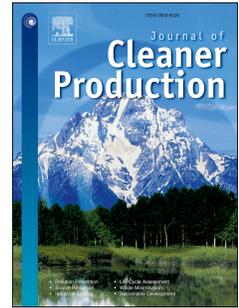


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Mapping Product Knowledge to Life Cycle Inventory Bounds: A Case Study of Steel Manufacturing

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Abstract

This study develops and demonstrates a bounding methodology to quantify uncertainty in Life Cycle Inventory (LCI) results arising from lack of detailed information on constituent materials. The method starts with the observation that the LCI of a material can change significantly with different attributes such as country of origin and recycled content, information often not specified in available bill-of-materials data. This lack of detailed information can be mapped to numerical bounds for LCI results. We demonstrate this idea via a case study of the contribution of steel manufacturing to the cumulative energy demand (CED) and life cycle global warming potential (GWP) of residential buildings. If steel type, recycled content and country of origin are all unknown, life cycle CO₂-equivalent emissions of steel can vary from 0.7-5.9 kg CO₂eq/kg. When used in compiling an LCI of a building, this wide range leads to overlapping results in a comparison of life cycle GWP impact between steel- and concrete-framed buildings. That is, without knowledge of the particulars of steel used, Life Cycle Assessment (LCA) cannot distinguish between the two building types. In contrast, with knowledge that the steel is low or un-alloyed, produced in the U.S., and has greater than 60% recycled content, uncertainty bounds are reduced to 0.8–1.4 kg CO₂eq/kg steel. With this range, the net impact of concrete-framed buildings is unambiguously smaller than steel-framed residences. While demonstrated here for steel manufacturing, this bounding approach is broadly applicable in LCA.¹

Keywords: Life cycle assessment, Uncertainty, Product knowledge mapping, Steel Manufacturing, Bill of Attributes

1. Introduction

Uncertainty analysis has long been recognized as an important aspect of life cycle assessment (LCA) (Heijungs, 1996). However, serious analysis of uncertainty continues to be the exception rather than the rule in LCA practice (Blengini and Di Carlo, 2010; Finnveden et al., 2009; Heijungs and Huijbregts, 2004; Björklund, 2002). This is problematic because as LCA becomes more influential in informing policy decisions, uncertainty analyses become imperative due to

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¹ Abbreviations: LCA: Life cycle assessment; CED: cumulative energy demand; GWP: global warming potential; GHG: greenhouse gases; LCI: life cycle inventory; EAF: electric arc furnace; BOF: blast oxygen furnace.

1 the large costs associated with these decisions (Lloyd and Ries, 2007). There are many prior
2 frameworks to describe and assess uncertainty in LCA, e.g. (Heijungs, 1996; Björklund, 2002;
3 Huijbregts, 1998; Heijungs and Huijbregts, 2004; Williams et al., 2009, Lloyd and Ries, 2007;
4 Finnveden et al., 2009; Huijbregts et al., 2003). The bulk of work focuses on uncertainty in the
5 Life Cycle Inventory (LCI) stage of an LCA.

6 Among the different types of uncertainty, parameter uncertainty of LCI is most often studied.
7 Characterizing parameter uncertainty involves quantifying the range in model outputs that arise
8 from uncertainty and variability in input parameter values. The central challenge in treating
9 parameter uncertainty is how to develop robust distributions for input parameters. Developing
10 uncertainty distributions mixes differing degrees of input from empirical data, modeling and
11 expert opinion. Empirical input can take several forms. For a specific facility, uncertainty can
12 arise from measurement error and/or temporal variability in inputs and outputs. For a generic
13 process, uncertainty/variability can be characterized using multiple data points for the “same”
14 quantity, e.g. a process input-output table. Often sample size is small, e.g. there may be only two
15 or three publicly available sources of data for a particular process.

16 In modeling uncertainty, analysts must choose a form of distribution, i.e. rectangular, normal,
17 log-normal or otherwise. When data and/or knowledge of the sampling process are limited, the
18 choice of rectangular (or uniform) distribution, while yielding the largest variability in results, is
19 presumably most robust. Rectangular distributions are equivalent to bounds or intervals
20 (Heijungs, 1996; Chevalier and Le Téo, 1996; Björklund, 2002; Williams et al., 2002; Deng et
21 al., 2011). LCA analysts have fit empirical data to other distributions, e.g. normal in (Williams,
22 2004) and log-normal in (Ciroth et al 2013). Note that the process of gathering LCI data often
23 does not match the statistical concept of a random sample. Using estimators for a particular
24 distribution thus represents an assumption by the analyst.

25 We explore how to develop numerical bounds to treat parameter uncertainty for process data
26 in LCA. Our focus on rectangular, as opposed to other distributions, is motivated by their
27 robustness given the typical paucity of process data. In particular, we investigate how knowledge
28 of product or material attributes can be used to derive quantitative bounds. Bills-of-attributes
29 vary in specificity, for example the content of a type of material (e.g. kg of steel) might be listed,
30 but no details on the quality or origin of the material. The cradle-to-gate inventory of a material
31 can vary substantially on location of production (Puettmann et al., 2010), purity (Williams et al.,
32 2002; Williams et al. 2011), recycled content (Hammond and Jones, 2008; Eckelmann, 2010)
33 and other attributes. Our method maps what is known about the attributes of a constituent
34 material or component to bounds on its life cycle inventory. The more that is known about a
35 product, the narrower the bound on LCI. In prior literature, e.g. (Chevalier and Le Téo, 1996),
36 methods are developed to obtain bounds in LCI results given numerical bounds for individual
37 processes. Olivetti et al (2013) introduce the idea that under specification of attributes of
38 constituent materials connects to the degree of uncertainty. Our contribution to the literature is an
39 approach to derive numerical bounds for LCI results given different levels of product knowledge.

40 This method is demonstrated through a case study showing how knowledge of the attributes
41 of steel in a residential building affects its life cycle energy and carbon flows. The motivation for
42 studying energy related to steel in buildings for the case study is threefold. First, the large
43 volume of steel produced means its global energy footprint is significant. Around 5% of global
44 energy demand is due to steel production (Williams et al., 2012a). Second, because buildings
45 consume 40% of global energy and resources, it is important to understand the variability in
46 commonly used construction materials, such as steel, in order to better inform policy on the

1 environmental impacts of choices made in building design and construction (UNEP, 2013).
2 While the materials extraction and production life cycle energy make up a smaller share (4-20%)
3 of the total life cycle energy of a building as compared to operation energy (80-95%) in prior
4 building LCA studies, the choice of materials impacts the entire life cycle, including total
5 operation energy (Cole and Kernan, 1996; Adalberth, 1997; Keoleian et al., 2001; Junnila et al.,
6 2006; Ramesh et al., 2010; Sharma et al., 2011). For example, (Xing et al. 2008) suggest that
7 while a steel-framed office building demands less energy for materials extraction and production
8 than a comparable concrete-framed office building, the steel-framed office building had higher
9 operation energy, resulting in higher total life cycle energy. Third, the high variability in both the
10 energy and carbon intensities used for steel in previous LCA work, e.g. (Hammond and Jones,
11 2008; Keoleian et al., 2008; Buchanan and Honey, 1994; Zabalza Bribián et al., 2011; Scheuer et
12 al., 2003) suggests a need to understand uncertainty.

14 2. Materials and Methods

16 2.1 Overview

18 Figure 1 summarizes the method to obtain bounds for a LCI result based on lack of specific
19 data on material characteristics. The first step is to use process modeling to obtain relationships
20 connecting characteristics and LCI results. LCI results depend on material characteristics. For
21 example, higher recycled content often results in lower embedded energy (Hammond and Jones,
22 2008). The purity of a product can affect the life cycle inventory. For example, the energy
23 needed to produce electronics grade silicon is 160 times that of industrial grade silicon
24 (Williams et al., 2002). Differences between manufacturing facilities lead to intra and
25 international variability in material flows to make a similar product. For example, (Puettmann et
26 al., 2010) analyze and identify distinctions in life cycle inventory of hardwood and softwood
27 manufacturing processes across four different regions of the United States. The authors found
28 that the Northeast/Northcentral regions of the United States use more wood biomass fuel than the
29 western regions whose primary fuel is natural gas (Puettmann et al., 2010). (Macmillan and
30 Keoleian, 2010) examine temporal and geographic variation in life cycle greenhouse gas (GHG)
31 emissions of primary aluminum ingots, finding that the GHG emission intensity relates to the
32 type of fuel used for electricity production, which varies substantially by region (Macmillan and
33 Keoleian, 2010).

34 In the second step, the ranges of materials characteristics are determined from the bill of
35 materials, or more generally, bill of attributes. The bill of attributes for a product specifies
36 physical quantities of constituent materials and components. Bills of attributes vary widely in
37 their specification of material characteristics, often times simply listing the material type (e.g.
38 steel, copper) without specifying the composition (e.g. recycled content) or history (e.g. country
39 of origin). We use rectangular distributions to describe material characteristics, e.g. if no
40 information is presented on recycled content, it is safest to assume that it varies from 0 to 100%.
41 The third step combines the first two steps to translate the ranges in material characteristics to
42 ranges in LCI results.

43

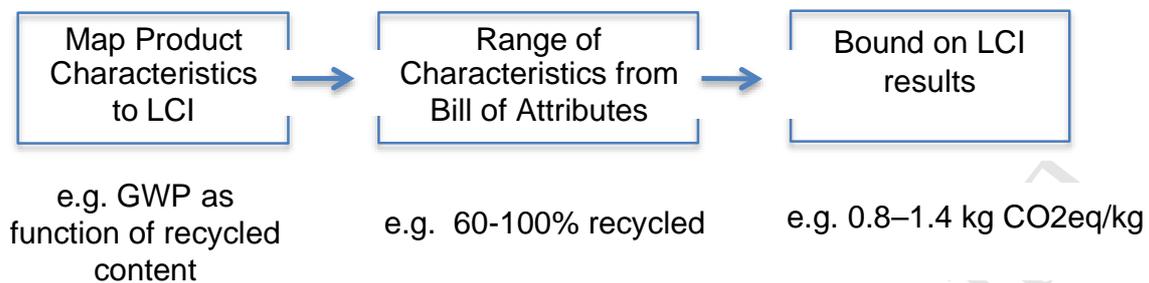


Fig. 1. Overview of method to develop numerical bounds for Life Cycle Inventory (LCI) result (GWP = Global Warming Potential).

2.2 Case study of mapping product characteristics to LCI results: steel

We implement the method from the previous section via a case study of steel used in a U.S. building. We treat three sources of variability in steel production: region of production (U.S., Europe or China), recycled content (0-100%) and steel type (low alloy or chromium). First, spatial variability is examined due to regional differences in production technologies, including in electricity grid mixes. For example, in 2012, the U.S. used coal as a fuel for 37% of the electricity generation, in contrast with 65% of coal-based electricity in China in 2011 (U.S. EIAa and c, 2013). These differences can cause significant variability in the impacts of GWP, particularly from an electric arc furnace (EAF) process that relies almost entirely on electricity.

The second potential source of variability, recycled content, changes as a function of the technology used for steel production. Two processes currently dominate steel manufacturing, the blast oxygen furnace (BOF) process and the EAF (Fenton, 2005). The BOF process reduces iron from ore, then makes steel by blasting oxygen through molten pig iron. While iron ore is the main source of iron in BOF steel, scrap can constitute up to 30% of the “charge” (AISI, 2012). In contrast, the EAF process uses an electric arc as the heat source, and scrap constitutes up to 100% of the charge (AISI, 2012). Not surprisingly, the energy requirements of the two technologies are very different, with BOF process requiring 19 GJ/tonne on average versus 8MJ/kg for EAF steel (Williams et al., 2012a).

Finally, types of finished steel are also examined for potential influences to CED and GWP. Alternative types of steel such as low- or high-alloyed steel require the use of different processes. Low-alloyed steels contain small amounts of alloyed elements, less than 5% in total, and are characterized by high strength (Fenton, 2005; Classen et al., 2009). In contrast, high-alloyed steels or stainless steels, contain larger amounts of alloyed elements such as chromium, at a minimum of 10%, and are characterized by high strength and resistance to abrasion (Fenton, 2005; Classen et al., 2009). Therefore process data for these different types of finished steels are examined.

2.2 LCI methodology

A process-sum methodology is utilized to complete a cradle-to-gate LCA of steel manufacturing. This common approach is a bottom-up process model, based on facility level

1 material flow data and resulting environmental impacts between processes. We analyze cradle-
2 to-gate energy and greenhouse gas emissions including the material extraction and
3 manufacturing. As a result, the study scope only includes those elementary material, energy, and
4 emission flows that contribute to the CED (MJ/kg steel produced) and the GWP (kg CO₂eq/kg
5 steel produced) in the manufacture of steel (IPCC, 2007). The system boundary diagram appears
6 in figure S1 of the supporting documentation.

7 The process-sum approach is used to examine the impacts to CED and GWP as a result of
8 varying specific aspects of the steel manufacturing process. First, the type of finished steel
9 (either low-alloyed or chromium steel) is varied requiring two functional units for the process-
10 sum approach: 1 kg of low alloy steel and 1 kg of chromium steel (high alloy). Second, spatial
11 variability is considered by taking into account the different regional electrical grid mixes from
12 the U.S. Europe and China. Finally, the technology used to produce the steel is varied in order to
13 model differing recycled steel content (secondary steel content). It is assumed in this study that
14 the BOF process reflects primary steel, or steel that has no recycled content (no secondary
15 content). In contrast, it is assumed that the EAF process reflects secondary steel or steel that has
16 100% recycled content (100% secondary content). Therefore, the reference flows are 1 kg of
17 finished steel, both low-alloyed and chromium (high-alloyed) steel, produced in different
18 regions, while varying the amounts of primary and secondary steel used.

19 The data points for CED and GWP for the process-sum approach comes from the ecoinvent
20 database (ecoinvent Centre, 2007). The finished steel types from the database used in this study
21 are 1 kg of low-and un-alloyed steel, and 1 kg of chromium (18%) steel (ecoinvent Centre,
22 2007). Modifications were made to the database to reflect the electricity grid mixes for Europe,
23 the U.S. and China. This was not an exhaustive modification, rather only the top 5 processes
24 with the highest impacts from electricity consumption were modified. Moreover, for each
25 region, the amount of primary versus secondary steel used was varied in 25% increments. For
26 example, if 1 kg of low- and un-alloyed steel contained 0% primary steel, then it must contain
27 100% secondary steel. Similarly, if 1 kg of low- and un-alloyed steel contains 25% primary
28 steel, secondary steel content is 75%, and so on. As a result, there are 30 different data points
29 modeled each for CED and GWP, reflecting the variations in types of steel, regions of
30 production, and % primary and secondary content. Tables S1 and S2 of the supporting
31 documentation contain sample input and output flows (life cycle inventory) for primary low- and
32 un-alloyed and chromium steel from U.S., China and Europe.

34 **2.3 Contribution of cradle-to-gate steel LCI bounds to overall uncertainty in LCA of multi-** 35 **family residence**

36
37 Steel is not in itself of interest to household consumers; rather it is an important constituent
38 material of many consumer goods. In order to get a sense of how the uncertainty bounds for steel
39 might affect the life cycle of a final consumer product, we analyze the effect of the bounds on the
40 GWP of a multi-family residence. We base this analysis on the previous study of (Gong et al.,
41 2012) who analyze the GWP of concrete-framed construction (CFC) and steel-framed
42 construction (SFC). The analysis involves removing the contributions to life cycle GWP from
43 steel in the original study and replacing these contributions using the three bounded ranges
44 established in the previous section. Table S6 in the supporting documentation details the
45 contributions from the original study.

3. Theory

LCI is the compilation of supply chain resource use and emissions associated with a product or service. Constructing an LCI proceeds by combining bill-of-attributes with process input-output data. Bill-of-attributes, a generalization of bill-of-materials, specifies quantities and other attributes of materials and components contained in a product. Given a bill-of-attributes, materials flows in associated processes are modeled by following the supply chain upstream, finding material input-output data for individual processes. The degree to which bill-of-attributes data specify information beyond mass, e.g. origin and recycled content, is variable and often incomplete. For process data, it is common for analysts to gather specific data on a few critical processes and rely on commercial database such as (ecoinvent Centre, 2007) for other processes.

Parameter uncertainty is the type most commonly addressed in LCA. Parameter uncertainty relates to how choices in numerical values for process input-output tables and bill-of-attributes influence results. Sources of parameter uncertainty include data quality, representativeness, and timeliness. Data quality issues relate to how well the numerical values for process input-output tables and weight/composition from bill of attributes accurately reflect the targeted process/product LCI. Assessing data quality is difficult given a general lack of information on how process and bill-of-attributes data were collected. Representativeness is the question of how closely the choices of data reflect the actual processes for the product in question. It is typical for much of the supply chain to be modeled with “standard” production processes data, as opposed to a specific set of facilities in the supply chain. Representativeness is thus a potential issue for most LCA studies. Finally, timeliness is related to the potential changes in process and product attributes over time not accurately represented in the LCI.

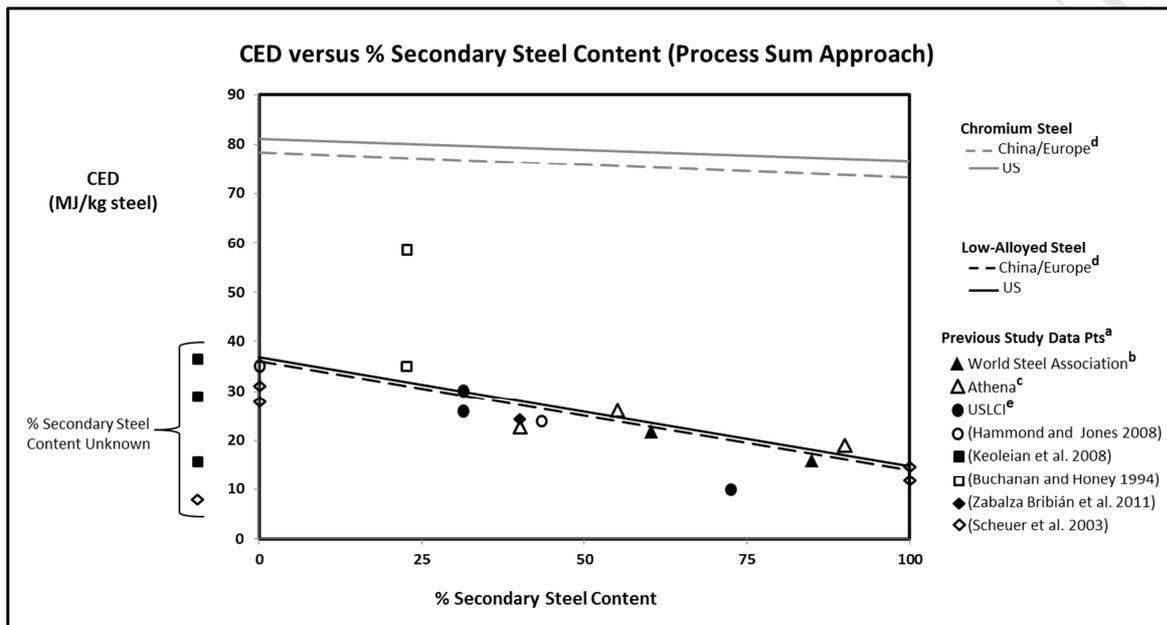
Parameter uncertainty is generally treated by representing a parameter as a distribution rather than a single number. Given distributions for model inputs, distributions of model outputs are typically calculated using Monte Carlo Analysis, a numerical simulation approach (Sonnemann et al., 2003). For specific distributions, such as rectangular, there are analytical approaches to estimate outputs (Chevalier and Le T no, 1996).

Expert opinion is also used to develop uncertainty distributions. The pedigree matrix is a well-known and popular theoretical approach to estimate variance in process data. Developed by Weidema and used in LCA software tool SimaPro (PRE Consultants, 2012) and database (ecoinvent Centre, 2007), the pedigree matrix is a formula that converts analysts’ judgments of data quality to quantitative uncertainty distributions (Weidema, 1996; Weidema, 1998; Frishknect et al., 2007; Goedkoop et al., 2010; Blengini and Di Carlo, 2010). While an expert-opinion driven approach could, in principle, give results comparable to empirical measures, this remains an open question. To our knowledge, Citroth et al (2013) is first to begin exploring this issue. We argue that using theoretical approaches such as the pedigree matrix should be predicated on work that establishes correlation with empirical measures. Empirical methods such as the one developed here can hopefully inform such future work.

4. Results

4.1 CED and GWP of steel as a function of country of origin, recycled content and steel type

1 Figures 2 and 3 contain the results for GWP and CED versus percent secondary steel content
 2 by region and type of steel, respectively. Tables S3 and S4 in the supporting documentation
 3 contain the data point values. Moreover, in order to examine the results in the context of the
 4 broader literature, values for GWP, CED and percent secondary steel content used in previous
 5 studies and published reports are included in the respective figures, and, are detailed in S5 in the
 6 supporting documentation.
 7



8
 9 Fig. 2. Process-sum model results for cradle-to-gate cumulative energy demand for steel as a function of
 10 secondary steel content, region and type of steel (solid and dashed lines), and prior process LCA studies
 11 (circles, triangles, squares and diamonds). CED = cumulative energy.

12 ^a Actual values are included in table S5 in the supporting information.

13 ^b (Crawford, 2013).

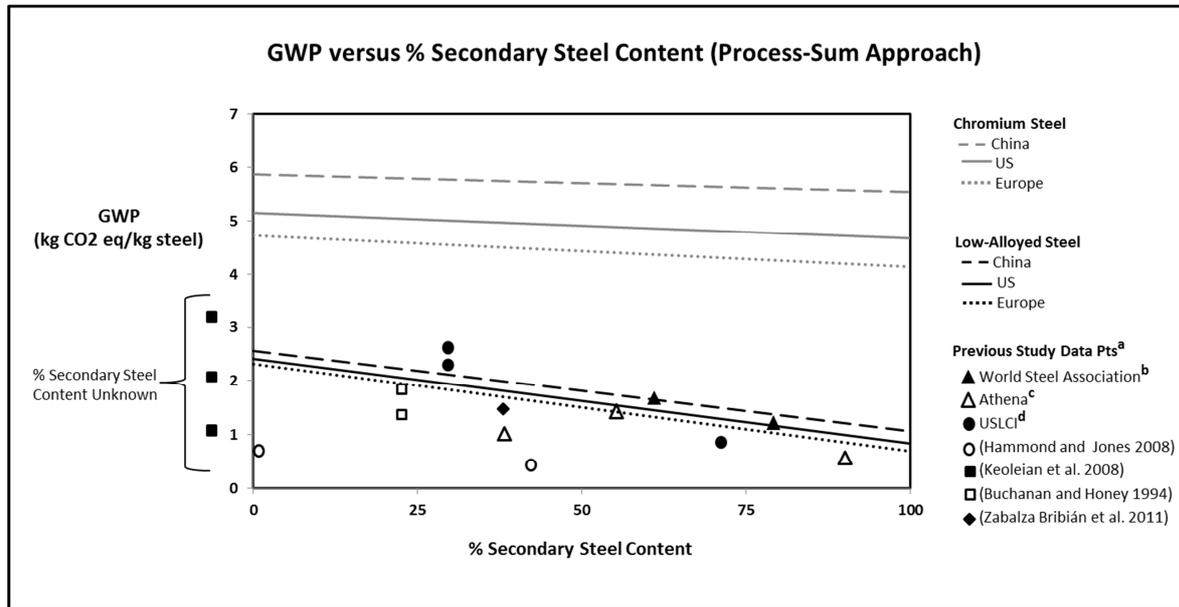
14 ^c (Markus Engineering Services, 2002).

15 ^d CED trendlines for China and Europe overlap.

16 ^e (NREL, 2012)

17

1



2

3 Fig. 3. Process-sum model results for cradle to gate global warming potential for steel as function of
 4 secondary steel content, region and type of steel (solid and dashed lines), and prior process LCA studies
 5 (circles, triangles, squares and diamonds). GWP = global warming potential; kgCO₂eq/kg steel =
 6 kilogram carbon dioxide equivalent per kilogram of steel.

7 ^a Actual values are included in table S5 in the supporting information.

8 ^b (Crawford, 2013).

9 ^c (Markus Engineering Services, 2002).

10 ^d (NREL, 2012)

11

12 Figures 1 and 2 illustrate the expected impacts from different regional electricity grid mixes, the
 13 benefits of recycling, and, the impacts of differing amounts of alloys in steel. One notable
 14 finding is the large degree of variability in results in previous studies and reports. This indicates
 15 a need to develop distribution versus point estimate approach.

16

17 4.2 Combining LCI relationships and product knowledge to obtain LCI bounds for steel

18

19 In this section, the relationships between LCI and product characteristics from section 4 are
 20 combined with different levels of product knowledge to realize bounds in the cradle-to-gate LCI
 21 for steel. The first step is to develop three cases of specification to product characteristics that
 22 might be seen in a bill of attributes. These cases are shown in Table 1. They are intended as
 23 illustrative examples, in general one would extract the level of product knowledge from a bill of
 24 attributes. If the bill of attributes only lists “steel”, the steel might be any type, manufactured
 25 anywhere, and have any recycled content. We call this “General Product Knowledge”. If the bill
 26 of attributes were to list “low-alloyed steel”, then one could rule out chromium and other high
 27 alloy steels. We call this “Finished Product Knowledge”. If the bill of attributes listed country of
 28 origin (e.g. the U.S.) and recycled content range, for example, we call this “Finished Product and
 29 Origin” knowledge.

30

1
2 Table 1: Product knowledge cases used in this study.

Product Knowledge	Details
General Product Knowledge	An LCA practitioner may not be an expert in steel manufacturing, and therefore, not familiar with processes used, material composition, finished products, region of production or applications. This general knowledge maps to a lower and upper bounding range of .70 – 5.9 kgCO ₂ eq/kg steel. ^a
Finished Product Knowledge	Finished product knowledge of low-alloyed steel maps to a lower and upper bounding range of .70 – 2.6 kgCO ₂ eq/kg steel. ^{a,b}
Finished Product and Origin Knowledge	Product knowledge revealing region of production in the U.S., and percent secondary steel content of between 64% and 99.9%, maps to a lower and upper bounding range of .8 - 1.4 kgCO ₂ eq/kg steel. ^c

3 *Note:* kg CO₂eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel.

4 ^a Values found in table S6 of the supporting documentation.

5 ^b Source: (Classen et al., 2009)

6 ^c Source: (Nucor Corporation, 2013); upper bound value was determined using the regression line for U.S. (max): $y = (-.4)x + 2.8$. Lower bound is from table S4 (for the U.S.) in the supporting documentation.

8
9 Product knowledge leads to bounds for LCI via the following approach, described for the
10 example of Finished Product and Origin Knowledge. Knowledge that the steel is low-alloyed
11 and produced in the U.S. implies that the production process is some combination of U.S.
12 average primary and EAF steel. The only variable is recycled content, known to range between
13 64% and 99.9%. The lower/upper bound for a given inventory items is the lower/higher value for
14 a process (64% EAF + 36% primary) or (99.9% EAF + 0.1% primary). The results of calculation
15 for select energy resources inputs are shown in Table 2. Note that while only process inputs are
16 shown in Table 2, the method is equally applicable to outputs, including emissions.

17
18

1 Table 2: Bounded LCI for Energy Inputs for Finished Product and Origin Knowledge (Steel
 2 produced in U.S., secondary steel content 64%-99.9%)

1 kg of Low-Alloyed Steel ^{a,b}		ecoinvent ^a	
		US	
Inputs ^b	(64%-99% secondary content)		unit
Coal, hard, unspecified, in ground	2.6E-01 - 5.8E-01		kg
Coal, brown, in ground	3.9E-02 - 4.8E-02		kg
Gas, natural, in ground	1.2E-01 - 1.3E-01		m ³
Gas, mine, off-gas, process, coal mining/m ³	2.0E-03 - 5.1E-03		m ³
Crude Oil	4.4E-02 - 5.5E-02		kg
Uranium, in ground	4.2E-06 - 4.3E-06		kg
Energy, solar, converted	4.7E-04 - 5.0E-04		MJ
Energy, potential (in hydropower reservoir), converted	2.6E-01 - 7.4E-01		MJ
Energy, kinetic (in wind), converted	1.7E-02 - 2.0E-02		MJ
Energy, gross calorific value, in biomass, primary forest	1.2E-05 - 1.4E-05		MJ
Energy, gross calorific value, in biomass	1.3E-01 - 1.7E-01		MJ
Total CED (MJ/kg)		1.5E+01 - 2.2E+01	
Outputs ^b			
Carbon Dioxide	7.89E-01 - 1.30E+00		kg
Methane	1.82E-03 - 3.68E-03		kg
Total CO₂eq (kg/kg)		8.3E-01 - 1.4E+00	
Conversions		value	unit
Coal, hard, unspecified, in ground		19.1	MJ/kg
Coal, brown, in ground		9.9	MJ/kg
Gas, natural, in ground		38.3	MJ/m ³
Gas, mine, off-gas, process, coal mining/m ³		39.8	MJ/m ³
Crude Oil, in ground		45.8	MJ/kg
Uranium, in ground		5.6x10 ⁵	MJ/kg
Methane GWP ^b		25	

3 Note: LCI = life cycle inventory; kg = kilogram; m³ = cubic meter; MJ = megajoule; MJ/kg = megajoules per
 4 kilogram = MJ/m³: megajoules per cubic meter.

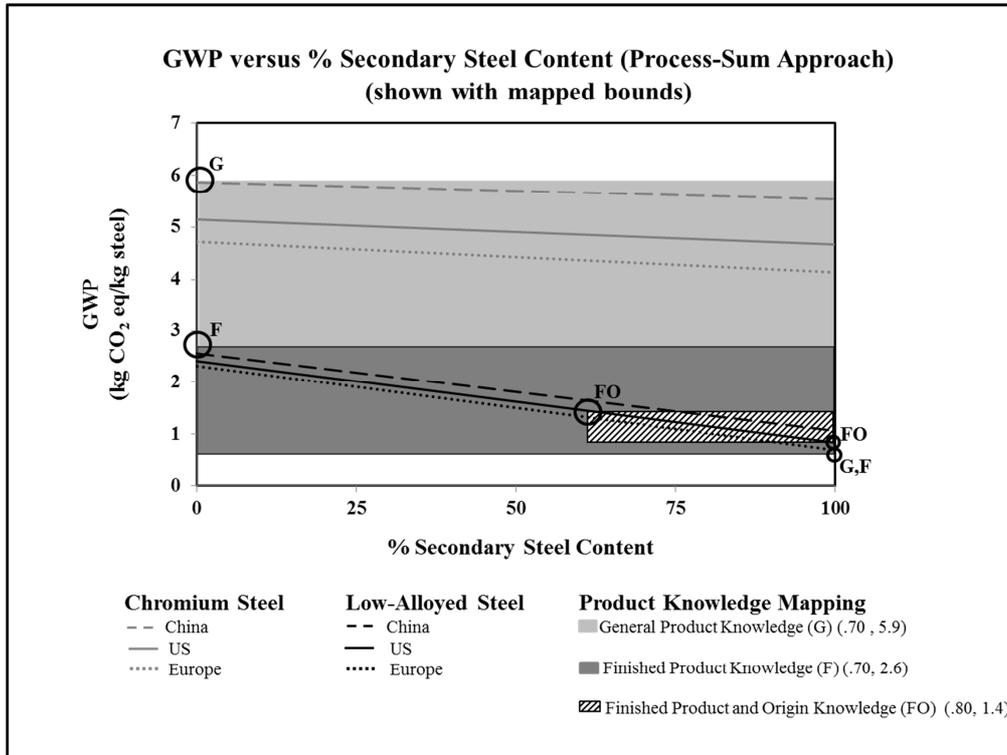
5 ^a Source: (ecoinvent Centre, 2007); Available data are for low-and un-alloyed steel.

6 ^b Source: (IPCC, 2007).

7
 8 The results for CED from bounded LCI for all three product knowledge cases are shown in
 9 Figure 4, overlaid with graphical representation of how the bounding process works. Explaining
 10 the Finished Product and Origin Knowledge example in this graphical format, knowledge that
 11 the steel is low-alloy produced in the U.S. restricts process to follow the lower solid line on
 12 Figure 4. The 64% and 99.1% bounds on recycled content map to the two FO points on Figure 4,
 13 thus GWP is bounded between 0.8 and 1.4 kg CO₂eq per kg of steel.

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Fig. 4. Bounds mapped from product knowledge. Circles denote reference points used in bounding. GWP = global warming potential; kgCO₂eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel. The circles in the graph identify the bounds mapped from different types of product knowledge. General Product Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge = steel type known, % secondary steel content and region of production known; Finished Product and Origin Knowledge = steel type, % secondary steel content and region of production known.

10

11 Recall the degree of variability in values from previous studies and reports illustrated in Figures
 12 1 and 2. Using Finished Product Knowledge mapping would capture most of the variability from
 13 prior studies for GWP. Assuming knowledge that the steel is low-alloyed, choosing Finished
 14 Product Knowledge bounds would account for potential variability from different data
 15 sources/model assumptions.

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4.3 Effects of Steel product knowledge bounds on the LCI of multifamily residences

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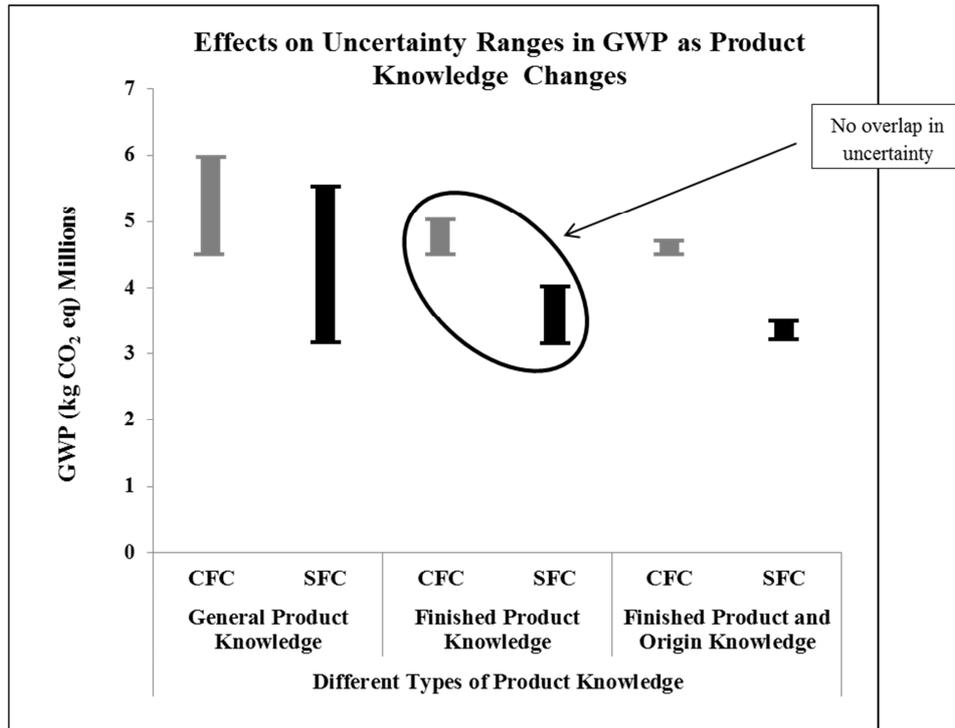
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27

As discussed in section 2.3, we explore how ranges in the LCI of a constituent material (steel) affect the LCI of a finished product (multifamily residence). Figure 5 shows uncertainty bounds for different levels of steel product knowledge yield ranges in the LCI of concrete frame construction (CFC) and steel frame construction (SFC) multifamily residences. With General Product knowledge, a definitive statement on the relative GWP intensity of the two construction types cannot be made. With Finished Product Knowledge, an unambiguous distinction can be made: SFC buildings emit less GWP than CFC. If the purpose of the LCI study is to establish this order, more detailed product knowledge on the secondary steel content of the building would not be needed.



No overlap in uncertainty

1
2 Fig. 5. Effect of knowledge-based bounds for steel on total life cycle GWP of multifamily residential
3 building. GWP = global warming potential; kgCO₂eq = kilogram carbon dioxide equivalent; CFC =
4 concrete-framed construction; SFC = steel-framed construction; General Product Knowledge = steel type,
5 % secondary steel content and region of production unknown; Finished Product Knowledge = steel type
6 known, % secondary steel content and region of production unknown; Finished Product and Origin
7 Knowledge = steel type, % secondary steel content and region of production known.

8
9 Tables 3 and 4 show in numerical form the results contributing to Figure 5. Table 3 details the
10 contribution of steel to life cycle GWP of a multifamily residence. Table 4 shows the ranges for
11 total GWP with ranges arises from the product knowledge of steel.

12
13 Table 3: Steel contribution to life cycle GWP of multifamily residence

Construction Type	Quantity of steel (tonne)	GWP General Product Knowledge (kg CO ₂ eq)		GWP Finished Product Knowledge (kg CO ₂ eq)		GWP Finished Product and Origin Knowledge (kg CO ₂ eq)	
		lower bound ^a	Upper bound ^a	lower bound ^a	upper bound ^a	lower bound ^a	upper bound ^a
CFC	282	2x10 ⁵	1.7x10 ⁶	2x10 ⁵	7.3x10 ⁵	2.3x10 ⁵	3.9x10 ⁵
SFC	459	3.2x10 ⁵	2.7x10 ⁶	3.2x10 ⁵	1.2x10 ⁶	3.7x10 ⁵	6.4x10 ⁵

15 Note: GWP = global warming potential; kgCO₂eq = kilogram carbon dioxide equivalent. General Product
16 Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge

1 = steel type known, % secondary steel content and region of production unknown; Finished Product and Origin
 2 Knowledge = steel type, % secondary steel content and region of production known.
 3 ^a Previously established bounds from figure 4 in terms of kgCO₂eq/kg of steel, or, kilogram carbon dioxide per
 4 kilogram of steel.

6 Table 4: Total Life Cycle GWP of multifamily residence from three levels of steel product
 7 knowledge.

Construction Type	GWP General Product Knowledge (kg CO ₂ eq)		GWP Finished Product Knowledge (kg CO ₂ eq)		GWP Finished Product and Origin Knowledge (kg CO ₂ eq)	
	lower bound ^b	Upper bound ^b	lower bound ^b	upper bound ^b	lower bound ^b	upper bound ^b
	.7	5.9	.7	2.6	.8	1.4
CFC	4.5x10 ⁶	6x10 ⁶	4.5x10 ⁶	5x10 ⁶	4.5x10 ⁶	4.7x10 ⁶
SFC	3.1x10 ⁶	5.5x10 ⁶	3.1x10 ⁶	4x10 ⁶	3.2x10 ⁶	3.4x10 ⁶

8 *Note:* GWP = global warming potential; kgCO₂eq = kilogram carbon dioxide equivalent; General Product
 9 Knowledge = steel type, % secondary steel content and region of production unknown; Finished Product Knowledge
 10 = steel type known, % secondary steel content and region of production unknown; Finished Product and Origin
 11 Knowledge = steel type, % secondary steel content and region of production known.
 12 ^a Previously established bounds from figure 3 in terms of kgCO₂eq/kg of steel, or kilogram carbon dioxide per
 13 kilogram of steel.

16 5. Discussion

18 There is always uncertainty in the uncertainty. In this section we describe some of the
 19 uncertainties in the previous analysis. This data source used for steel manufacturing,ecoinvent
 20 (ecoinvent Centre, 2007), relies heavily on data from Europe to establish electricity grid mixes,
 21 for example Dones et al. (2007). Therefore, additional sources were examined in order to put the
 22 results in context with the broader literature and reports. While variable, these data points were
 23 found to generally fall within the bounds identified using Finished Product Knowledge mapping,
 24 further highlighting the appropriateness of using a bounding approach rather than a single value
 25 approach.

26 Another area of uncertainty is introduced as part of the regional electricity grid mixes. The
 27 impacts to GWP and CED from different electricity grid mixes was completed by modifying the
 28 default European grid mix in SimaPro (PRE Consultants, 2012) to reflect the region of interest.
 29 This was not an exhaustive modification. Only the top 3-5 highest CED and GWP contributing
 30 processes were modified to reflect the region of interest. This approach was assumed to reveal
 31 contrast between regions by focusing on the highest contributors without being excessively time
 32 consuming and adding relatively minimal value to the study. As a result, the overall impacts to
 33 GWP in particular from electricity grid mix, will be higher in both the US and China.
 34 Furthermore, the type of coal used in both the US and China, primarily bituminous and
 35 anthracite, respectively, contain higher amounts of carbon as compared to the coal used in
 36 Europe, primarily sub-bituminous and lignite (WEC, 2010). Higher amounts of carbon content
 37 result in higher emissions of greenhouse gases (GHG) (U.S. EIA, 2013). In fact, between 2007

1 and 2011, China emitted greater than 3 times the amount of CO₂ as the U.S. and Europe due
2 solely to the consumption of coal (U.S. EIAc, 2013). This distinction is not fully represented in
3 the results. Consequently, the overall impacts to GWP in general will be higher in both the US
4 and China. This is because coal is not only used for electricity generation, but also as an energy
5 source for manufacturing processes such as providing a heat source for the BOF. While
6 uncertainties remain, the analysis did demonstrate a practical approach for mitigating uncertainty
7 in LCA.

10 **6. Conclusions**

11
12 The steel case illustrated the feasibility of the product knowledge mapping method. Future
13 development of the approach involves creating characteristic to LCI mappings for a variety of
14 materials and even, components. In buildings for example, mappings for concrete, wood and
15 gypsum board would be natural next steps to better understand variability in materials
16 production. One could also develop bounds for operational and end-of-life phases. For example,
17 there is significant variability in the energy use of U.S. residences (U.S. EIAc, 2013). Note that
18 the steel attribute to LCI mapping developed here can be used in *any* LCA of a steel-containing
19 product. The critical point is that the mapping need only be developed once. Creating an attribute
20 to LCI mapping is data and time intensive. Presumably for many materials and components,
21 limited data will preclude their construction. While this is a constraint, assuming continued
22 progress in process databases, developing mappings for more materials and components will
23 become feasible. It is also important to note that the mappings themselves can be improved with
24 further work. We mentioned uncertainty issues associated with our steel mapping, further work
25 could presumably address these.

26 A second element to further the product knowledge mapping method is work to gather more
27 detailed bills of attributes. It is typical for bills of attributes to specify materials and components
28 in general terms and it is likely that the resulting range from knowledge-based bounds will, in
29 many cases, be large. In contrast with process material flows, bills of attributes in LCA have
30 received almost no attention in research and data development (Kahhat et al., 2011; Kasulaitis et
31 al 2015). It is worth distinguishing between extrinsic (e.g. country of origin) and intrinsic
32 (quality attributes). While quality can in principle be determined from a sample of the product, in
33 general, extrinsic attributes require knowledge of its history available only to manufacturers.
34 Depending on the material, there are opportunities to improve product knowledge. Considering
35 steel, for example, recent trends and technologies contribute to better product knowledge.
36 Materials documentation required for Leadership in Energy and Environmental Design (LEED)
37 certification leads to better information on product origin. The type of steel used in a structural
38 design is typically specified by the steel code and/or the design (in the US), and handheld XRF
39 analyzers allow simple measurement of steel type.

40 In summary, increased attention to product knowledge will enable better measurement and
41 management of LCI uncertainty.

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44
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31
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39 Supporting Information

40 Supporting information may be found in the online version of this article:

41
42 **Supporting Information S1:** The supporting information contains: details on the system boundary, life
43 cycle inventory data and life cycle impact assessments, and, uncertainty range details for product
44 knowledge mapping.

Highlights

- We use life cycle assessment to examine environmental impacts of steel production.
- We map life cycle inventory bounds to product characteristics.
- Increasing product knowledge decreases life cycle inventory bounds.
- We demonstrate a practical method to quantify uncertainty in life cycle assessment.

**Supporting Information for:
Mapping Product Knowledge to Life Cycle Inventory Bounds:
A Case Study of Steel Manufacturing**

Kim R. Bawden, Eric D. Williams, Callie W. Babbitt

Number of pages: 8
Number of figures: 1
Number of tables: 6

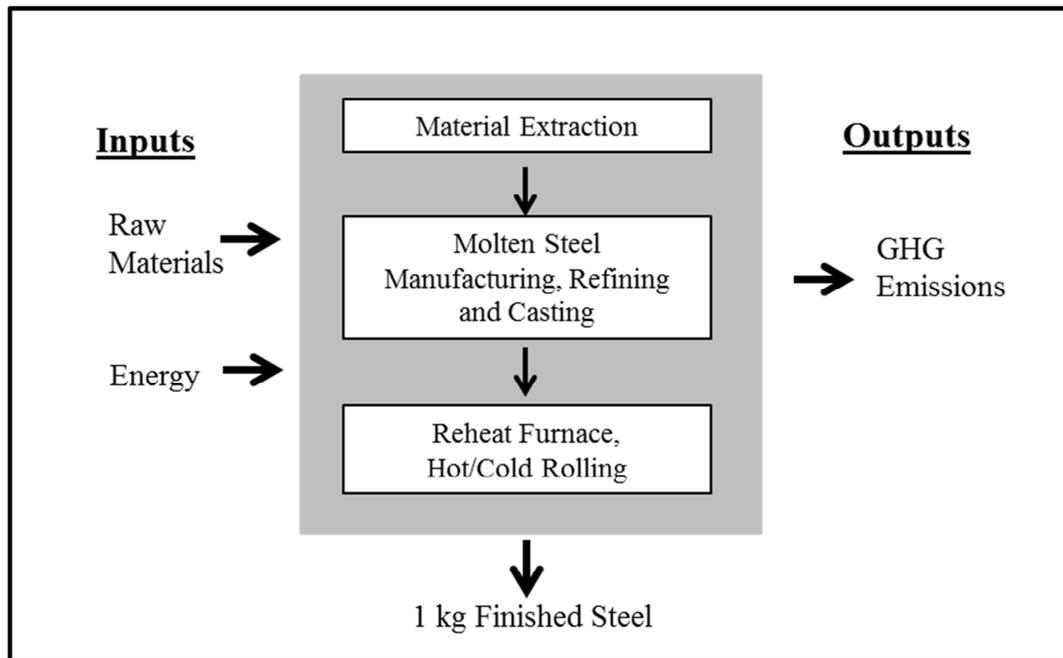


Figure S1: System Boundary Diagram

Table S1 Input and output flows to produce 1 kg of primary, low-alloyed steel in the U.S., China and Europe.

1 kg of Low- and Un-Alloyed Steel^{a,b}	ecoinvent^a		ecoinvent^a		ecoinvent^a	
	US		China		Europe	
Inputs^b	primary	unit	primary	unit	primary	unit
Coal, hard, unspecified, in ground	1.2E+00	kg	1.2E+00	kg	1.1E+00	kg
Coal, brown, in ground	7.3E-02	kg	6.0E-02	kg	1.3E-01	kg
Gas, natural, in ground	1.4E-01	m ³	1.2E-01	m ³	1.4E-01	m ³
Gas, mine, off-gas, process, coal mining/m ³	1.1E-02	m ³	1.2E-02	m ³	1.0E-02	m ³
Crude Oil	7.5E-02	kg	7.5E-02	kg	7.5E-02	kg
Uranium, in ground	4.7E-06	kg	2.7E-06	kg	5.3E-06	kg
Energy, solar, converted	5.9E-04	MJ	3.7E-04	MJ	7.8E-04	MJ
Energy, potential (in hydropower reservoir), converted	1.6E+00	MJ	1.7E+00	MJ	1.7E+00	MJ
Energy, kinetic (in wind), converted	3.0E-02	MJ	2.6E-02	MJ	5.4E-02	MJ
Energy, gross calorific value, in biomass, primary forest	1.9E-05	MJ	1.8E-05	MJ	1.9E-05	MJ
Energy, gross calorific value, in biomass	2.4E-01	MJ	2.2E-01	MJ	2.4E-01	MJ
Total CED (MJ/kg)	3.7E+01		3.6E+01		3.6E+01	
Outputs^b						
Carbon Dioxide	2.2E+00	kg	2.3E+00	kg	2.1E+00	kg
Methane	7.1E-03	kg	9.1E-03	kg	6.9E-03	kg
Total CO₂eq (kg/kg)	2.4E+00		2.5E+00		2.3E+00	
Conversions	value	unit				
Coal, hard, unspecified, in ground	19.1	MJ/kg				
Coal, brown, in ground	9.9	MJ/kg				
Gas, natural, in ground	38.3	MJ/m ³				
Gas, mine, off-gas, process, coal mining/m ³	39.8	MJ/m ³				
Crude Oil, in ground	45.8	MJ/kg				
Uranium, in ground	5.6x10 ⁵	MJ/kg				

Methane GWP^b

25

Note: kg = kilogram; m³ = cubic meter; MJ = megajoule; MJ/kg = megajoules per kilogram = MJ/m³: megajoules per cubic meter.

^a Source: (ecoinvent Centre, 2007); Available data is for low-and un-alloyed steel.

^b Source: (IPCC, 2007).

Table S2 . Input and output flows to produce 1 kg of primary, chromium steel in the U.S., China and Europe.

1 kg of Chromium Steel ^a	ecoinvent ^a US		ecoinvent ^a China		ecoinvent ^a Europe	
	primary	unit	primary	unit	primary	unit
Inputs^b						
Coal, hard, unspecified, in ground	1.9E+00	kg	2.2E+00	kg	1.5E+00	kg
Coal, brown, in ground	1.2E-01	kg	5.7E-02	kg	4.0E-01	kg
Gas, natural, in ground	4.7E-01	m ³	3.8E-01	m ³	4.6E-01	m ³
Gas, mine, off-gas, process, coal mining/m ³	1.6E-02	m ³	2.2E-02	m ³	1.5E-02	m ³
Crude Oil	1.7E-01	kg	1.7E-01	kg	1.7E-01	kg
Uranium, in ground	1.3E-05	kg	3.6E-06	kg	1.6E-05	kg
Energy, solar, converted	1.4E-03	MJ	3.5E-01	MJ	2.3E-03	MJ
Energy, potential (in hydropower reservoir), converted	9.6E+00	MJ	1.0E+01	MJ	9.9E+00	MJ
Energy, kinetic (in wind), converted	4.9E-02	MJ	2.8E-02	MJ	1.6E-01	MJ
Energy, gross calorific value, in biomass, primary forest	6.0E-05	MJ	5.8E-05	MJ	6.1E-05	MJ
Energy, gross calorific value, in biomass	6.2E-01	MJ	5.6E-01	MJ	6.3E-01	MJ
Total CED (MJ/kg)	8.1E+01		7.9E+01		7.8E+01	
Outputs^b						
Carbon Dioxide	4.8E+00	kg	5.3E+00	kg	4.4E+00	kg
Methane	1.2E-02	kg	2.2E-02	kg	1.1E-02	kg
Total CO₂eq (kg/kg)	5.1E+00		5.8E+00		4.7E+00	
Conversions	value	unit				
Coal, hard, unspecified, in ground	19.1	MJ/kg				
Coal, brown, in ground	9.9	MJ/kg				
Gas, natural, in ground	38.3	MJ/m ³				
Gas, mine, off-gas, process,	39.8	MJ/m ³				

coal mining/m ³		
Crude Oil, in ground	45.8	MJ/kg
Uranium, in ground	5.6x10 ⁵	MJ/kg
Methane GWP ^b	25	

Note: kg = kilogram; m³ = cubic meter; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/m³ = megajoules per cubic meter.

^a Source: (ecoinvent Centre, 2007)

^b Source: (IPCC, 2007).

Table S3 Results showing CED impacts of steel manufacturing using the process-sum approach.

% Secondary Content	% Primary Content	Low-Alloyed Steel (MJ/kg steel)			Chromium (Stainless) Steel (MJ/kg steel)		
		Europe	China	US	Europe	China	US
0	100	36	36	37	79	78	81
25	75	30	30	31	77	77	80
50	50	25	25	26	76	76	79
75	25	19	19	20	75	74	78
100	0	14	14	15	73	73	77

Note: CED = cumulative energy demand; MJ/kg = megajoules per kilogram of steel; % Secondary content = percent of recycled steel (scrap) used in production; % Primary content = percent virgin steel used in production.

Table S4 Results showing GWP impacts of steel manufacturing using the process-sum approach.

% Secondary Content	% Primary Content	Low-Alloyed Steel (kg CO ₂ eq/kg steel)			Chromium (Stainless Steel) (kg CO ₂ eq/kg steel)		
		Europe	China	US	Europe	China	US
0	100	2.3	2.6	2.4	4.7	5.9	5.2
25	75	1.9	2.2	2.0	4.6	5.8	5.0
50	50	1.5	1.8	1.6	4.4	5.7	4.9
75	25	1.0	1.4	1.2	4.3	5.6	4.8
100	0	0.7	1.1	0.8	4.1	5.5	4.7

Note: GWP = global warming potential; kg CO₂eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel; % Secondary content = percent of recycled steel (scrap) used in production; % Primary content = percent virgin steel used in production.

Table S5 GWP/CED results from previous studies and reports for the process-based approach.

Source	Type of Finished Steel	CED (MJ/kg steel)	GWP (kg CO ₂ eq/ kg steel)	Approximate % Secondary Steel Content
World Steel Association (Crawford, 2013)	Sections	16	1.2	85
	Tinplate	22	1.7	60
(A) Athena (Markus Engineering Services, 2002)	Rebar, rod and light sections	19	.60	90
	Cold-rolled sheet	23	1.0	40
	Hot-rolled sheet	26	1.5	55
USLCI (NREL, 2013)	Iron and steel mix	10	.90	70
	Hot-rolled sheet	26	2.3	30
	Cold-rolled sheet	30	2.6	30
(Hammond and Jones, 2008)	Typical steel 42.3% secondary steel	24	.48	42
	Primary steel	35	.75	0
(Keoleian et al., 2008)	Stainless ^e	16	1.2	Unknown ^f
	Cold-rolled ^e	29	2.1	Unknown ^f
	Extruding/galvanizing	37	3.2	Unknown ^f
(Buchanan and Honey, 1994)	General	35	1.4	24 ^d
	Sections	59	2.0	24 ^d
(Zabalza Bribián et al., 2011)	Reinforcing	24	1.5	40 ^e
(Scheuer et al., 2003)	EAF technology ^a	12	Unknown ^f	100
	Secondary, Hot-rolled ^a	14	Unknown ^f	100
	Primary, Cold-rolled ^a	28	Unknown ^f	0
	Electrogalvanized	31	Unknown ^f	0
	Stainless	8	Unknown ^f	Unknown ^f

Note: GWP = global warming potential; CED = cumulative energy demand; EAF = electric arc furnace; BOF = blast oxygen furnace; MJ/kg steel = megajoules per kilogram of steel; kg CO₂eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel; Secondary steel = recycled steel; Primary steel = virgin steel.

^a EAF technology is assumed to be comprised of 100% secondary (recycled) steel; BOF technology is assumed to be comprised of 100% primary (virgin) steel.

^b Values based on the percentage of EAF and BOF technologies used in these regions in 2002 (WSA, 2013).

^c Values based on the percentage of EAF and BOF technologies used globally when in 1983 when study was completed (WSA, 2013).

^d Values based on the percentage of EAF and BOF technologies used in Europe in 2007 when study was completed (WSA, 2013).

^e Values do not include primary fabrication energy.

^f Values were not included in previous work.

Table S6 Quantity, GWP and contribution from steel in original residential building LCA study (Gong et al. 2012).

Construction Type	Quantity (tonne)	GWP (kg CO ₂ eq/kg steel)	Contribution to GWP from steel in original study kg CO ₂ eq (Gong et al. 2012)
CFC	282	2.2	621
SFC	459	2.2	1011

Note: GWP = global warming potential; kg CO₂eq/kg steel = kilogram carbon dioxide equivalent per kilogram of steel; kg CO₂eq = kilogram carbon dioxide equivalent.

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