	**Energy Intensity (GJ/t cement)**
India (this study)	***2013-2014***	***6.62***
Nigeria *(Ohunakin et al., 2013)*	2003-2011	4.20
United States *(Worrel, 2001)*	1994	5.50
China *(Worrel, 2001)*	1994	5.00

3.7. Material intensity of manufacturing cement

Approximately 1.5 metric tons of material inputs were directly required to produce 1 metric ton of cement.

Among the top 90% of the total materials/energy inputs required to make OPC were: limestone, clay, gypsum, and coal.

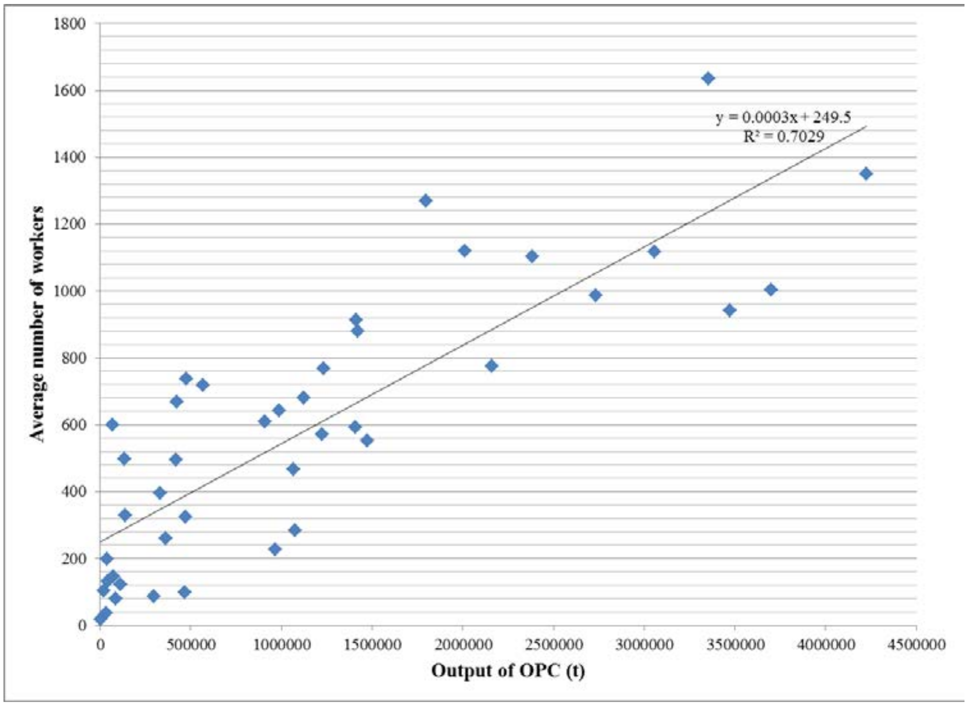
Figure 3.7.A: Broad categories of inputs in metric tons for each metric ton of OPC produced. The solid colors represent the direct inputs. The dashed lines represent the indirect “second round” inputs.



3.8. Labor intensity of manufacturing cement

ASI requires that factories report the average numbers of workers in the plant during the year surveyed. Figure 3.8.A shows the relation between the average number of workers and the output of OPC (metric tons) of the factories in the sample. The average number of metric tons of OPC per worker was 1780.

Figure 3.8.A: Relation between labor (average number of workers) and the output of OPC from the factories in the sample.


1800
1600
1400
1200
1000
800
600
400
200
0
Average number of workers
y = 0.0003x + 249.5
R² = 0.7029
0
500000
1000000
1500000
2000000
2500000
3000000
3500000
4000000
4500000
Output of OPC (t)

Chapter 4: Steel

4.1. What is iron and steel?

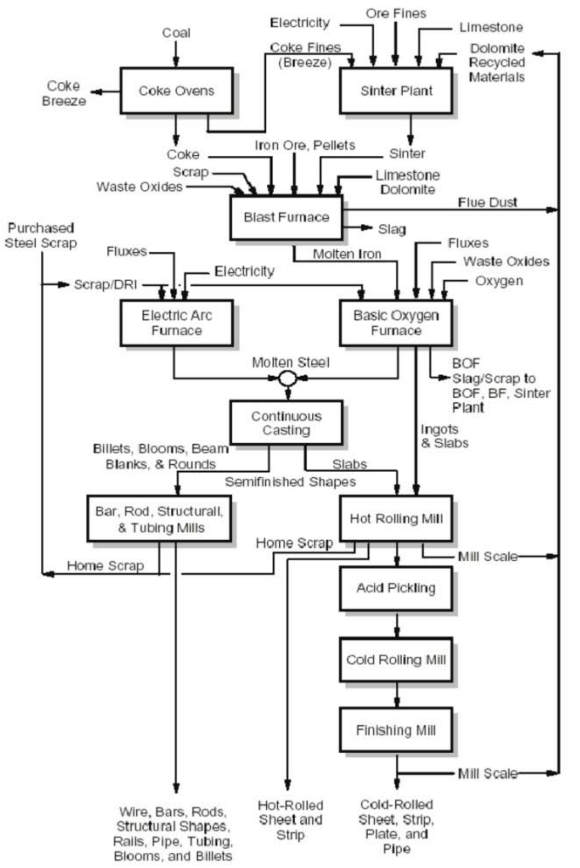
Iron is a metallic element that is highly abundant in nature which is used for many purposes in construction. Iron is the main component of steel, which is an alloy (mixture) that contains mostly iron with small portions of carbon. Steel is mostly used as a structural material.

4.2. How is steel made?

The process of making primary steel starts with the smelting of iron ores. Iron ores are rocks that are mined in nature and that contain important amounts of iron. These are heated along with chemical agents that help to separate the iron from impurities. The result of smelting the ores is an intermediary material which is called pig iron. At this point the material is not ready for construction purposes, given that it has high carbon content and it breaks easily. The pig iron is heated again. Oxygen is blown in to the molten pig iron, which reduces the amount of carbon until this finally becomes steel. An alternative path for making steel is using waste steel and melting it to make new recycled steel. This is much less energy intensive, since it skips the mining and the making of pig iron.

The difference between alloy and non-alloy steel is that, alloy steel is made by combining iron with other metals such as aluminum. Non-alloy steel is when there are no additional metals added to the iron during the smelting. Steel is molded and sold in many forms depending on its function in construction.

Figure 4.2.A: Diagram of the basic steps involved in manufacturing steel.



Source: Adapted from U.S. Council on Wage and Price Stability, *Report to the President on Prices and Costs in the United States Steel Industry, 1977* (COWPS, October 1977).

Figure from Fazel Zarandi et al., (2010)

4.3. Methodology overview

The material and energy intensity was estimated for the manufacturing of non-alloy steel in ingots from a selected 50 factories in India.

Alloy steel was not selected because this material is combined with other metals in varying proportions, which could confound the analysis of materials and energy intensity. Non-alloy steel does not contain other metals hence it is more appropriate for the analysis.

4.4. Summary of the analysis

Table 4.4.A: Summary of the inputs of materials, energy and labor for the total output of non-alloy steel from the factories in the sample.

Product: Non-alloy steel in ingots n = 50 Total Quantity Manufactured = 952,152 t		**Amount per 1000 metric tons produced**
Output	Economic Output (US Dollars)	525,746
Material and Energy Inputs	Biomass Fiber (t)	2 (direct)
	Metal (t)	524 (direct) + 424 (indirect)
	Non-Metallic Mineral (t)	8 (direct) + 145 (indirect)
	Coal/Petrochemical	831 (indirect)
	Energy - Electricity (tons of coal equivalent)	133 (direct) + 10 (indirect)
	Energy - Coke (t)**	165 (direct)

	Energy - Coal (t)	8 (direct) + 82 (indirect)
	Energy - Natural Gas (tons of coal equivalent)	1 (direct) + 23 (indirect)
	Waste Reutilized (t)	354 (direct) + 4 (indirect)
Labor Input	Average Number of Employees	3.34

** Coke is used both as an ingredient of steel and as a source of heat.

4.5. Electric intensity of manufacturing steel

The estimated electricity intensity of making one metric ton of non-alloy steel was 661.103 kWh/t (n = 50).

The values obtained for the year 2006 in a different study by Hasanbeigi et al., (2014) were: 675.8 kWh/t in the United States and 431.7 kWh/t in China.

8 out of 50 plants were generating their own electricity. From those plants generating electricity, their own generation accounted for an average of 6% (s = 9%) of the total electricity demand of the factory.

4.6. Direct primary energy intensity of manufacturing steel

Non-alloy steel primary energy intensity in India was calculated for steel manufacturing plants (n = 50).

Table 4.6.A: Lists some international comparison for energy intensity of steel manufacturing.

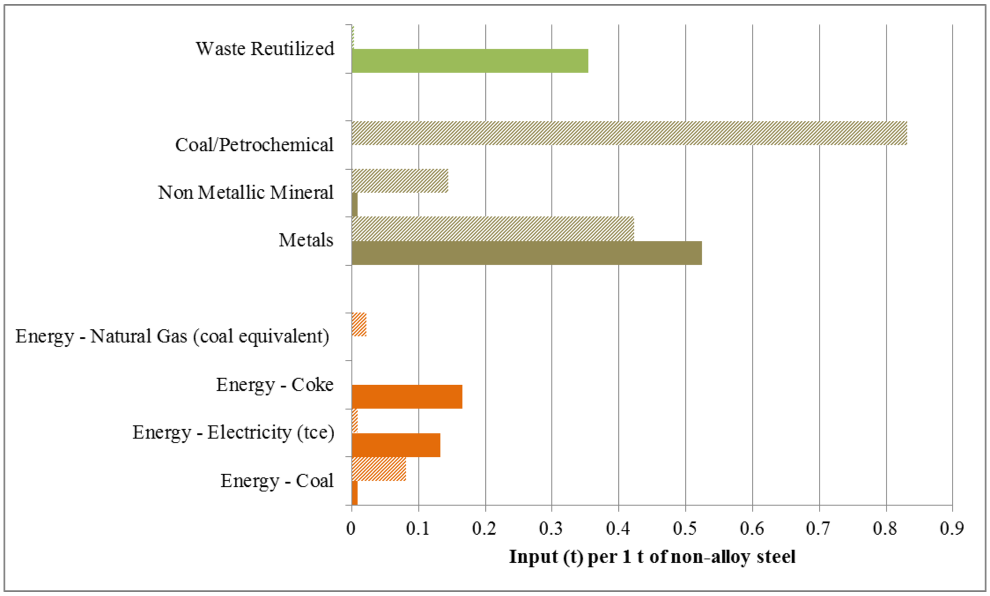
Country	**Year**	**Energy Intensity (GJ/t of steel)**
India (this study)	***2013-2014***	***12.39***
United States *(Hasanbeigi et al., 2014)*	2006	14.24
China *(Hasanbeigi et al., 2014)*	2006	19.01

4.7. Material intensity of manufacturing steel

The material intensity of non-alloy steel was estimated for the sample of 50 factories. Figure 4.7.A. shows the main inputs of making one metric ton of non-alloy steel in ingots. The dashed lines show the indirect material intensity from the manufacturing of top 90% materials.

Among the biggest materials/energy inputs required to make non-alloy steel were: scrap steel, iron ores and electricity.

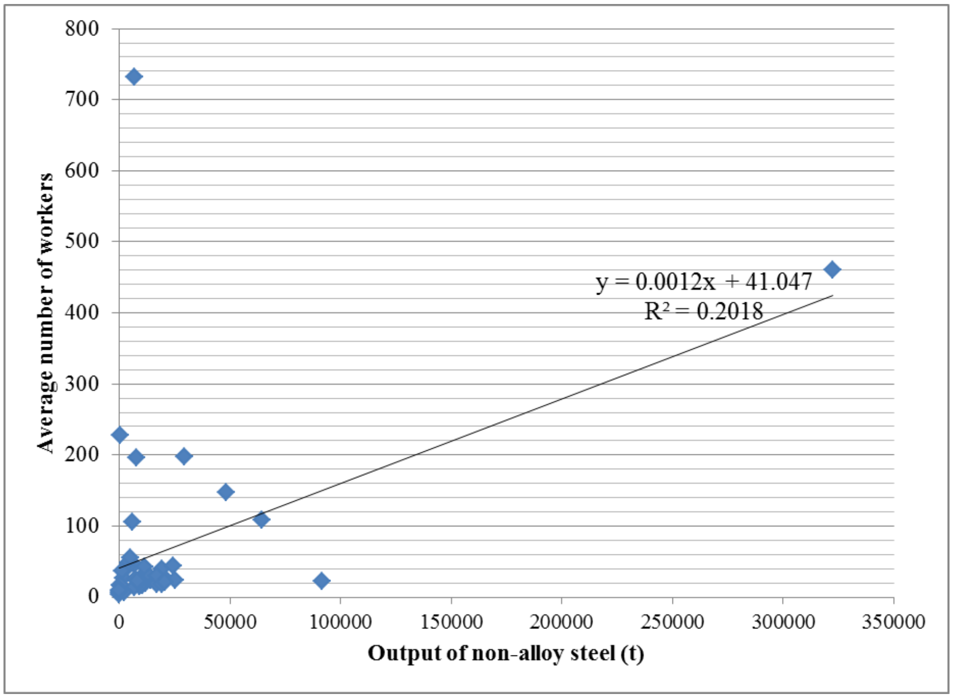
Figure 4.7.A: Broad categories of inputs in metric tons for each metric ton of non-alloy steel produced. The dashed lines represent the indirect footprint of each material per ton of output.



4.8. Labor intensity of manufacturing steel

The number of tons of non-alloy steel per worker was 3.34.

<u>Figure 4.8.A</u>: Relation between labor (average number of workers) and the output of non-alloy steel from the factories in the sample.


800
700
600
500
400
300
200
100
0
Average number of workers
0
50000
100000
150000
200000
250000
300000
350000
Output of non-alloy steel (t)
y = 0.0012x + 41.047
R² = 0.2018

Chapter 5: Secondary Aluminum

5.1. What is aluminum?

Aluminum is a metallic element that is used for many purposes in construction, but mostly as a structural material. The extraction of aluminum from nature is an energy intensive process. However, aluminum can be recycled without losing its quality. Manufacturing recycled aluminum requires much less energy (Morris, 1996).

5.2. How is aluminum made?

Aluminum is not commonly found pure in nature. It must be extracted from ores in natural deposits, mostly bauxite which contains aluminum hydroxide ($Al(OH)_3$). India's bauxite deposits are around 5% of the total world deposits (TERI, 2009). Aluminum hydroxide goes through a series of chemical reactions which require heat and pressure to make alumina (Al_2O_3) in what is known as the Bayer process. Alumina becomes aluminum metal by the Hall-Héroult process which is also energy intensive. The resulting product is called primary aluminum. However, since aluminum is a recyclable material, in many cases new aluminum is made from recycled waste. When aluminum is made from recycled materials, it is called secondary aluminum. Secondary aluminum can be around 95% more energy efficient than primary aluminum (The Aluminum Association, 2011). Secondary aluminum making involves the re-melting of the scraps and the casting of the new recycled material.

5.3. Methodology overview

The energy and material intensity of manufacturing secondary aluminum ingots was estimated for a sample of 14 factories in India.

Secondary aluminum was selected because there was more data available. There are also previous estimates of primary aluminum energy intensity for India.

5.4. Summary of the analysis

Table 5.4.A: Summary of the main inputs and economic output of manufacturing 1000 metric tons of aluminum in ingots.

Product: Secondary Aluminum in Ingots n = 14 Total Quantity Manufactured = 57,732 t		**Amount per 1000 metric tons produced**
Material and Energy Inputs	Coal/Petrochemical (t)	360 (indirect)
	Metal (t)	116 (direct) + 93 (indirect)
	Energy - Electricity (tons of coal equivalent)	45 (direct) + 10 (indirect)
	Energy - Natural Gas (tons of coal equivalent)	65 (direct)
	Energy - Coal (t)	120 (direct) + 18 (indirect)

	Waste Reutilized (t)	1624 (direct) + 94 (indirect)
Labor Input	Average Number of Employees	12

5.5. Electric intensity of manufacturing secondary aluminum

The electricity intensity of manufacturing secondary aluminum in ingots was estimated to be 127 kWh/t of aluminum.

Manufacturing of secondary aluminum is significantly less energy intensive than primary aluminum production. TERI (2009) reported an approximation of the electric intensity of primary aluminum to be 14,000 to 17,000 kWh/t.

4 out of 14 plants were generating their own electricity. From those plants generating electricity, their own generation accounted for an average of 29% (s = 20%) of the total electricity demand of the factory.

5.6. Direct primary energy intensity of manufacturing secondary aluminum

The primary energy of manufacturing secondary aluminum in ingots was 6.98 GJ/t (n = 14).

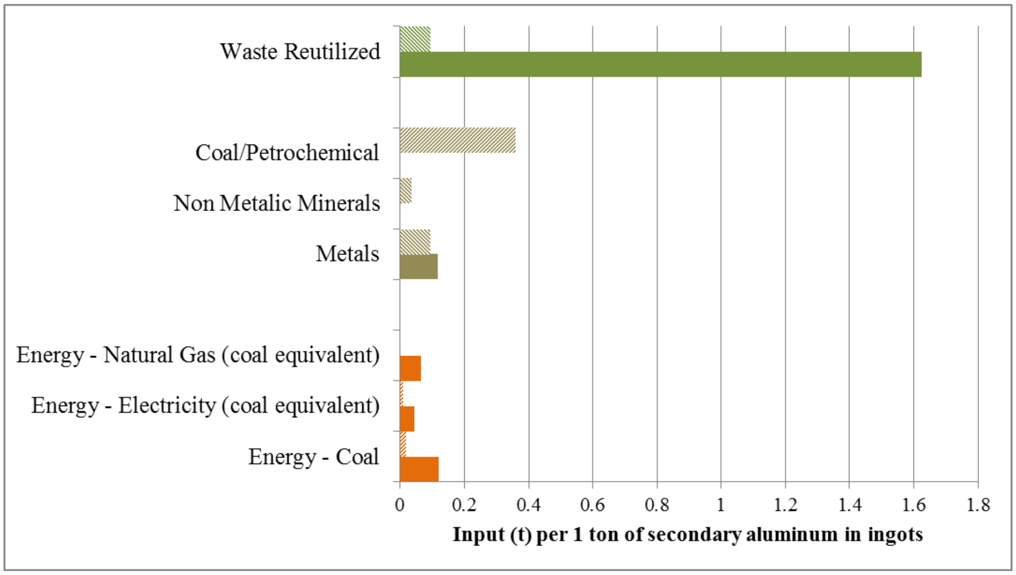
Approximately 20% of the energy input was electricity, 50% was coal, and 30% was natural gas.

5.7. Material intensity of manufacturing secondary aluminum

The material intensity of secondary aluminum in ingots was estimated for the sample of 14 factories. Figure 5.7.A. shows the main inputs of making one metric ton of aluminum in ingots. The dashed lines show the indirect material intensity from the manufacturing of the main direct input materials (>90% of the total).

Among the main materials/energy inputs required to make secondary non-alloy steel were: metal scraps, electricity, and natural gas.

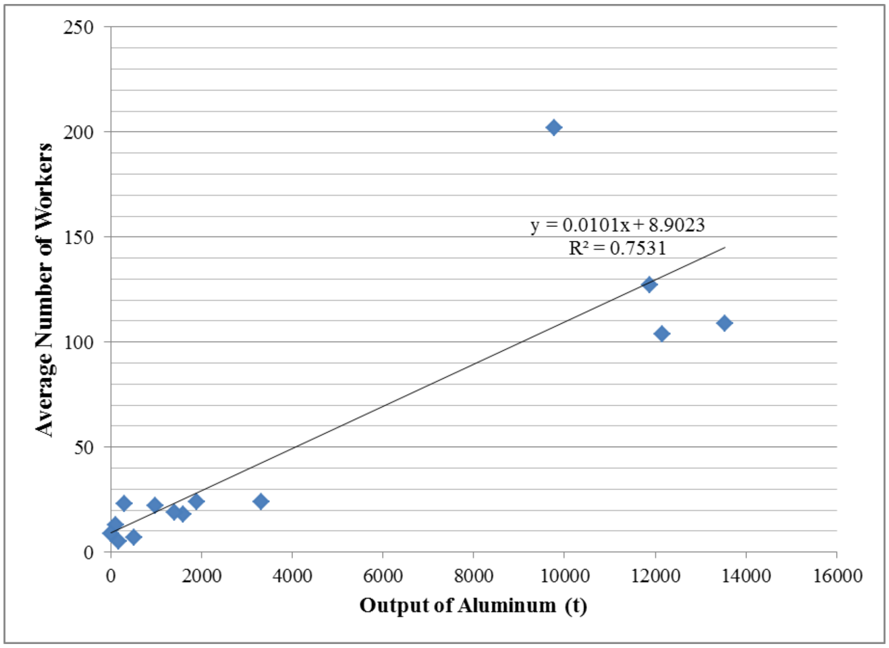
Figure 5.7.A: Broad categories of inputs in metric tons for each metric ton of secondary aluminum produced.



5.8. Labor intensity of manufacturing secondary aluminum

The number of tons of secondary aluminum per worker was 82 (n = 14).

<u>Figure 5.8.A:</u> Relation between labor (average number of workers) and the output of non-alloy steel from the factories in the sample (n = 14).


250
200
150
100
50
0
Average Number of Workers
0
2000
4000
6000
8000
10000
12000
14000
16000
Output of Aluminum (t)
y = 0.0101x + 8.9023
R² = 0.7531

Chapter 6: Discussion

6.1. Main findings

The current study has estimated the direct and indirect material/energy footprint of manufacturing three construction materials: ordinary Portland cement, non-alloy steel and secondary aluminum in India using data from the Annual Survey of Industries and a new proposed bottom-up methodology. Additionally, the study has provided quantitative metrics on energy intensity, material intensity, and labor intensity for the materials, which could be used to inform policies related to resource efficiency.

Material and energy efficiency policy is important for a more sustainable construction industry, which is forecasted to grow as the global population increases and demands more resources. It is essential for policies to have metrics which allow tracking their effect. Energy and material footprints have been used as a measure of the impact of construction materials from their life cycle. In India, metrics about the direct material and energy flows of construction are available. However, footprints that look at indirect flows are scarce, partially because there are not proper life cycle inventories or input/output models that facilitate estimating inter-industry demand. This study has suggested an approach to estimate the footprint of commodities using data that is accessible and yearly updated through the Indian government.

Construction materials generate a large percentage of GHG emissions (Allwood, 2010). Hence, it is important to prioritize strategies that could decrease their energy and materials footprint. The proposed methodology and the data set that informs this analysis have been corroborated for the most part with existing metrics for other countries.

6.2. Other findings

The analysis provides evidence that some manufacturers of ordinary Portland cement, steel and secondary aluminum in India are taking advantage of practices that are more sustainable and potentially cost saving such as: waste reutilization and electricity co-generation.

Waste reutilization decreases the need for virgin materials, which generally require more energy and resources to be obtained. Metal recycling for example, can significantly decrease the energy intensity required for making new metals. Electricity co-generation means that factories might take advantage of their heat generation to produce electricity, which is a good indicator of energy efficiency. For the sample of cement factories, the co-generation of electricity satisfied around 28% of the total electric demand. Co-generation of electricity could also lead to more resource efficiency if conventional fuels are substituted with alternative fuels like waste biomass (Aranda Usón et al., 2013).

The use of alternative recycled materials has repeatedly been suggested as one of the most promising solutions to make cement more sustainable (Schneider et al., 2011). One waste material that was utilized in the manufacturing of cement was fly ash. Fly ash is typically combined in the concrete mix to substitute some of the Ordinary Portland Cement. Mixing fly ash and cementitious content has lower CO2e emissions and embodied energy and makes a material that meets the strength and durability requirements of concrete (Liu et al., 2012). Other studies suggest viability of using construction and demolition waste to substitute some of the materials that go into making cement clinkers (Galbenis and Tsimas, 2006). These are examples of strategies that could be induced by policy and tracked with a bottom-up approach for material and energy footprints.

6.3. Study limitations

There are limitations with the current analysis. Some of the limitations derive from the ASI data collection methodology while others are inherent in the assumptions made to perform this analysis.

6.3.1. Sample selection and size

One potential limitation of this study is that factories were selected when they had only one output, and not selected when they had multiple outputs. The ASI reports the most important outputs of factories, which in many cases is more than one. It was decided to keep factories that were manufacturing only the construction material of interest. This was to avoid making assumptions about input allocation to different outputs. It is probable that the results would have been different if factories with more than one output were included in the sample. Some factories were also reporting their waste as an output.

6.3.2. Limited list of fuels for energy

It could be that some of the waste materials reported as inputs were being used for combustion, to generate heat for some of the industrial processes involved in the manufacturing of the analyzed materials. However, the survey does not tell whether a material (other than a limited list of fuels) is used for generation of heat. For example, if waste biomass is used to generate heat, this cannot be known.

6.3.3. Lack of reporting of water

Another limitation was the lack of reporting of water as an input material. To manufacture almost any commodity, water is required. However, this resource was scarcely reported in the ASI. A recommendation to improve the data collection would be to ask specifically for the water input that goes into factories. This would help to answer questions about the water intensity of construction or any other sector.

6.3.4. Electricity generated at facility

To estimate the primary energy of the analyzed commodities, electricity was converted to joules using a set of assumptions. The electricity generated at the factories was assumed to come all from coal. However, this might not be always the case. Additionally, some inputs that were not initially classified by the survey as fuel for heat generation were identified as such, as in the case of coke and fuel oil.

6.3.5. Truncation

One of the limitations often attributed to bottom-up process-based Life Cycle Assessments is that they often lead to incomplete models that tend to underestimate the actual resource (or energy) requirements of a unit of analysis at upstream stages of the supply chain. In other words, bottom-up approaches result in lower estimates of the indirect material and energy flows. This is known as the “truncation error” or “truncation bias” (Lewandowska and Foltynowicz, 2004). It occurs because it is not feasible to make a complete Life Cycle Inventory of an entire economy. There are flows that are not captured even with very detailed inventories. This could be the case in the current analysis. Only one additional round of inputs was calculated to obtain the indirect materials and energy. This was considered appropriate as construction materials tend to be close to the extraction of raw materials when looking at their supply chains.

6.4. Recommendations to improve data collection and future work

The Indian authorities that implement the ASI could improve the design of the survey to facilitate bottom-up footprinting. One simple way is by asking for more specificity in the sections of the survey to ask for the inputs and outputs of a factory.

As mentioned before, one of the limitations is that the survey provides limited list of materials that are distinguished as fuels. To have an accurate estimation of the energy intensity and waste reutilization of factories, it would be helpful to know if any biomass (or any waste material) is burned. There are non-conventional fuels that are reported with the direct inputs (without distinguish them as fuels) and this makes it hard to know if these are indeed used fuels or part of the composition of the material. One suggestion is to ask to specify which inputs are used for fuel.

Future studies could try to make an estimate of the greenhouse gases footprint of manufacturing construction materials by using the energy and material intensity metrics and making calculations about the emissions from the direct and indirect processes involved. This could help inform Indian policy on climate change.

Chapter 7: Conclusion

India’s demand for construction materials increases as its economy grows. This has raised concerns about the impact of manufacturing construction related materials on the environment because these tend to be very energy and natural resource intensive.

Policies could improve the sustainability of construction related industries. Nevertheless, proper policy making requires quantitative metrics that take into consideration not only the direct but the indirect or “hidden” flows of energy and materials. This study has proposed a methodology to estimate the material and energy footprint of construction materials in India. A bottom-up approach was tested using three of the most energy intensive construction materials: cement, steel and aluminum. The methodology was benchmarked using national and international comparison for metrics such as direct energy intensity, material intensity and labor intensity.

Given that the results for this metrics are in the most part, consistent with the benchmarks, the proposed bottom-up methodology can be a good alternative for countries that lack life cycle inventories or input output models if they have (or could implement) a similar survey.

Additionally, there is evidence that Indian factories are using reutilized waste in manufacturing new construction materials. Reusing waste means that less virgin materials must be extracted from nature. In the case of metals, it means important reductions in energy consumption from avoiding the smelting of ores.

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Appendix

Table A.1: Frequency of inputs (shown as a percentage) for manufacturing Ordinary Portland Cement from the sample of 39 factories.

Input commodity	Classification	Unit	Frequency
Electricity purchased	Energy - Electricity	kWh	100%
Gypsum	Non Metallic Mineral	Kg	87%
Lime stone	Non Metallic Mineral	Metric ton	82%
Coal consumed	Energy - Coal	Metric ton	74%
Coal ash	Waste Reutilized	Metric ton	64%
Electricity own generated	Energy - Electricity	kWh	38%
Coal	Coal/Petrochemical	Metric ton	28%
Ash and residue (except from the manufacture of iron or steel), containing metals or metallic compounds, except precious metals	Waste Reutilized	Metric ton	21%
Iron ores	Metals	Metric ton	21%
Iron ores, Hematite	Metals	Metric ton	18%
Bauxite raw	Metals	Metric ton	13%
Slag, dross, scalings and other waste from the manufacture of iron or steel	Waste Reutilized	Metric ton	13%
Cement, slag	Non Metallic Mineral	Metric ton	10%
Clay, mud	Non Metallic Mineral	Metric ton	10%

Clay, white / red	Non Metallic Mineral	Metric ton	10%
Clays;	Non Metallic Mineral	Metric ton	10%
Gas consumed	Energy - Natural Gas	Kg	10%
Bauxite calcined	Metals	Metric ton	8%
Clay, powder	Non Metallic Mineral	Metric ton	8%
Gypsum; anhydrite; limestone flux; limestone and other calcareous stone, of a kind used for the manufacture of lime or cement;	Non Metallic Mineral	Metric ton	8%
Ash containing precious metal or precious metal compounds	Waste Reutilized	Metric ton	5%
Bricks fire blocks	Non Metallic Mineral	Th. Nos	5%
Cement, dry slag	Non Metallic Mineral	Metric ton	5%
Chalk and dolomite	Non Metallic Mineral	Metric ton	5%
Clay, fire	Non Metallic Mineral	Metric ton	5%
Clay, shale	Non Metallic Mineral	Metric ton	5%
Copper oxide	Coal/Petrochemical	Metric ton	5%
Dolomite chip	Non Metallic Mineral	Metric ton	5%
Iron ore, Magnetite	Metals	Metric ton	5%
Aluminium billets	Metals	Metric ton	3%
Briquettes, coal, coal dust	Coal/Petrochemical	Metric ton	3%
Carbon, electropaste	Coal/Petrochemical	Kg	3%
Clay, black	Non Metallic Mineral	Metric ton	3%
Clay, china	Non Metallic Mineral	Metric	3%

		ton	
Clay, common	Non Metallic Mineral	Metric ton	3%
Clay, earthen	Non Metallic Mineral	Metric ton	3%
Coke breeze	Coal/Petrochemical	Metric ton	3%
Coke hard	Coal/Petrochemical	Metric ton	3%
Coke soft	Coal/Petrochemical	Metric ton	3%
Copper and copper alloys, worked .	Metals	Metric ton	3%
Feldspar(Moonstone)	Non Metallic Mineral	Carat	3%
Granite	Non Metallic Mineral	Metric ton	3%
Gypsum marine	Non Metallic Mineral	Metric ton	3%
Iron oxide	Coal/Petrochemical	Metric ton	3%
Lime powder	Non Metallic Mineral	Metric ton	3%
Marble chip	Non Metallic Mineral	Metric ton	3%
Molasses	Biomass Food	Metric ton	3%
Petroleum coke	Coal/Petrochemical	Metric ton	3%
Plaster of paris	Non Metallic Mineral	Metric ton	3%
Portland cement, aluminous cement, slag cement and similar hydraulic cements, except in the form of clinkers	Non Metallic Mineral	Metric ton	3%
Powders of iron	Metals	Metric ton	3%
Red oxide, natural	Coal/Petrochemical	Metric ton	3%
Red oxide, others	Coal/Petrochemical	Metric ton	3%

Sacks and bags, of a kind used for the packing of goods;	Biomass Fiber	Nos.	3%
Silica	Non Metallic Mineral	Metric ton	3%
Tiles, flagstones, bricks and similar articles, of cement, concrete or artificial stone	Non Metallic Mineral	Metric ton	3%

Table A.2: Frequency of inputs (shown as a percentage) for manufacturing steel from the sample of 50 factories.

Input commodity	**Classification**	**Unit**	**Frequency**
Electricity purchased	Energy - Electricity	KWh	100%
Scrap iron/steel	Waste Reutilized	Metric ton	44%
M.s scrap	Waste Reutilized	Metric ton	40%
Gas consumed	Energy - Natural Gas	Kg	18%
Iron ores	Metal	Metric ton	18%
Electricity own generated	Energy - Electricity	KWh	16%
Alloy pig iron	Metal	Metric ton	8%
Ferro silico magnesium	Metal	Metric ton	8%
Manganese, silica	Metal	Metric ton	8%
Non alloy pig iron	Metal	Metric ton	8%
Pig iron and spiegeleisen in pigs, blocks or other primary forms.	Metal	Metric ton	8%

Scrap cast iron	Waste Reutilized	Metric ton	8%
Sponge iron	Metal	Metric ton	8%
Coal consumed	Energy - Coal	Metric ton	6%
Ferro silicon	Metal	Metric ton	6%
Ferrous products from direct reduction of iron ore	Metal	Metric ton	6%
Silicon, ferro	Metal	Metric ton	6%
Iron blocks, lumps and similar forms	Metal	Metric ton	4%
Manganese, ore	Metal	Metric ton	4%
Other ferro-alloys,	Metal	Metric ton	4%
Remelting scrap ingots of iron or steel	Waste Reutilized	Metric ton	4%
Slag, dross, scalings and other waste from the manufacture of iron or steel	Waste Reutilized	Metric ton	4%
Aluminium natural	Metal	Metric ton	2%
Bolts, screws, nuts, iron /steel	Metal	Kg	2%
Coke cp	Energy - Coke	Metric ton	2%
Coke hard	Energy - Coke	Metric ton	2%
Ferro silico manganese/Silico manganese	Metal	Metric ton	2%
Ferro-manganese	Metal	Metric ton	2%
Ingots of high carbon steel	Metal	Metric ton	2%
Iron ore, Magnetite	Metal	Metric ton	2%
Iron ores, Hematite	Metal	Metric ton	2%

Magnesite, raw	Metal	Metric ton	2%
Molasses	Biomass Food	Metric ton	2%
Natural sponges of aquatic animal origin	Biomass Fiber	Metric ton	2%
Other non-ferrous metal ores and concentrates (other than uranium or thorium ores and concentrates)	Metal	Metric ton	2%
Paint	Non Metallic Mineral	Metric ton	2%
Pans of cast iron not enameled	Waste Reutilized	Kg	2%
Parts . of boring or sinking machinery and of derricks, cranes, mobile lifting frames, straddle carriers and works trucks fitted with a crane; parts . of moving, grading, levelling, scraping, excavating, tamping, compacting, extracting or borin	Waste Reutilized	Nos.	2%
Quartz	Non Metallic Mineral	Metric ton	2%
Roasted iron pyrites	Metal	Metric ton	2%
Scrap, aluminium	Waste Reutilized	Metric ton	2%
Waste and scrap of primary cells, primary batteries and electric accumulators; spent primary cells, primary batteries and electric accumulators	Waste Reutilized	Metric ton	2%
Zinc carbonate	Non Metalic Mineral	Kg	2%

Table A.3: Frequency of inputs (shown as a percentage) for manufacturing secondary aluminum from the sample of 14 factories.

Input commodity	**Classification**	**Unit**	**Frequency**
Electricity purchased	Energy - Electricity	KWh	100%
Scrap, aluminum	Waste Reutilized	Metric ton	57%
Electricity own generated	Energy - Electricity	KWh	29%
Scrap, copper	Waste Reutilized	Metric ton	29%
Silicon	Metals	Metric ton	29%
Waste and scrap of aluminum	Waste Reutilized	Metric ton	29%
Coal consumed	Energy - coal	Metric ton	21%
Gas consumed	Energy - Gas	Kg	21%
Aluminum alloys profile hollow	Metals	Metric ton	14%
Aluminum ingots	Waste Reutilized	Metric ton	7%
Aluminum natural	Metals	Metric ton	7%
Ferro-manganese	Metals	Metric ton	7%
Furnace oil	Energy - Oil	Liters	7%
Magnesium flakes	Metals	Kg	7%
Manganese, ore	Metals	Metric ton	7%
Other non-ferrous metal ores and concentrates (other than uranium or thorium ores and concentrates)	Metals	Metric ton	7%
Scrap cast iron	Waste Reutilized	Metric ton	7%
Scrap, nickel	Waste Reutilized	Metric ton	7%

Silicon steel coil	Waste Reutilized	Metric ton	7%
Zinc, alloyed	Waste Reutilized	Metric ton	7%