Strategies for reducing energy demand in the materials sector

By

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ABSTRACT

This research answers a key question – can the materials sector reduce its energy demand by 50% by 2050? Five primary materials of steel, cement, aluminum, paper, and plastic, contribute to 50% or more of the final energy use and CO_2 emissions by industry, and thus are of primary focus. Both technical and demand-side strategies are evaluated to conclude that halving energy demand by 2050 is unlikely given the limitations governed by thermodynamics, scrap availability, and producer/consumer preferences, however some of the strategies analyzed offer encouraging opportunities and should be pursued.

The thesis starts with understanding the evolution of material demand as society transforms from a developing to a developed economy. Economic scopes of global, USA, China, and India are assessed. The evolution trends are starkly different. The US shows strong signs of saturation while; both developing economies of China and India do not. The actors of material demand are analyzed to determine what is driving the difference. Results show that consumer income and population have been consistently increasing, but in the second half of the 20th century, the US industry has demanded less material per dollar output, while the US industry output has continued to grow. Collectively they tend to cancel each other, presenting a material saturation phenomenon. For China and India not only is the industry income and industry share of GDP growing, for each unit value addition, industry has continued to demand more material, avoiding demand saturation.

One major way to reduce energy used for materials is to decrease the energy intensity of material production. Four technology based strategies are investigated without regard to cost: 1) widespread application of best available technology (BAT), 2) BAT to cutting edge technologies, 3) aggressive recycling, and finally, 4) significant improvements in recycling technologies. Taken together these aggressive strategies could produce impressive gains, on the order of a 20% reduction in energy relative to 2005, but well short of the goal of 50% reduction. Ultimately, we face fundamental thermodynamic and scrap availability constraints. Thus reducing material demand without compromising any service (called "material efficiency") is outlined as an approach to solving this dilemma.

One way to increase material efficiency is use products for longer. Remanufacturing can support this by bringing used products back to like-new condition. Remanufactured products that substitute for new products are claimed to save energy. This comes from only looking at the materials production and manufacturing phases of the life cycle. However, when the use phase is included, the situation can change radically. For the 25 product cases we analyzed, 8 cases clearly saved energy, 6 did not, and 11 were too close to call. The drivers for this difference are explained. Thus the energy saving potential of remanufacturing seems complex and uncertain, especially given the trend of powering up of products followed by improvement of their energy efficiencies. As a result focusing remanufacturing efforts on passive products is recommended.

Thus scalable material efficiency strategies need to be discovered. However even with the optimistic energy efficiency strategies deployed, in order to achieve the targets, demand increase for the materials needs to be restricted to under 25% of 2005 quantities. This entails that by 2050 we would need to reduce global demand per capita by 10% of today's global average and by 70% of today's US average which is an insurmountable task. Material efficiency strategies hold an impressive technical potential but face severe economic and behavioral challenges that future research needs to overcome.

Thesis Supervisor: Timothy G. Gutowski

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Table of Contents

Chapter 1: Introducing the material-energy space 13

Chapter 2: Research Objectives, Methodologies, and Prior Work 23

Research Objectives 23

Methodologies 24

Prior Work 67

Chapter 3: Evolution of a materials society 85

Abstract 85

Introduction 86

Prior work 86

Materials and methods 89

Results 90

Discussion 98

Summary and next steps 103

Chapter 4: Energy efficiency of materials production 104

Abstract 104

Introduction 104

Framework 105

Embodied energy 106

Material substitution 114

Calculation details 116

Scenario and sensitivity analysis 119

Summary and next steps 121

Chapter 5: Material efficiency through remanufacturing 124

Abstract 124

Introduction to material efficiency through remanufacturing 125

Introduction to remanufacturing 126

Energy saving potential of product remanufacturing 128

Life cycle energy analysis of products 129

Research results 131

Discussion 142

Chapter 6: Material efficiency targets, feasibility, and future work 144

Feasibility of achieving material efficiency targets 144

Material efficiency options 145

Material efficiency challenges 147

Summary and future work 148

References 155

Appendix 176

List of Figures

Figure 1: Global extraction of materials in the 20th century. (1 Gt = 10^{12} kg) [1] 14

Figure 2: Breakdown of industrial minerals produced globally into the major components by weight. 'Other' includes the highly fragmented set of remaining materials with none being consumed at over 5% of total industrial minerals and most in fact less than 1% [2] 15

Figure 3: The carbon emission in kg CO_2 per kg of material produced versus the embodied energy [4, 5]. 16

Figure 4: Total energy used for the production of 29 materials worldwide, cumulative scale on the right [3, 5]. 17

Figure 5: Breakdown of industrial energy consumption and carbon dioxide emissions [4, 6, 7].. 18

Figure 6: (a) Apparent consumption (mass) trends for key metals and minerals over the last 45 years in USA, China, India, and globally. The consumption data is presented as indices with the 1960 quantity for each individual material been normalized to 1. The percentages along each curve are the corresponding CAGRs [9]. (b) Embodied energy and CO_2 of key materials (primary energy for primary production) [[5], Copper and Zinc from [10]]. (c) Material production quantities and total energy to produce them for different geographies across 25 years [11] 21

Figure 7: Embodied energy scatter from various sources gathered together by the Bath University ICE database [10]. The y-axis is embodies energy in MJ/kg and x-axis is the time period in years 27

Figure 8: System for thermodynamic framework 30

Figure 9: An ideal separation process [29] 34

Figure 10: Schematic of a material life cycle. Quantities of flows are shown in grey. Fractions are shown in black. Names of different kinds of scrap in blue. 42

Figure 11: Model for estimating scrap availability through a material flow analysis 45

Figure 12: Primary and secondary production energy intensities for different materials and their current recycling rates, r, as fraction of supply. Final energy does not include losses in electricity production [4]. 47

Figure 13: Detailed schematic of material life cycle flow used to construct a detailed model of recycling, by Graedel et al. [44] 48

Figure 14. Life Cycle Inventory inputs and outputs. The dotted line reveals the primary scope of analysis for this thesis (modified version of an original figure taken from [48]). ... 49
Figure 15: Relationship between material price, embodied energy, and world production for different materials [4, 5]. ... 61
Figure 16: Consumption of light against (β*GDP)/CoL taken from Tsao et al [70]. 'β' is a constant and thus the chart presets consumption per capita [y-axis] vs. consumer capacity [x-axis] as defined above ... 62
Figure 17: Demand (y-axis) vs. buying capacity (x-axis) plotted for the different materials and different geo-economic scopes. Buying capacity is defined as the ratio of industry income for the particular economy and the corresponding material price. Each data-point corresponds to a particular year, and the temporal range is given in parenthesis. ... 94
Figure 18: YtY changes in demand per capita and the corresponding actors mentioned in Equation 59. Also plotted is the change in 'M', material intensity of industry, which is the product of F and 1/p. ... 98
Figure 19: Simplified representation of conclusions drawn from Figure 18. Colors are comparing different actors for same geo-economic scope. Darker is larger magnitude, green(ish) is positive, and red(ish) is negative. '*'s are comparing different geo-economic scopes for same actor with more '*'s referring to a larger magnitude. ... 98
Figure 20: Forecasts of material demand by the IEA up to 2050. Both 'high' and 'low' projections are plotted as bands [6]. The 'blue-line' is explained in Chapter 6. ... 106
Figure 21: Embodied energy of 16 metals [5] plotted against the dilution, or inverse of concentration, of the common ores used to produce the metals [117]. See SI for more discussion of this plot. ... 107
Figure 22: Historic trends in global average energy requirements for production of pig iron from ore, and for aluminum smelting, versus the respective global production volumes. The corresponding years are labeled above the chart. Also included are the theoretical minimum values for the two processes. For aluminum the primary energy is shown on the right vertical axis using global average electricity factor of 9.3 MJ/kWh. Data for iron energy intensity is obtained from [143] and that for aluminum from [105]. Production data is obtained from [9]. Pie chart data is taken from [85], [105], [21] ... 111
Figure 23: Historical Regional data for the energy intensity of aluminum smelting (taken as is from [6]). ... 112

Figure 24: Cumulative reduction in ‘e’ and ‘E’ relative to 2050 values for the most conservative low-demand case. Target for ‘E’ reduction is 50% shown in green. BAU 2050 assumes no change in ‘e’ through 2050. 119

Figure 25: Total energy reduction in 2050 relative to 2005 for the various scenarios considered. The target of 50% reduction is shown as the green line. 121

Figure 26: Expected savings for key materials (absolute in Mt (columns) and as a fraction of global production (circles)) if all units of the considered products are remanufactured successfully at end of use. Note axis for absolute savings is in logarithmic scale........ 129

Figure 27: Comparative life cycle energy assessment between new and remanufactured refrigerators from 1966 to 2008. The insert shows the distribution of life cycle energy use across the different phases, for refrigerators manufactured in the corresponding years. The labels “Remanufacture” and “Buy New” are the decisions the consumer should make to reduce energy if the data point falls in it’s respective half of the plot area. 134

Figure 28: Comparative LCI of energy use between new and remanufactured products. See Table 9 for a legend to the case numbers. 139

Figure 29: Percentage life cycle energy saving by choosing to remanufacture over new for the 25 product case studies. See Table 9 for a legend to the case numbers. 140

Figure 30: Demand per capita comparison between today “2005” and IEA projections of “2050-low” and “2050-high”, as well as US average labeled “2005-USA”, and what a 25% restriction on Q increase would mean, labeled “2050-target”. The numbers in the green bar are for 2050-low. 145

Figure 31: Potential areas of future work (research and strategy deployment) from this thesis. 151

List of Tables

Table 1: Research objectives and scope of work ... 23
Table 2: Attributes and example questions used for data qualification ... 26
Table 3: Example of data scatter for steel with information available for qualification ... 28
Table 4: Exergy analysis of an integrated steel plant (adopted from [21]). 'trs' refers to tonne of rolled steel. ... 40
Table 5: Summary of key prior work and comparison to contribution of thesis. Solid filling refers to a more comprehensive contribution of reference (row) to area of research (column), hatched refers to partial contribution ... 69
Table 6: List of prior work, their scope of work, their contribution to this research, and additional contribution by this thesis ... 70
Table 7: Recycling parameters for top five materials. ('Cur' = current average; 'CE' = cutting edge; 'r' = Recycling rate as a fraction of supply). Details are provided in the Appendix. 113
Table 8: The magnitude of effect relative to price of increasing energy price or imposing a CO_2 tax. Prices same as in Figure 15. Energy fraction of cost taken from [101], and CO_2 intensities from [5]. ... 122
Table 9: Comparative LCI of energy use between new and remanufactured products [173] ... 138
Table 10: Challenges associated with the different material efficiency strategies in consideration ... 147

Chapter 1: Introducing the material-energy space

Materials aid societal development in a variety of ways. Many of the anthropogenic demands, directly or indirectly, are provided by materials. Without materials there would be no cars to drive around, no houses to live in, and there would also be no computers to rely on. It is almost impossible to imagine a world without materials. It is this reliance that has driven a steep growth in consumption for materials around the globe. Figure 1 exhibits the global trend in material extraction in the 20th century classified into three classes – biomass, fossil fuels, and industrial minerals. In 2006, we extracted almost 60 billion tonnes of materials with 50% of these being industrial minerals, 33% biomass, and the rest 17% fossil fuels. Also interesting are the growth rates in consumption of the different material types. Clearly industrial minerals seemed to have grown the fastest at a cumulative annual growth rate (CAGR) of 4.3% over the second half of the 20th century. On the other hand fossil fuels consumption has grown at 2.8% while biomass at 1.3%. This means that not only is industrial materials the largest class of materials extracted, their extracted quantities are also growing the fastest. At 4.3% CAGR, the extraction for industrial minerals expectedly doubles every 16-18 years.

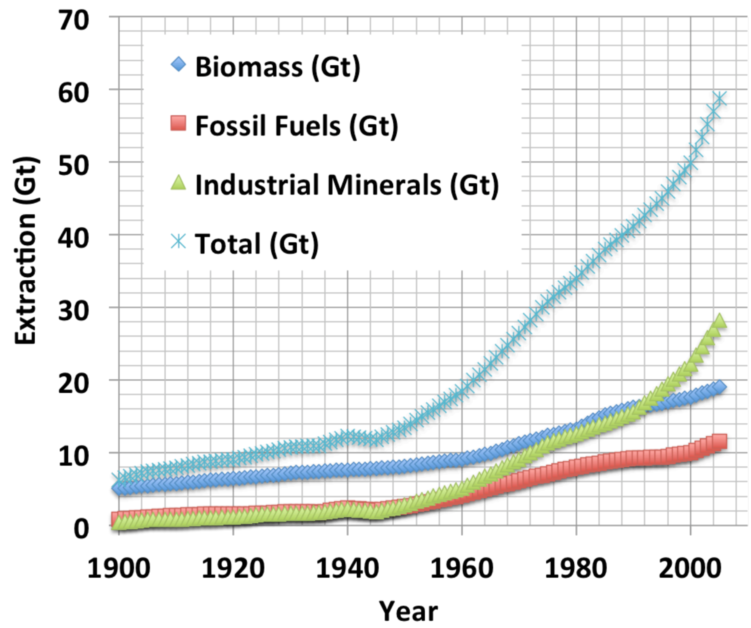


Figure 1: Global extraction of materials in the 20th century. (1 Gt = 10^{12} kg) [1]

In this thesis we thus focus on industrial minerals to understand how we can reduce the energy associated with their demand. This includes materials that make up most of the products we consume today, both at home and in industries, such as metals, ceramics, polymers, composites, semiconductors, etc. Figure 2 gives a breakdown by weight of the industrial materials produced globally for the 20th century (note that Figure 1 presents extraction mass which includes the material of interest and the matrix, while Figure 2 refers only to the produced mass of the material of interest). Only two materials – cement, and iron and steel have dominated this sector with consistently increasing influence of cement. Demand for steel has grown as well but at rates lower than cement. ‘Other’ materials is the highly fragmented portion comprising of all other materials with each less than 5% contribution and most less than even 1%. Some of the biggest ones within these are salt; sand and gravel; phosphate, sulfur, and potash used in fertilizers; non-renewable organics like plastics, waxes, rubber, etc.; paper; and of course other metals like aluminum, copper, zinc, and manganese.

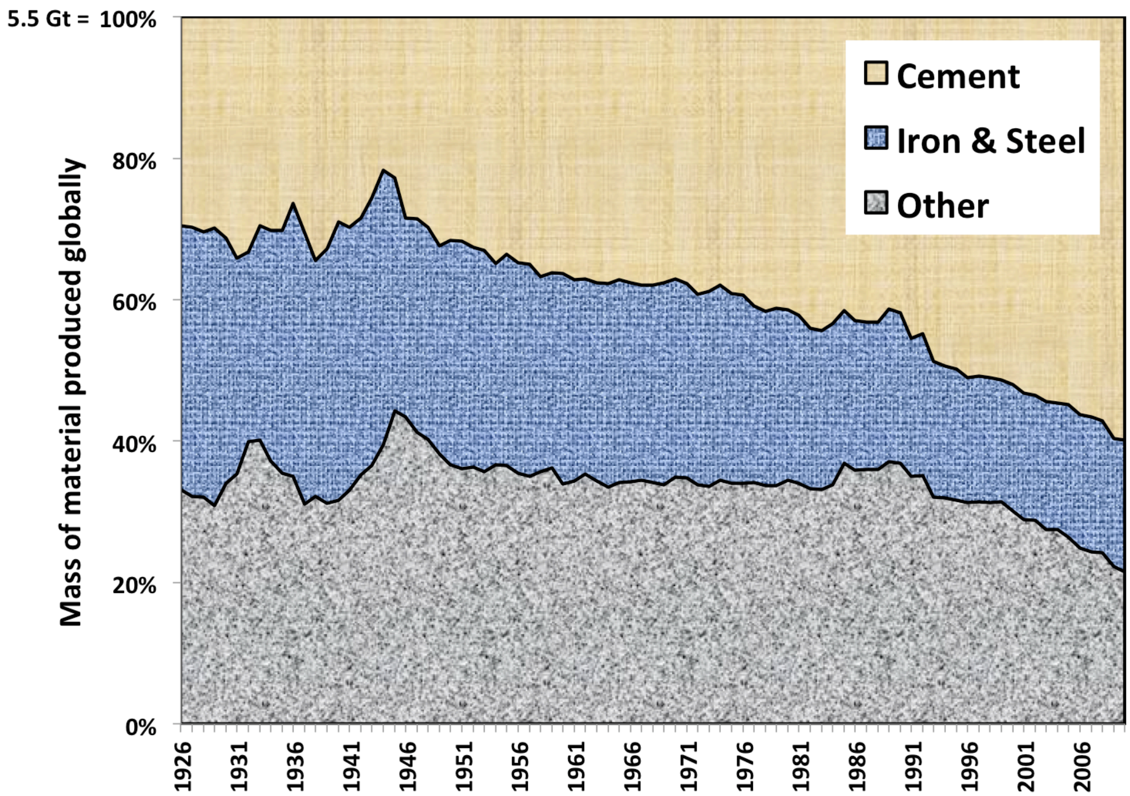


Figure 2: Breakdown of industrial minerals produced globally into the major components by weight. 'Other' includes the highly fragmented set of remaining materials with none being consumed at over 5% of total industrial minerals and most in fact less than 1% [2]

Clearly, we consume a lot of materials (global average of slightly less than 500 kg of cement and 150 kg of iron and steel, per capita per year (in 2008)), but of course they make our day-to-day products that serve us with many of our needs. From an environmental perspective one needs to look deeper into the environmental attributes of the different materials and ask which ones dominate from that front, and more importantly what is the potential to mitigate their corresponding environmental impacts. In this thesis we specifically focus on the energy footprint of the materials sector and how we can reduce it. One can also consider other impacts like carbon, water, land use, resource depletion, toxicological impacts, etc., but these are beyond the scope of this work.

In the materials sector, at least, there exists a strong correlation between the energy and carbon footprint across materials, referring to the large fraction of the CO_2 emissions originating from energy use. This is shown graphically in Figure 3, with the correlation coefficient higher than 0.93. Overall, IPCC has shown that close to 91% of the total carbon from the sector is from the energy use [3]. However, some materials emit CO_2 during the chemical processing involved to convert the material from ore to a more useful form. One example of this is cement, a majority of which is clinker. Clinker is produced through calcination which involves heating of calcium carbonation to lime / clinker, emitting CO_2. Stoichiometrically, around half of the CO_2 footprint of cement comes from this process, while the rest is from the fuel combustion on site and for electricity production. Similarly 30% of the CO_2 emissions associated with steel production are from the process of coke reacting with iron oxide in the blast furnace.

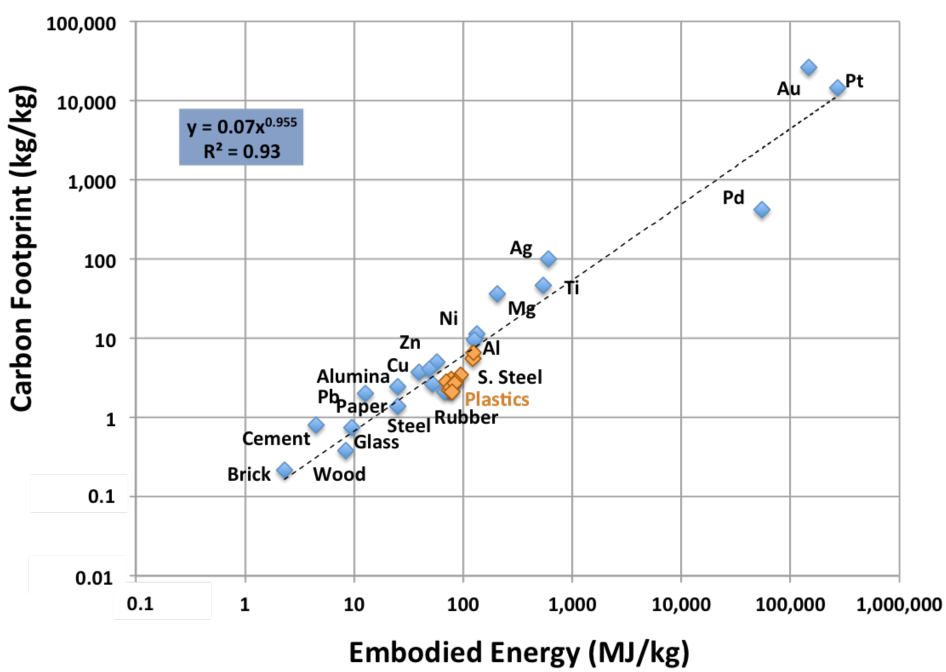


Figure 3: The carbon emission in kg CO_2 per kg of material produced versus the embodied energy [4, 5].

Given this, our primary focus is thus to reduce the energy demand to provide the materials we use which will automatically lead to an almost proportional carbon reduction. A closer look into this helps focus even further as shown in Figure 4.

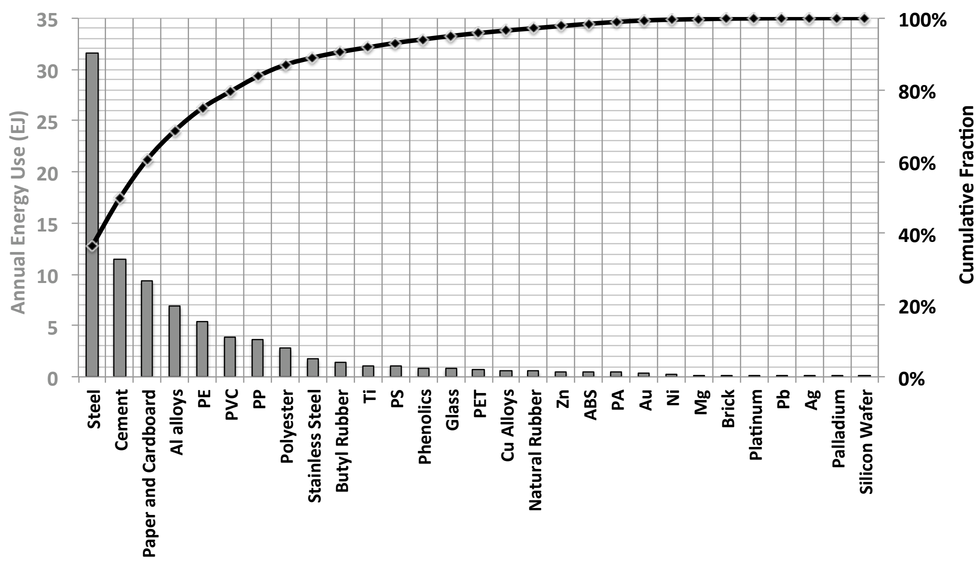


Figure 4: Total energy used for the production of 29 materials worldwide, cumulative scale on the right [3, 5].

This shows the material-energy space as a *Pareto* representation of over 29 high-energy consuming materials sorted in descending order of their total annual energy use. Also shown through the *black* line is the cumulative distribution function for the energy consumed by these materials. If the different plastics were to be combined into one material 'plastic', it is highly revealing to note that just five materials consume close to 90% of the total energy consumed by these chosen set of 29 commonly used materials. These are steel, aluminum, plastic, paper, and cement. In fact when compared to the total energy or carbon consumed by the global industrial sector, these five materials collectively dominate, with almost 50% of the final energy footprint (see Figure 5). Amongst these steel has the largest footprint, followed by plastics (half of which is the fuel value), then cement, paper, and relatively smallest but significant contribution by aluminum. Note the difference between the energy and carbon contribution for cement. This relates to the previously described process based CO_2 emissions associated with cement production. With industry energy and carbon being roughly a third of total global footprints [3, 4, 6, 7], these five materials contribute a significant 15% of the global impacts. We thus try to focus our analysis to these materials, but consider others as and when needed.

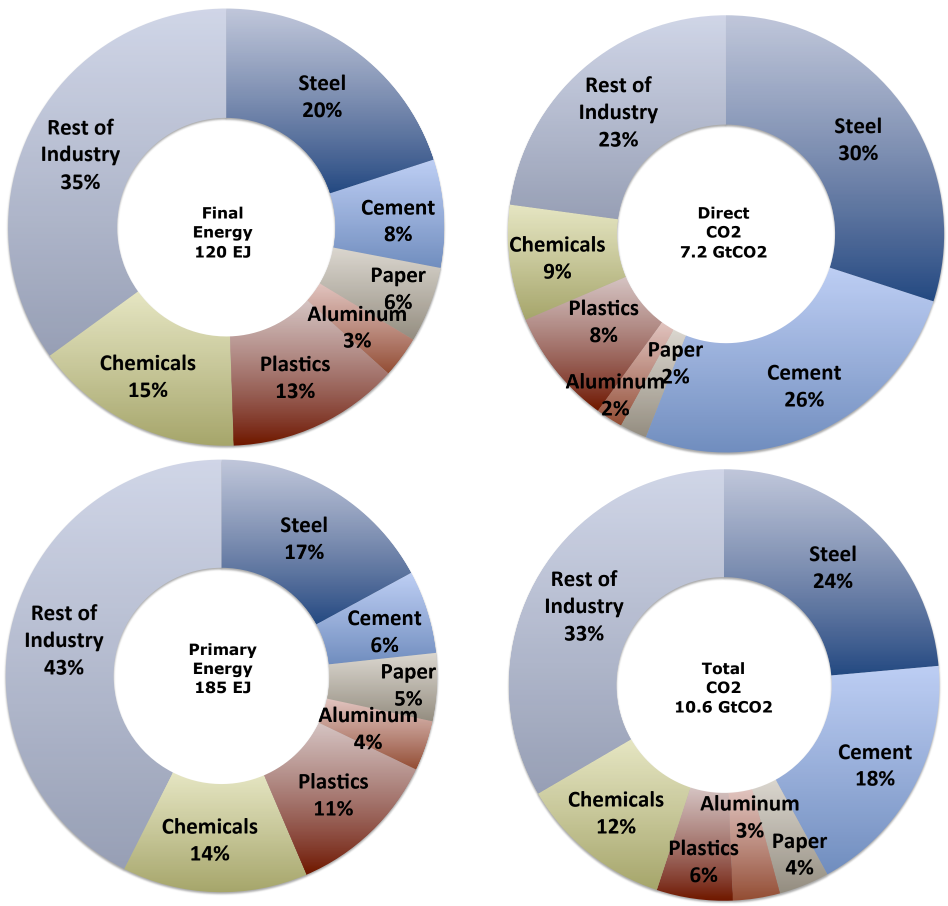
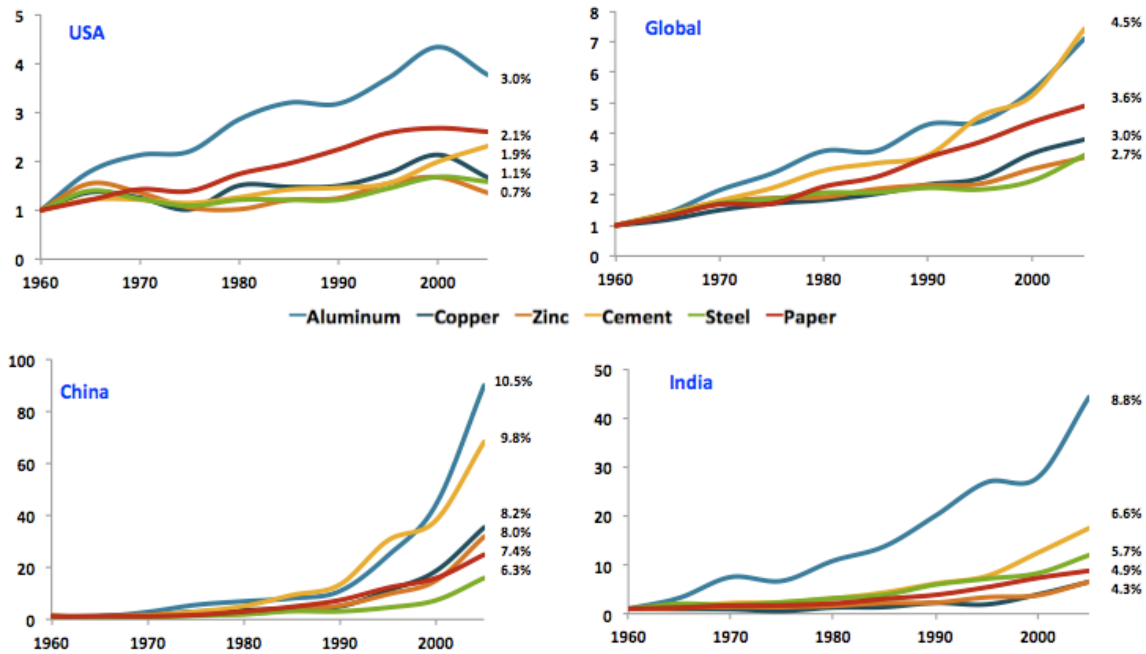


Figure 5: Breakdown of industrial energy consumption and carbon dioxide emissions [4, 6, 7]

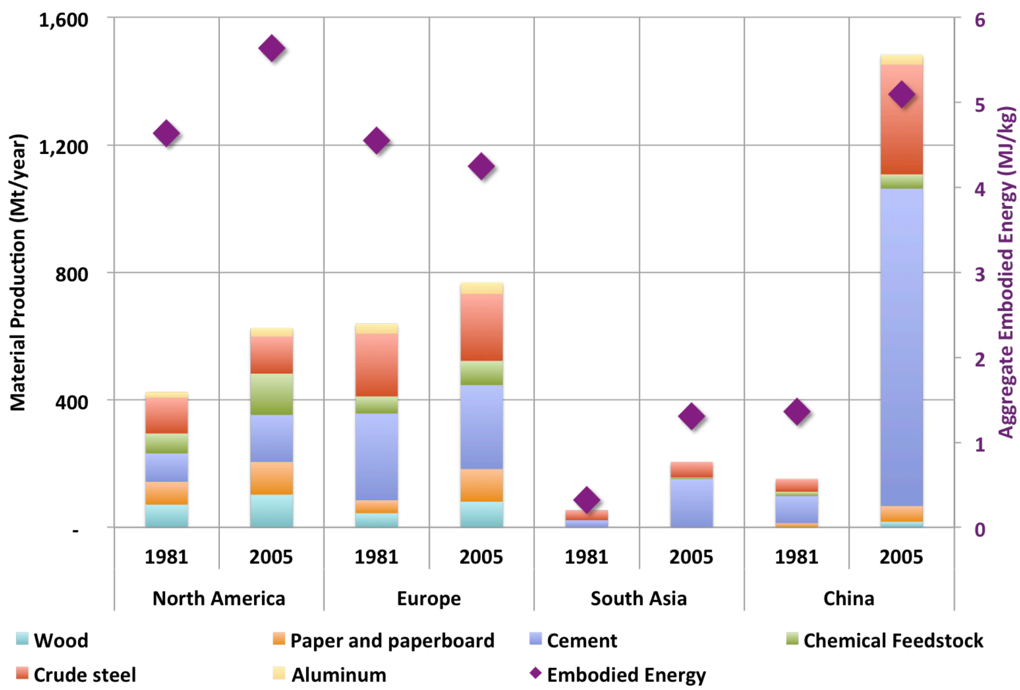
Note, both Figure 4 and Figure 5 exhibit the total energy for each material, which simply put, is the product of the total quantity of material produced, and the average energy requirement to produce a unit quantity of material, sometimes referred to as embodied energy or energy intensity. Another term, 'material intensity,' will be used to refer to the ratio of material demand and some measure of economic performance like GDP or GNP. Figure 6 elaborates on material demand and embodied energy further. First, material apparent consumption is presented for the US, China, India, and at the global level, over the second half of the 20th century. High quality data for plastics was not obtained and thus omitted. For each material, in each geography, the consumption is normalized to index the 1960 value to 1. The CAGR are also shown to the right of each curve. As expected, the growth rates in China are significantly higher, especially in the recent decades. Globally material demand has risen at ~ 3-4.5% per annum, while for the US its around 1-3%. Demand for aluminum has exhibited the highest growth for all scopes ranging from 3% in the US to 10.5% in China and India each. Steel has been slower, which might also have to do with the large quantities in which steel is consumed, either making the percentage changes small or due to some kind of saturation, or both. The reasons for the different apparent consumption rates can relate to a broad range of characteristics, some specific for the individual materials, but eventually correspond to the final utilization of these materials in providing the services demanded. Part (b) of Figure 6 presents the material specific embodied energy data. The embodied energy and carbon vary by over an order of magnitude across these materials, with the most consumed material cement having the lowest, and aluminum having the highest. More details about the composition of the footprints and their temporal and geographical variation will be provided in subsequent chapters. However it can be summarized that while impact per unit produced has significantly reduced over time for these materials (roughly at 1% per annum), the growth in apparent consumption has often outpaced it, causing the total impact to grow [4, 8]. Part (c) of Figure 6, shows how the material production and the associated total energy use has changed between 1981 and 2005 for four regions around the world. Note the significant increase in cement and steel production in China with an undesirable increase in embodied energy by over 400% driven mainly by the compositional change in materials consumed. Also interesting is how Europe has managed to reduce its embodied energy over this period, even though the material production composition seems to have been almost the same. Compositionally there has been little change for North America as well, however its embodied energy has increased by over 20%. We analyze the details in the subsequent chapters.



(a)

Material	Embodied Energy (MJ/kg)	Embodied CO_2 (kg CO_2/kg)
Steel	32	2.5
Cement	5	0.8
Paper	32	1.5
Plastic	90	3
Aluminum	199	9.5
Copper	70	3.8
Zinc	72	3.9

(b)



(c)

Figure 6: (a) Apparent consumption (mass) trends for key metals and minerals over the last 45 years in USA, China, India, and globally. The consumption data is presented as indices with the 1960 quantity for each individual material been normalized to 1. The percentages along each curve are the corresponding CAGRs [9]. (b) Embodied energy and CO_2 of key materials (primary energy for primary production) [[5], Copper and Zinc from [10]]. (c) Material production quantities and total energy to produce them for different geographies across 25 years [11].

In this chapter we have determined a relevant scope for assessing energy reduction strategies for the materials sector. Specifically we found that assessing five key materials of steel, aluminum, cement, paper, and plastic, is crucial, and to look at addressing strategies for both embodied energy reduction, as well as material demand reduction.

In the next chapter we start with framing the thesis with the targeted research questions, methodologies and frameworks for analysis, and an overview of prior work. In Chapter 3 we move ahead understanding material demand, specifically what drives demand and what that can mean for future demand, so as to gain insight into what levers we can target. Then we look at energy efficiency in chapter 4 where we estimate the potential to reduce material embodied energy through various technical strategies. In chapter 5 we move into the other set of strategies – material efficiency – and comprehensively analyze the energy saving potential of remanufacturing products over replacing them with newer ones. In the final chapter, chapter 6, we assess the overall feasibility of material efficiency to help meet the targets, followed by a summary of key conclusions and suggestions for future work.

Chapter 2: Research Objectives, Methodologies, and Prior Work

Research Objectives

Sustainability guidelines for energy and carbon emissions suggest that we need to halve our energy use from 2000 to 2050[1] or act even faster [12, 13]. This means that while we have to allow for the developing world to continue increasing their demand for material services, we need to find ways to decrease the overall global energy use. Thus the motivation of this thesis is to evaluate strategies that can potentially reduce energy demand by the materials sector to half, specifically focusing on five primary structural materials – steel, aluminum, cement, paper, and plastic, as they dominate the industrial energy and carbon impacts. The specific questions / objectives for each section of the thesis and the corresponding scope of research are presented below.

Table 1: Research objectives and scope of work

	Material demand	***Energy efficiency***	***Remanufacturing***	***Material Efficiency***
Research Questions/ Objectives	Understand how demand for materials has changed historically and how various actors have contributed to this change	Estimate the potential to reduce energy through decreased energy intensity of materials	Test the hypothesis that remanufacturing products saves energy	Gauge the feasibility of material efficiency strategies in achieving targets
Scope of	Novel method	Assess the	Conduct 25	Evaluate

[1] For example, the IPCC recommends reducing CO_2 by 50% to 80% by 2050. Among the options available; 1) energy efficiency, 2) development of a renewables electricity grid, and electification of materials production, and 3) carbon capture and storage, we focus on the first, which appears to have significant near term and scalability advantages over the other two options.

work	to analyze how demand has changed and using IPAT analysis to study the role of population, affluence, material price, and industry choice in driving these changes	potential of deploying best available and cutting edge technologies for primary production as well as increasing recycling rates and recycling energy efficiency on decreasing overall energy requirement to provide materials	product case studies and compare the life cycle energy need from using a remanufactured product versus life cycle energy need from using a new product	targets for material efficiency and compare them to historic trends in material demand to guide future research in this area

Methodologies

Provided below are the various frameworks and models used for data procurement and calculations.

Energy demand by the materials sector

Framework objective: To quantify the total energy used for materials production as a product of the quantity produced and the energy use per unit production

$$E_i = Q_i \cdot e_i$$

Equation 1

where

E_i = energy use per year for material "i" (Joules)

Q_i = material production per year (mass)

e_i = energy intensity (MJ/kg) (also referred to as 'embodied energy')

Total energy use across different materials or different grades of materials is the sum $E_T = \mathbf{\Sigma}\, E_i = Q_T e_{avg}$, where e_{avg} is the average energy intensity across the selected material set and calculated as the ratio of the total energy use per year for all the materials E_T and the total quantity produced per year for all the materials Q_T.

Data used were of two kinds:

(1) Procured practical data from either secondary databases or personal communications with industrial experts
(2) Estimated theoretical minimum data through thermodynamic models

In the case of energy intensity data, 'e', (1) and (2) were compared to get a sense of the efficiency of current processes and thus the potential for improvement.

Procured practical data from secondary sources

Framework objective: To qualify data procured from external sources by developing an attribute test set to check for consistency with the scope of this work

Practical data refers to data of processes and technologies as they as practiced today, or historically. This data is mostly sourced from reputed secondary data sources but often also complemented with primary data surveys by contacting industrial experts. Provided in the Appendix are the data and sources used for all the primary calculations presented in this thesis. Key references and their use in this research is also provided in the next section on Prior Work. The respective references as well as others used in this thesis have been carefully chosen to ensure accurate representation to the scope of this work. This includes a close verification for consistency across the different data through qualification of the data through important attributes. The process of collecting appropriate data is unfortunately not simple. For instance, energy intensity data is normally collected from surveys of individual companies by organizations like International Energy Agency (IEA) for various sectors, World Steel Association for steel, IAI for aluminum, etc. However geographic and temporal boundaries, allocation methods, and process specifics vary a lot across the data, making it often inconsistent for comparison. A significant portion of the effort and contribution of this thesis is in aggregating high quality data and references, to draw valuable and reliable inferences. Listed below in Table 2 are some of the attributes we have observed and tracked in the qualification of data:

Table 2: Attributes and example questions used for data qualification

Attribute	Example Questions
Source	Is the source of data credible? Has it published similar reputable data of this kind elsewhere?
Process boundary	Is finishing included? What process is used for material processing?
Operating conditions	What are the operating conditions? Is there any rate dependence? How does economic downturn alter the data?
Temporal boundary	Does the data correspond to the desired year? Is the inter-temporal data normalized appropriately for comparison?
Geographic scope	Is the data global average, or country or region specific?
Energy accounting	Is it primary or final energy? Is fuel value included? How has primary energy been calculated, if its primary energy? Is it the lower heating value (LHV)?
Secondary fraction	How is recycling rate calculated? As a fraction of supply, or discards? Does it include new / home / old scrap?
Mix of material demand	Is the energy intensity for primary, secondary, or mixed production? What are the specifics if mixed?
Material demand	Is the quantity considered production or consumption or apparent consumption or apparent supply?

Along with the above list of attributes we have also tried to follow Carl Sagan and Michael Sherman's ideas on what to consider before relying on the data or claims made by a source [14, 15]. These provide great guidance for data collection and synthesis.

We have often observed a common lacking regarding clarity and consideration of the above attributes. The Bath University through the Inventory for Carbon and Energy has consolidated energy intensity data from different sources. Figure 7 presents this for the five basic materials of interest. The plastic embodied energy estimates include the fuel value. It shows the large scatter in reported data and the lack of adequate qualification to draw confident comparisons [10].

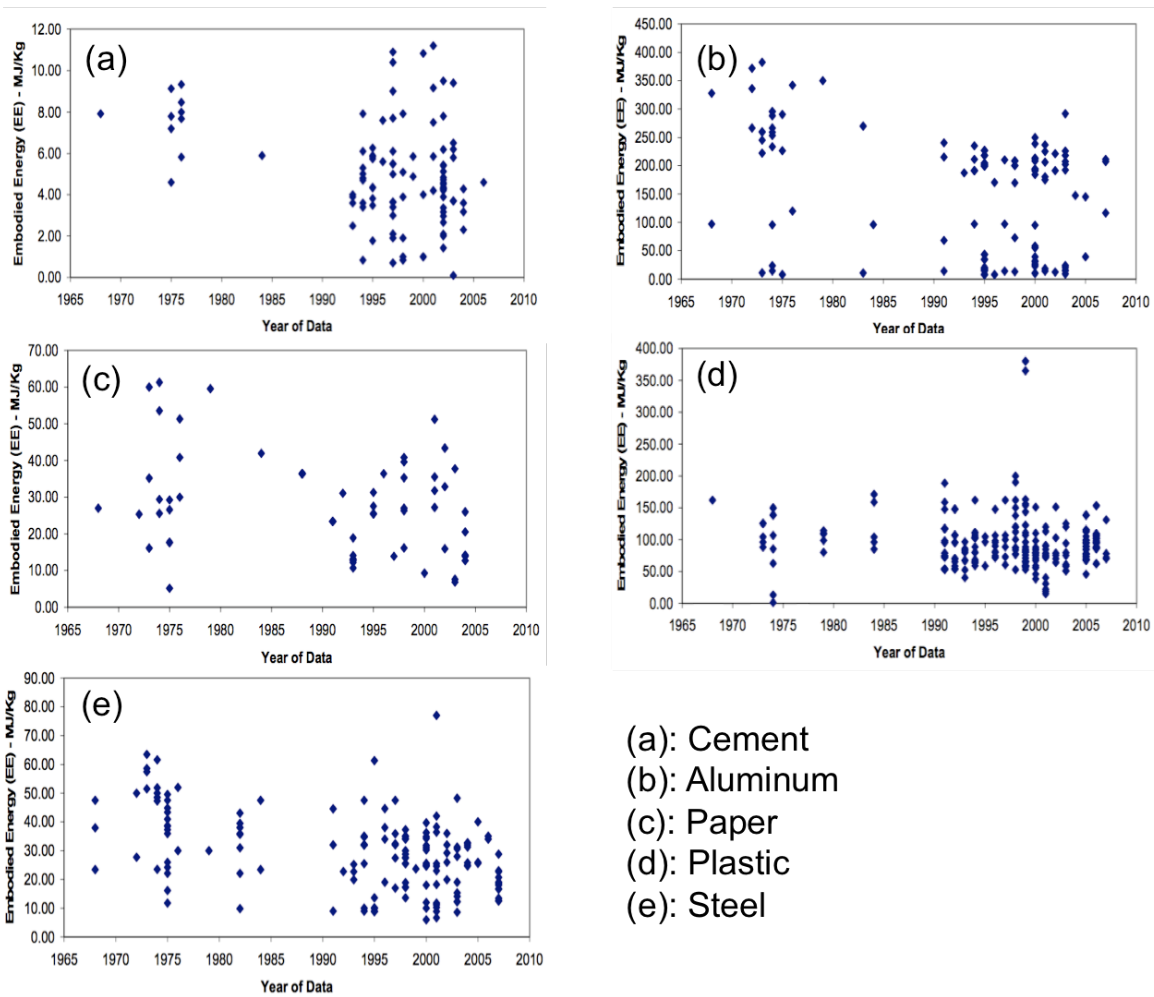


Figure 7: Embodied energy scatter from various sources gathered together by the Bath University ICE database [10]. The y-axis is embodies energy in MJ/kg and x-axis is the time period in years.

As an example of data variation, references [5, 6, 11, 16-26] are credible sources providing energy intensity information for steel. The reader is encouraged to read and compare these to understand the complications behind data qualification. We give a subset of the data values and information directly available to qualify the data in Table 3.

Table 3: Example of data scatter for steel with information available for qualification

Reference	**Data value (MJ/kg)**	**Qualification** *(checked for data qualifiers including geographic boundary, time stamp, process boundary, secondary fraction, type of energy: final or primary)* **Only available information presented**
IEA [6, 11]	19	Global average, with 37% secondary fraction, corresponds to 2005, process boundary includes steel making and finishing, final energy
Ashby [5]	22	42% secondary fraction
EnerData [16]	17.5	Global average, 2007
Bath University ICE [10]	24.4	UK mix, with 42.7% secondary fraction
US Dept of Energy [17]	18.4	US average, with 45.5% EAF fraction and 54.5% BOF fraction, 1998, process boundary includes steel making and finishing
Worrell et al. [18]	20.4	US average, with 39% EAF fraction and 61% Integrated steel mills fraction, 1994, process boundary includes steel making and finishing, primary energy
US EPA [19]	12	US average, with 53% EAF fraction, 2004
de Beer et al. [20]	20.1	US average, primary steel, includes 2.7MJ/kg for casting/rolling
US DOE [20]	8.9	US average, secondary steel, includes 2.8 MJ/kg for casting/rolling
World Steel Association [21]	24	World average, 1990, process boundary includes steel making and finishing, primary energy

Note: Integrated steel mills input a fraction of steel scrap along with ore

All data used in this work has been checked for the above attributes. However, given general operational variation, and uncertainty or potential errors in data collection and reporting, we complement the calculations with extensive sensitivity testing and scenario analyses. This ensures robustness of the results and inferences, as well as guides future research in prioritization of data collection and accuracy verification.

Detailed guidance on data collection and qualification can be obtained through various standards like ISO 14000, GHG protocol, etc. [27, 28]. However the general steps followed in this research are presented below:

a) Referencing data from credible sources like IEA, UN, USGS, EnerData, as well as from authors known to have published extensively in this space
b) Data qualification through understanding the various associated attributes
c) Benchmarking data with other sources to ensure accuracy
d) Conducting a sensitivity analysis if expected uncertainty in data is high, and / or if the specific data is crucial to the undertaken objective of the study
e) Clearly presenting all assumption made regarding data and their application

Theoretical minimum data estimated through thermodynamic models

Framework objective: To estimate the theoretical minimum energy requirement for material production using thermodynamic models and exergy analysis

The purpose of this is to construct a thermodynamic model to estimate the energy used through the different steps of material processing. The goal is not to perfectly model practical systems, but in stead to determine the theoretical minimum energy requirements for the respective material processing steps so as to gauge the potential for improvement.

Thermodynamic Framework

First lets understand the thermodynamic framework. This has been adopted from the work by Bakshi, Gutowski, and Sekulic [29]. The system is depicted in Figure 8. It consists of a material processing subsystem and energy supply subsystem that provides energy for the material processing. The boundaries and the control volumes are also shown. The environment outside of the system is at standard temperature, pressure, and chemical potential.

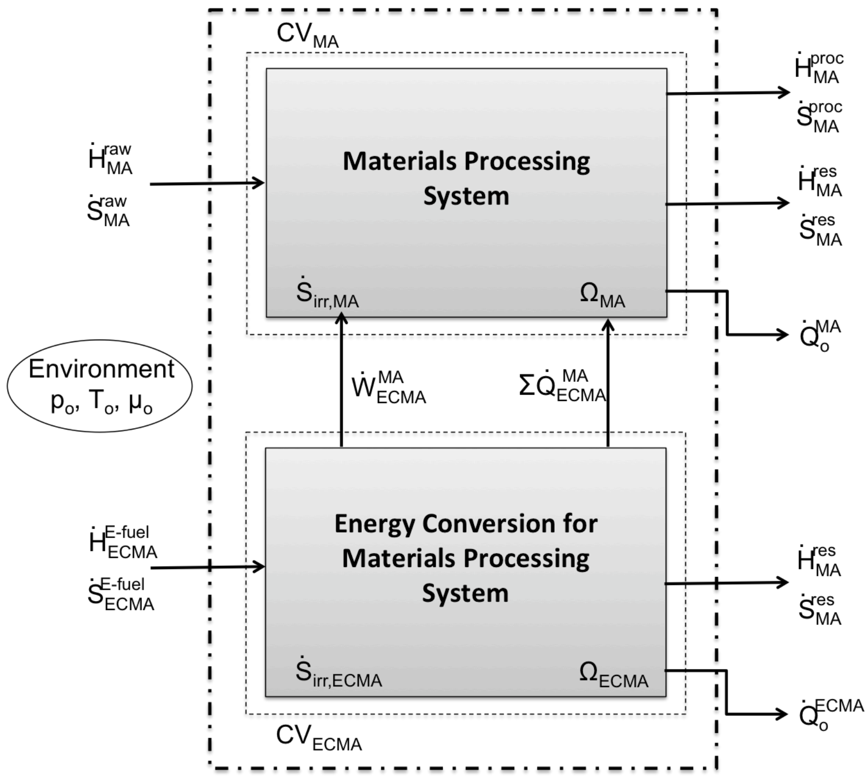


Figure 8: System for thermodynamic framework

The energy conversion subsystem (Ω_{ECMA}) provides energy in the form of work W and heat Q to the material processing system that then converts the incoming raw materials into processed materials. For the overall system boundary, three basic equations can be written for Ω_{MA}'s mass M_{MA}, energy E_{MA}, and entropy S_{MA} balance:

Mass Balance:

$$\frac{dM_{MA}}{dt} = \left(\sum_{i=1} \dot{N}_{i,in}\tilde{M}_i\right)_{MA} - \left(\sum_{i=1} \dot{N}_{i,out}\tilde{M}_i\right)_{MA}$$

Equation 2

where $\dot{N}_i$ is the amount of matter per unit time of the i[th] component entering or leaving the system and $\tilde{M}_i$ is the molar mass of that component.

Energy Balance:

$$\frac{dE_{MA}}{dt} = \sum_k \dot{Q}^{MA}_{ECMA,k} - \dot{Q}^{MA}_0 + \dot{W}^{MA}_{ECMA} + \dot{H}^{raw}_{MA} - \dot{H}^{prod}_{MA} - \dot{H}^{res}_{MA}$$

Equation 3

Where $\dot{Q}^{MA}_{ECMA,k}$ and $\dot{W}^{MA}_{ECMA}$ represent rates of heat and work interactions, respectively, between Ω_{MA} and its energy supplying subsystem Ω_{ECMA}. The $\dot{H}$ terms signify the cumulative sums of the enthalpy rates of all raw materials, processed materials, and residues in and out of the system.

Entropy Balance:

$$\frac{dS_{MA}}{dt} = \sum_k \frac{\dot{Q}^{MA}_{ECMA}}{T_k} - \frac{\dot{Q}^{MA}_0}{T_0} + \dot{S}^{raw}_{MA} - \dot{S}^{proc}_{MA} - \dot{S}^{res}_{MA} + \dot{S}_{irr,MA}$$

Equation 4

where $\dot{Q}^{MA}/T$ terms represent the entropy flows accompanying the heat transfer and $\dot{S}_i$ just like $\dot{H}$, represent the cumulative sums of the entropy rates of material flows. The term $S_{irr,MA}$ accounts for the entropy generation as a result of expected irreversibilities through the processes occurring in the system.

In creating this model we make the assumption that operations take place at steady state (left hand side of each of the above equations is 0), and eliminate $\dot{Q}_0$ between Equation 3 and Equation 4 to generate a model to estimate the work rate requirement for material processing:

$$\dot{W}_{ECMA}^{MA} = ((\dot{H}_{MA}^{proc} + \dot{H}_{MA}^{res}) - \dot{H}_{MA}^{raw}) - T_0((\dot{S}_{MA}^{proc} + \dot{S}_{MA}^{res}) - \dot{S}_{MA}^{raw}) - \sum_{k>0}\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_{ECMA}^{MA} + T_0\dot{S}_{irr,MA}$$

Equation 5

H-TS is the Gibbs free energy. We see above $H\text{-}T_oS$ appears. The difference between this and the same quantity evaluated at the reference state (denoted by the subscript "o") is called exergy. Exergy of a material flow represents the maximum amount of work that could be extracted from the flow considered as a separate system as it is reversibly brought to equilibrium with a well-defined environmental reference state. Similarly it can be the minimum amount of work required to take a material from the reference state to a new desired state.

$$\dot{E}x = (\dot{H} - T_o\dot{S}) - (\dot{H} - T_o\dot{S})_o$$

Equation 6

Broadly speaking, exergy can be written as a sum of two parts: chemical exergy and physical exergy

$$\dot{E}x = \dot{E}x^{ph} + \dot{E}x^{ch}$$

Equation 7

The physical exergy refers to the physical attributes of the system, namely the temperature and pressure, and is the maximum amount of work that can be delivered when the system is relaxed and allowed to come back to (T_0, p_0), known as the "*restricted dead state*." The chemical exergy contribution represents the additional available energy that can be extracted from the system by letting the chemical potential restore to the reference state, thereby returning the system to what is called *ultimate dead state,* or just the "*dead state*" (T_0, p_0, $\mu_{i,o}$) [29]. This reference state is typically taken to be the natural state in which materials are found in the earth's upper crust, atmosphere, and oceans. In this thesis, exergy values are calculated using the Szargut reference environment. Several updates and alternative references, environments are available, but they hardly change the accuracy of this development [30, 31].

Combining Equation 5, Equation 6, and Equation 7, one can rewrite the work flow as

$$\dot{W}_{ECMF}^{MF\leftarrow} = ((\dot{E}x_{MF}^{prod,ph} + \dot{E}x_{MF}^{res,ph}) - \dot{E}x_{MF}^{mat,ph}) + (\sum_{i=1}^{n} e_{x\,i,o}{}^{ch}\dot{N}_i)_{MF}^{prod} + (\sum_{i=1}^{n} e_{x\,i,o}{}^{ch}\dot{N}_i)_{MF}^{res}$$
$$-(\sum_{i=1}^{n} e_{x\,i}{}^{ch}\dot{N}_i)_{MF}^{mat} - \sum_{k>0}\left(1-\frac{T_0}{T_k}\right)\dot{Q}_{ECMF}^{MF\leftarrow} + T_0\dot{S}_{irr,MF}$$

Equation 8

Equation 8 provides the framework for estimating the minimum work input for any process, i.e., when irreversibilities are zero, $T_o S_{irr} = 0$. Equation 8 directly corresponds to an exergy balance between the inputs and outputs of the system with the exergy components being the following: (i) $\dot{E}x_{in/out} = \dot{E}x_{in/out}^{ph} + \dot{E}x_{in/out}^{ch}$, (ii) $\dot{E}x_{W,in/out} = \dot{W}_{in/out}$, (iii) $\dot{E}x_{Q,in/out} = (1 - T_o / T)\dot{Q}_{in/out}$, and (iv) $\dot{E}x_{destruction} = T_o\dot{S}_{irr}$. In general one can write:

$$\dot{E}x_{in} + \dot{E}x_{W,in} + \dot{E}x_{Q,in} = \dot{E}x_{out} + \dot{E}x_{W,out} + \dot{E}x_{Q,out} + \dot{E}x_{destruction}$$

Equation 9

Exergy destroyed ($\dot{E}x_{destruction}$) captures any work requirement beyond the theoretical minimum requirement for material processing.

Equation 8 and Equation 9 can thus be used to generalize the minimum work rate requirement for material processing, by setting $\dot{T}_o\dot{S}_{irr} = 0$.

$$\dot{W}_{min} = \dot{E}x^{proc} - \dot{E}x^{raw} = \dot{E}x^{out} - \dot{E}x^{in}$$

Equation 10

On a per unit basis, one can write

$$w_{min} = \frac{\dot{W}}{\dot{m}} = e_{out} - e_{in}$$

Equation 11

where 'e' (not to be confused with embodied energy) is the exergy per unit of material. Equation 11 gives the minimum work or energy requirement for a particular process. In other words, the difference in the sum of the exergies of the outputs and the inputs is the minimum energy needed.

Using this framework let's also estimate the minimum energy requirement for material separation be it for recycling or extraction of ore from the mine or purification of material. Here we assume that the mixture of materials being dealt with is ideal. This is not necessarily true for many recycling and extraction systems, but it provides for a simplified way for modeling the complex system with the results providing good guidance to understanding the theoretical minimum work requirements for material separation.

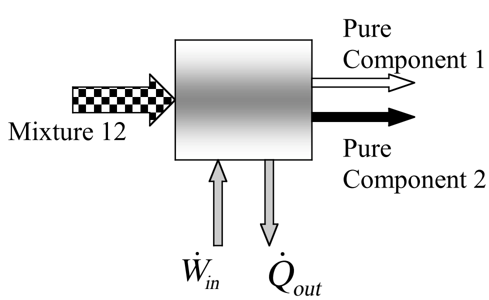


Figure 9: An ideal separation process [29]

Consider the open system shown in Figure 9. Once again the environment is assumed to be at standard temperature and pressure of T_o and p_o. A two component mixture denoted by "12" is separated into "1" and "2". One can again write the mass, energy, and entropy (accounting for the irreversabilities) balance equations, as we did for the material processing system before.

$$\frac{dN_{i,sys}}{dt} = \dot{N}_{i,in} - \dot{N}_{i,out} \quad i = 1,2$$

Equation 12

$$\frac{dE}{dt} = -\dot{Q}_{out} + \dot{W}_{in} + \dot{H}_{12} - \dot{H}_1 - \dot{H}_2$$

Equation 13

$$\frac{dS}{dt} = -\frac{\dot{Q}_{out}}{T_0} + \dot{S}_{12} - \dot{S}_1 - \dot{S}_2 + \dot{S}_{irr}$$

Equation 14

where N_i is the corresponding moles, and "S_{irr}" is the entropy production associated with irreversibilities in the system. Like before we assume steady state and solve for the desired flow of work.

$$\dot{W}_{in} = ((\dot{H}_1 + \dot{H}_2) - \dot{H}_{12}) - T_o((\dot{S}_1 + \dot{S}_2) - \dot{S}_{12}) + T_o\dot{S}_{irr}$$

Equation 15

Another way of writing the same is in intensive form,

$$\dot{W}_{in} = -\dot{N}_{12}(\Delta h_{mix} - T_0 \Delta s_{mix}) + T_0 \dot{S}_{irr}$$

Equation 16

or,

$$\dot{W}_{in} = -\dot{N}_{12} \Delta g^*{}_{mix} + T_0 \dot{S}_{irr}$$

Equation 17

To calculate the minimum work of separation per mol of mixture we set $\dot{S}_{irr} = 0$.

$$\dot{W}_{\min} = -\dot{N}_{12} \Delta g^*{}_{mix}$$

Equation 18

or in other words

$$w_{\min} = \frac{\dot{W}_{\min}}{\dot{N}_{12}} = -\Delta g^{*}{}_{mix}$$

Equation 19

That is, the minimum work of separation is negative the Gibbs Free Energy of mixing. Energy losses or other inefficiencies in the system such that $\dot{S}_{irr} > 0$, will make the work required larger and deviate from the minimum work requirement.

Since we assumed mixture 12 to be ideal, $\mathbf{\Delta} h_{mix} = 0$. Hence the minimum work for separation can be further simplified into

$$w_{min} = T_0 \mathbf{\Delta} s_{mix}.$$

Equation 20

The mixing entropy $\mathbf{\Delta} s_{mix}$ for non-interaction particles, can be calculated using statistical mechanics, essentially Boltzmann's entropy equation. See [29] for derivation.

$$w_{\min} = -T_0 R \sum_{i=1}^{n} x_i \ln x_i$$

Equation 21

Note that this result is not restricted to a mixture with two components only but is general and applied to one with n components. In the equation x_i is the mole fraction of the "i^{th}" constituent, and R is the universal gas constant, 8.314 J/(mol·K).

For the example considered in Figure 9, the minimum work requirement for separation is hence

$$w_{\min} = -T_0 R(x \ln x + (1-x)\ln(1-x))$$

Equation 22

These separation models can be used to calculate the minimum energy requirement for materials separation like in the case of recycling. However, one can also use the same to analyze material extraction or material purification processes, as they relate to material separation as well. However the situation is slightly different. In this case only 1 is desired and the remaining materials (2 in the two component system) are not. We also assume that the mixture is large enough such extracting a mol of "1" does not significantly change the molar concentrations of the original mixture. Equation 22, written in its extensive form is as follows:

$$W_{min}^{(N_i)} = -T_0 R(N_1 \ln x + N_2 \ln(1 - x))$$

Equation 23

A similar equation can be written after 1 mol of component 1 is extracted.

$$W_{\min}^{(N_1-1)} = -T_0 R((N_1 - 1)\ln x + N_2 \ln(1 - x))$$

Equation 24

Subtraction the above two equations

$$w_{\min,1} = T_0 R(\ln\frac{1}{x})$$

Equation 25

N_i is the number of moles (or atoms) of each component. This is the minimum work to extract one mole of material "1" and concentrate it from mole fraction "x" to the pure form at x = 1.

Clearly the work required to extract goes to infinity as the mole fraction of the desired component goes to 0. In Chapter 4 we observe this phenomenon for metals with dilute ores like silver, gold, platinum, and palladium (see Figure 21). Similarly extracting an impurity from an ultra pure material requires a lot of work. However, for the problem of purification as per the model above the work required goes to zero as the impurity concentration becomes more dilute. In this case, the thermodynamics of separation for an ideal mixture does not agree with the common observation, that the work to extract an impurity per unit of valuable material actually increases as the concentration of impurity decreases. In none of the applications of the above model do we encounter such a situation and thus this does not influence the estimations made in this thesis.

Example Calculation of Theoretically Minimum Energy Demand

The example of primary steel is used to present the theoretical minimum energy demand calculation. Production of steel can be broadly categorized in 4 main steps:

(1) Extraction of iron ore
(2) Reduction of iron ore
(3) Adding elements to make the desired steel
(4) Shaping the product steel

The theoretical minimum energy for step (1), extraction of the ore, is estimated through the separation model in Equation 25. According to Szargut, iron is found in the earth's crust in the form of hematite, Fe_2O_3, at an average molar concentration of 1.3×10^{-3} [30]. In other words, when hematite is at this concentration at T_o, p_o, it is in the "Dead State" with exergy equal to zero. By a combination of geological processes followed by the anthropogenic processes of exploration, mining and separation the iron ore in the crust can be purified to pure Fe_2O_3. The theoretical exergy value of pure hematite is calculated using for a process that concentrates hematite from a molar concentration of 1.3×10^{-3} to 1. The result is given below.

$$e_x *_{Fe_2 0_3} = T_0 R \ln \frac{1}{1.3 \times 10^{-3}} = 16.5 kJ / mole \sim 8.25 \text{ KJ/mole of Fe} = 147 \text{ MJ/tonne Fe}$$

Equation 26

Note that in reality this process takes the ore from the concentration of the mine to pure metal concentration of 1. Mine concentration is higher than 1.3×10^{-3} and thus the above estimate includes a potential exaggeration.

In step (2) Equation 11 can be used for the primary reduction reaction for hematite. In this stage of purification, the iron is reduced from a pure oxide to a pure metal. The minimum work to create pure iron from Fe_2O_3 is equal to the exergy lost when pure iron is oxidized to Fe_2O_3. The oxidation reaction for this is as follows,

$$2Fe + \frac{3}{2}0_2 \rightarrow Fe_2 0_3$$

Equation 27

Using Equation 10 and Equation 11:

$$2e_x *_{Fe} + \frac{3}{2}e_x *_{0_2} - e_x *_{Fe_2 0_3} = -\Delta g *_{f(Fe_2 0_3)}$$

Equation 28

Using data from Szargut, the theoretical minimum energy demand for this step is 6.6 GJ/tonne of Fe. Note that this is significantly higher than the theoretical minimum energy requirement for Step (1).

Step 3 includes adding elements to adjust the composition to the desired steel. Along with carbon, C, common alloying elements include Si, Mg, P, S, Ni, etc. Adding these elements does not take any energy and the mixing process is in fact spontaneous. In the theoretical minimum calculation, the energy to produce these material or auxiliary materials that support the reactions is not included. However, sometimes heat treatment may be needed for the formation of certain compounds but the energy required is again negligible compared to step (2). As an example the Gibbs Free energy to form iron carbide (Fe_3C) is 0.11 GJ/tonne of Fe_3C. However, steel may only contain carbon, on average, at less than 0.5% by weight, the theoretical minimum energy demand for the carbide is only 0.002 GJ/tonne Fe [21].

Shaping the steel theoretically doesn't require any energy, as the energy content of shaped and nonshaped steel is almost the same. This is also the premise of the near net shape casting [21].

Thus the theoretical minimum energy requirement to make steel is mostly what is used in the iron ore reduction step and is roughly 6.6 MJ/kg while the rest of the steps contribute to less than 1%. This is found to be true for the other materials considered in this thesis as well given the nature of steps 1,3, and 4.

From theoretical to practical minimum energy demand

The above calculation focused on the absolute minimum energy demand for material processing. This did not include the energy requirement for producing the supporting materials input into the material processing steps, however, one may consider including some or all of these to calculate what is called the practical minimum energy requirement. Unlike the theoretical minimum energy demand, the practical minimum energy demand is a strong function of what is included in defining the practical process. To start with a detailed exergy analysis of an integrated steel plant is provided below [21].

Table 4: Exergy analysis of an integrated steel plant (adopted from [21]). 'trs' refers to tonne of rolled steel.

Input	GJ/trs	Output	GJ/trs
Coal	20.2	Rolled Steel	6.62
Scrap	1.87	Coal tar	0.92
Iron ore	0.22	Coke oven export gas	0.84
Fluxes	0.2	Recollected steel	0.76
LPG	0.05	Coke breeze	0.72
Air-various flows	0.03	Blast furnace slag	0.56

Pellets	0.03	Benzole	0.25
Oxygen	0.01	Basic oxygen furnace export gas	0.14
		Medium-pressure steam	0.1
		Total Useful Products	**10.9**
		Losses	11.62
Total	**22.6**	**Total**	**22.6**

Defining practical operations to include the production of all useful products from the plant, the practical minimum energy can be declared to be 10.9 MJ/kg. This would mean a potential for improvement of 11.6 MJ/kg in this reference plant. On the other hand one may argue that only some of the included useful products are needed or in fact their compositions may be different. A report by Energetics Inc., prepared for the US Department of Energy analyzes this in greater detail [32]. They show how the practical minimum may vary significantly if carbon inclusion in steel, Si and Mn inclusion in steel, slag, and coke ash, are accounted for in the practical minimum.

Given the operational dependence and accounting boundary dependence of practical minimum, this research uses the conservative absolute theoretical minimum for the base case analysis and later considers the effect of using practical minimum instead.

Scrap material availability for secondary production

Framework objective: To estimate the quantity of scrap material available for recycling to gauge the potential of recycling as an energy reduction strategy

Consider the total production Q_P subdivided into Q_{prim} (primary production) produced with energy intensity e_{prim}, and Q_{sec} (secondary production) produced with energy intensity e_{sec}. The total energy E_T for a given material then is,

$$E_T = Q_{prim}e_{prim} + Q_{sec}e_{sec} = Q_Pe_{avg}$$

Equation 29

and,

$Q_P = Q_{prim} + Q_{sec}$

Equation 30

Let r be one measure of recycling rate defined as follows. This is in sync with how USGS defines recycling rate [33, 34]:

$$r = \frac{Q_{sec}}{Q_P}$$

Equation 31

Thus using Equation 29, Equation 30 and Equation 31

$$e_{avg} = (1\text{-}r)*e_{prim} + r*e_{sec}$$

Equation 32

Note, production may be defined in different ways but we define production as the total output from the production facilities as recorded by organizations like USGS. The demand for material could be different due to the yield of the production facilities (some finished material / product is scrapped or returned by consumer). Since we are looking at the global scale, export and import are not factors of consideration. Refer to Figure 10 for a schematic of the material life cycle.

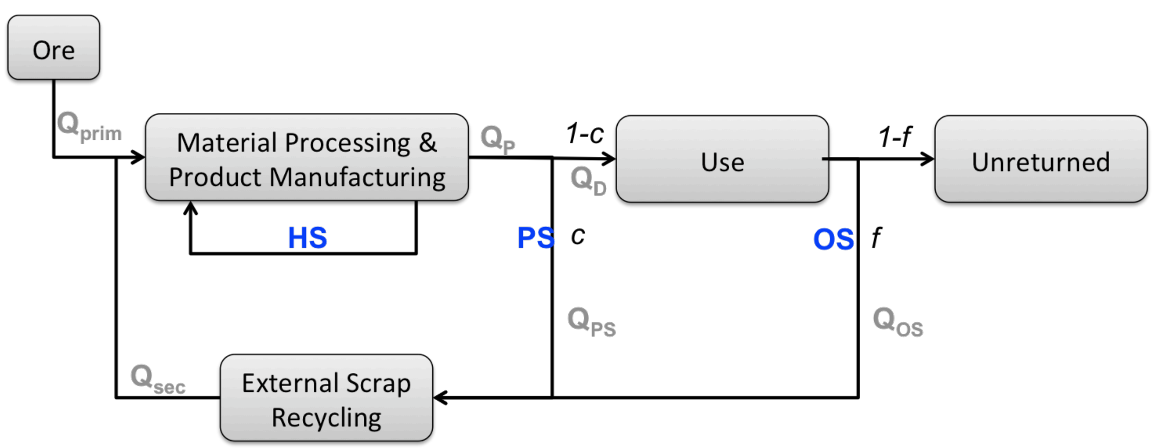


Figure 10: Schematic of a material life cycle. Quantities of flows are shown in grey. Fractions are shown in black. Names of different kinds of scrap in blue.

In this case,

$Q_D = Q_P(1\text{-}c)$

Equation 33

where Q_D is the quantity demanded defined as that entering "use." Scrap material is generated at each step of the life cycle due to inefficiencies of the processes. Typically there are three kinds of scrap – Home Scrap (HS), Prompt or New Scrap (PS) (Graedel and Müller call this industrial scrap [35]), and Old Scrap (OS). As per USGS, HS is scrap generated as process scrap and consumed in the same plant as generated. PS is scrap produced during the manufacture of metals and articles for intermediate or ultimate consumption and used in other facilities. OS is scrap from discarded products after serving a useful purpose. A recycler typically prefers PS over OS given the lower uncertainty of supply and composition, and usually higher quality [33, 34]. In fact in all the material flow models we have reviewed, PS is assumed to flow back in entirety to material processing. Note that c and f are the fractions exiting that phase of the life cycle that return for scrap recycling [7, 33-35]. (1-c) is the same as the material yield of the production process and typically quite high as it directly reduces operational costs [7, 11]. f is the old scrap collection efficiency and can range from being close to zero (e.g. for cement) to over 90% (e.g. for car batteries) depending on the material and product, and the economics of recycling it. It may also be driven by external factors like regulation (e.g. for lead). More details can be found in [36].

Using the above equations,

$Q_{sec} = Q_{PS} + Q_{OS}$

Equation 34

Q_{PS} and Q_{OS} are the quantity of prompt scrap and old scrap respectively. HS is usually not considered since it is recycled internally and an inherent property of the operations [33, 34]. e_{prim} usually incorporates HS.

Also,

$Q_{PS} = Q_P*c$

Equation 35

Allwood and coworkers claim that c is roughly around 10% for the materials under study (steel: 11%; Aluminum: 20%; plastic: 2%; paper: 6%) [7]. In other words 10% of the finished material produced is available for recycling in the form of PS. c has also improved tremendously over the years and is likely to do so into the future as well [11].

For modeling OS a slightly more complicated analysis is adopted. Figure 11 shows an exponential demand curve over time, growing at an average year-to-year growth rate of i.

The quantity of OS exiting use is essentially the quantity of material demand n years ago, where n is the residence lifetime for the material. Assuming a consistent material demand growth rate of i,

$$Q_{OS,max} = \frac{Q_D}{(1+i)^n}$$

Equation 36

where, $Q_{sec,max}$ is the maximum OS available today. However as shown in Figure 10 only a fraction f ($0 \leq f \leq 1$) is collected due to economic and technical challenges. Thus,

$$Q_{OS} = f\frac{Q_D}{(1+i)^n}$$

Equation 37

Figure 11 shows this schematically.

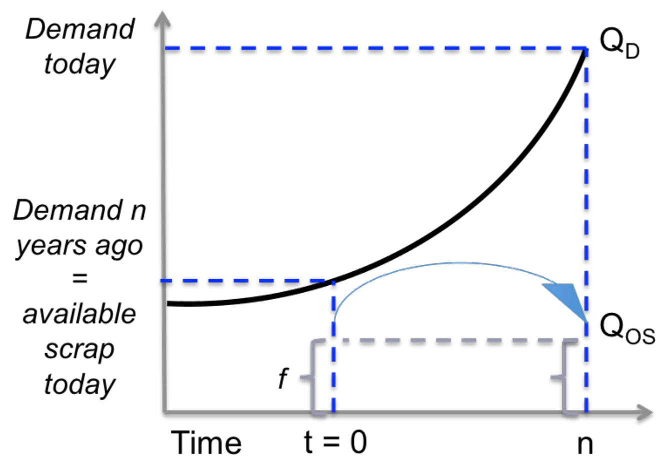


Figure 11: Model for estimating scrap availability through a material flow analysis

In other words, Q_{OS}, and thus r, are constrained by the efficiency of the recycling system as well as by the parameters of growth.

Combining Equation 31, Equation 33, Equation 34, Equation 35, and Equation 37, one can rewrite r as,

$$r = c + \frac{f(1-c)}{(1+i)^n}$$

Equation 38

In other words, as c increases the fraction of Q_{sec} that is PS increases and that of OS decreases, and vice versa. Typically $e_{sec} < e_{prim}$ (see Figure 12), which is especially true for the five materials studied in depth in this thesis. Given this, Equation 32 dictates increasing r as a means to reducing total energy E_T. This means there are two direct levers – increasing f and decreasing c. Increasing c may seem to increase r but it also increases Q_P given a certain demand Q_D, thus canceling out. This is better understood by deriving the expression for E_T, given Q_D, using Equation 38 and Equation 32,

$$e_{avg} = (1-c)\left[1 - \frac{f}{(1+i)^n}\right] e_{prim} + \left[\frac{f(1-c)}{(1+i)^n} + c\right] e_{sec}$$

Equation 39

and using Equation 29,

$$E_T = Q_P\left[(1-c)\left[1-\frac{f}{(1+i)^n}\right]e_{prim} + \left[\frac{f(1-c)}{(1+i)^n}+c\right]e_{sec}\right]$$

Equation 40

which can be rewritten using Equation 33

$$E_T = \frac{Q_D}{(1-c)}\left[(1-c)\left[1-\frac{f}{(1+i)^n}\right]e_{prim} + \left[\frac{f(1-c)}{(1+i)^n}+c\right]e_{sec}\right]$$

Equation 41

which is equal to

$$E_T = Q_D\left[\left[1-\frac{f}{(1+i)^n}\right]e_{prim} + \left[\frac{f}{(1+i)^n}+\frac{1}{(1-\frac{1}{c})}\right]e_{sec}\right]$$

Equation 42

Thus given Q_D by society, E_T can be decreased by increasing f and decreasing c, as $e_{sec} < e_{prim}$. Other ways include decreasing e_{prim} and e_{sec}, or even Q_D.

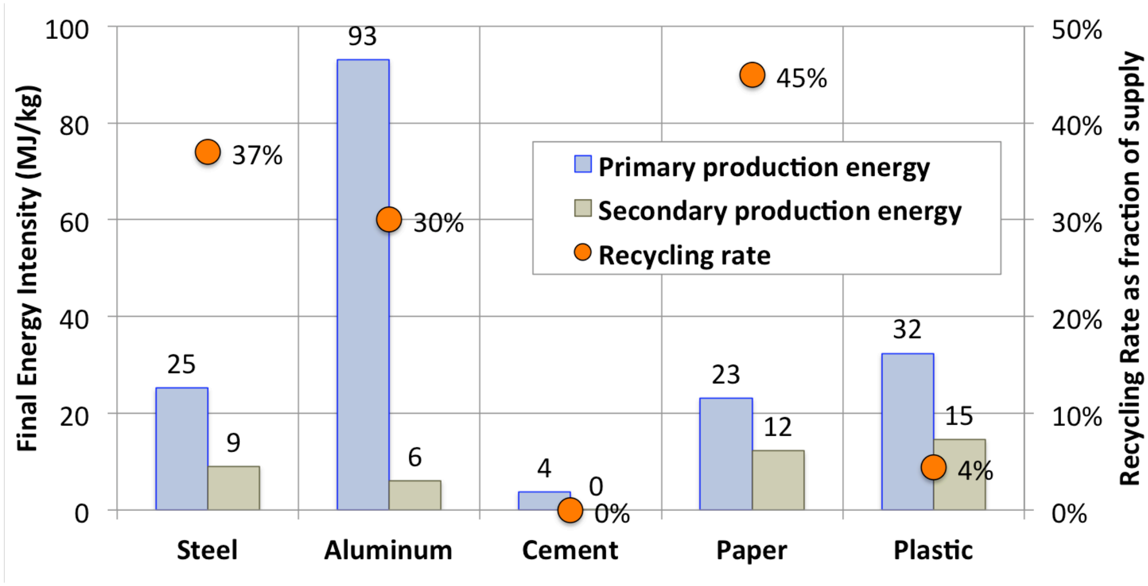


Figure 12: Primary and secondary production energy intensities for different materials and their current recycling rates, r, as fraction of supply. Final energy does not include losses in electricity production [4].

The model above is theoretical with simplifications. One can consider following more complicated models that account for time based changes in one or more of the following aspects:

- Material demand growth rate, i – the average growth need not be exponential and the growth rate may as well vary over time
- Residence lifetime, n – the average residence lifetime of the material may as well lengthen or shorten over time. This in fact is likely to be the case if some of the discussed material efficiency strategies come into play or if the end-product distribution changes
- Deviation from averages – a more complex model may include considering a similar or more complicated model to Equation 42 for each type of end-product, and in each geography, as opposed to an average as used in this thesis

A few researchers have been able to do this from a historic perspective. Two popular sets of studies are those by Graedel and co-workers [35, 37-45], and recycling reports by

USGS [33, 34]. As an example we provide the material flow details that Graedel and co-workers put together in Figure 13 which look at the flows at each stage of the material life cycle and through each of the end products. Müller and co-workers have also constructed detailed material flow models to estimate not only the flows but also the stocks. The details of their model can be found in [46]. However, for each product, their model is similar to Equation 42, which is what makes its use at the aggregated level also acceptable. Overall, prior research has indeed modeled such details and provided greater insight, but the purpose of this research is not to consider the details at the national or product level, nor during the interim period from now through 2050, but instead to estimate the global average statistics for 2050. To account for any uncertainty associated with this simplification, a detailed sensitivity analysis is completed and presented.

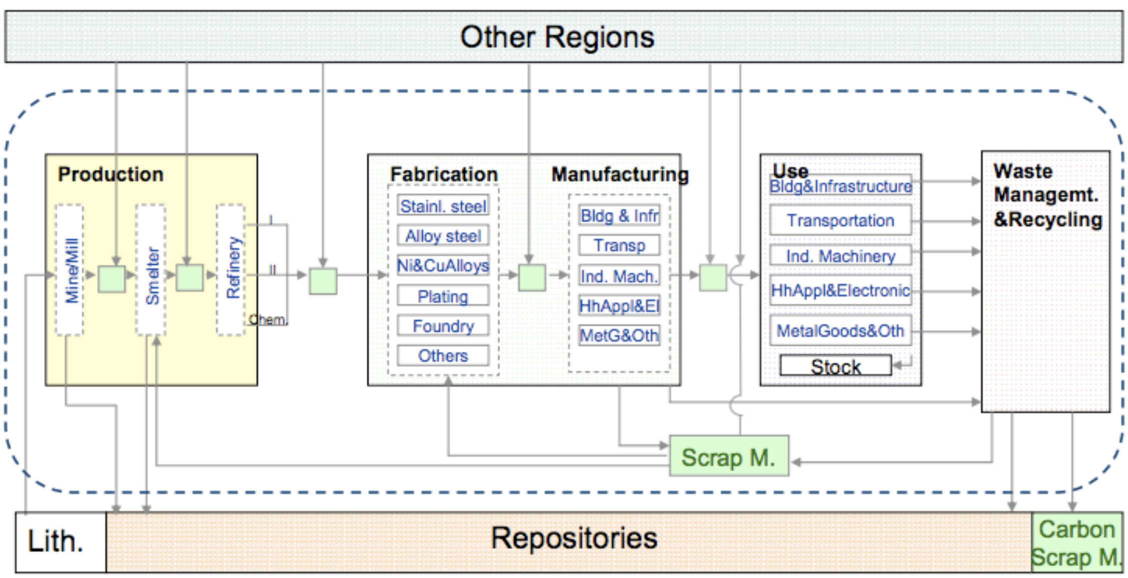


Figure 13: Detailed schematic of material life cycle flow used to construct a detailed model of recycling, by Graedel et al. [44].

Remanufacturing and comparative life cycle energy savings

Framework objective: To estimate the life cycle energy savings of choosing to remanufacture a product over replacing it with new

Introduction to life cycle inventory analysis

Life Cycle Inventory (LCI) is the quantification of raw materials requirements, energy demands, atmospheric emissions, waterborne emissions, solid wastes, and other inputs and outputs for the entire life cycle of a product, process, or activity [47]. As shown in Figure 14, LCI utilizes input-output inventories for main life cycle phases, which are as follows: raw materials processing, manufacturing and assembly, transport, use, and end-of-life.

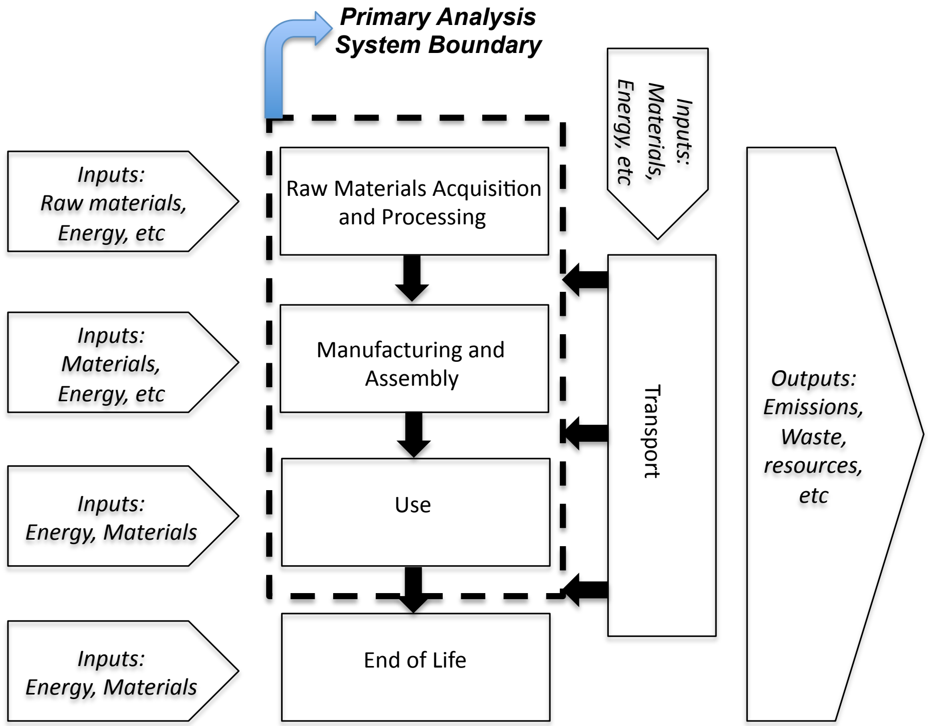


Figure 14. Life Cycle Inventory inputs and outputs. The dotted line reveals the primary scope of analysis for this thesis (modified version of an original figure taken from [48]).

In LCI each phase is considered to be a sub-system. Each sub-system requires inputs of materials and energy, and it has outputs associated to the activities and processes taking place in each stage. We choose energy consumption as inputs primarily for raw material acquisition and processing phase, manufacturing and assembly phase, and use phase, as shown by the dotted line in Figure 14. We gather all the relevant data, and organize it for compiling life cycle energy inventories. There are three popular methodologies for compiling life cycle inventories: process LCI, economic input-output LCI, and hybrid LCI [49]. We utilize process LCI for the purposes of this thesis.

Process LCI

The most common form of LCI is the process LCI [50]. The analysis for this methodology is based on viewing lifecycle environmental impacts from the perspective of a single product unit. More specifically, the objective of process LCI is to track the raw materials and energy inputs for each constituent stage of a product life [49]. The analytics for process LCI utilizes process flow diagram methods as well as matrix inversion methods to perform environmental computations [49, 51].

Life Cycle Inventory: Energy Demands Analysis

Raw Material Acquisition and Processing

Each raw material requires energy to be produced. The energy requirements encompass extraction, processing, and purification that bring raw materials to useful conditions. We determine the amount of energy (in MJ per kg for each raw material) required to acquire and process the raw materials used for constructing the product. We use the bill of materials of the product in combination with the raw materials energy requirements in order to quantify energy demands for the raw materials production phase. For example, more than 50% of the mass of a mid-size refrigerator (47 kg out of 84 kg) is made from steel [52]. According to [53], it takes about 20 to 25 MJ to produce 1 kg of Steel. As a result, it takes on average about 940 to 1,175 MJ to process the steel embedded in a mid-size refrigerator.

In general, we rely on three dominant sources for typical energy cost of raw materials, namely [53],[54],[10]. These references provide a range of energy requirements for processing various raw materials. Though we use the entire range for computation purposes, we take the upper bounds as the final values for life cycle assessment in order to be conservative in identifying the upper bound limit for remanufacturing energy savings. Also, for some products where a bill of materials was not obtainable, we utilize credible references, which have already computed the raw material processing energy demands. Refer to Appendix for a comprehensive set of reports with extra details on data, data sources, and methodology.

Manufacturing and Assembly

We rely on literature data and personal communications to determine the energy requirements for manufacturing and assembly for producing a product. Some of the references we consider use well-established sources that extensively study the manufacturing processes such as [55],[56],[5, 57-59]. These references provide an overview of manufacturing processes and provide energy analysis of industrial practices by calculating the primary energy required to manufacture the product starting with processed materials [56].

Use

The trends for unit energy consumption, service, and efficiency of products as studied in this report are from various sources such as governmental agency reports, prior academic researches, and industrial reports. We estimate the annual energy use consumption of products from these sources. Furthermore, we amortize the annual values over average useful lifetime to determine the use phase energy consumption of the products.

Energy is obtained from various sources including coal, nuclear power, wind, solar energy, solid waste, wood biomass, and natural gas. The energy demands for producing electricity is correlated to the sources of fuel used to generate the electricity and the efficiency of the power generation [60]. Since the generated electricity is mixed in the transmission lines of the utility, it is difficult to distinguish the source of electricity in the grid. Therefore, typically, the computational models utilize regional or national average fuel mix for producing electricity in the grid.

In determining the energy consumption of electronics products in the use phase, we take into account the energy efficiency of power generation as well as delivery transmission losses for the analysis. For example, theoretically 1 kWh of electricity can produce 3.6 MJ of energy (e.g. in the form of heat, etc.). However, this value does not take into account the primary sources of energy that are consumed to produce and transmit 1 kWh of electricity to consumer's location. By taking into account power generation inefficiencies and transmission line losses, 10.6 to 11.3 MJ of energy is required for 1 kWh of electricity delivered for useful work (e.g. variation in value is due to efficiency choices and transmission routes) [60]. The same discussion holds true for petroleum-based sources of energy such as automotive fuel. Therefore, for our studies for the use phase of electronics products we use 10.6 MJ/kWh (as opposed to 3.6 MJ/kWh) for quantifying the energy requirements. Similarly, for the use phase of products in automotive industry we use 142 and 146 MJ per one U.S. gallon of gasoline and diesel fuel, respectively (as opposed to 132 MJ/gallon).

Transportation and End-of-Life

Based on the boundary conditions of our analysis, we do not include transportation and end-of-life phases in the primary analysis. These are expected to cancel out in the comparison assuming the same for the remanufactured and new version. However, these stages are considered in cases where they are expected to not cancel out (e.g. air freight of new laptops) and at the least in the sensitivity analysis in order to determine their relative significance in changing the conclusions. Following the above process, we evaluate the energy consumption contributions for each LCA stage in order to determine which LCA stages are more dominating than others.

Comparative LCI Model

The life cycle inventory (LCI) for the new product includes raw material processing $E_{rm,new}$, manufacturing $E_{m,new}$, use $E_{u,new}$, disposal $E_{d,new}$, and transpiration between the phases summed as $E_{T,new}$. Similarly, for a remanufactured product the life cycle energy impacts include the remanufacturing $E_{reman,old}$ of the old product, use $E_{u,old}$, final disposal $E_{d,new}$, and transpiration between the phases summed as $E_{T,reman}$.

$$LCI_{NEW} = E_{rm,new} + E_{m,new} + E_{u,new} + E_{d,new} + E_{T,new}$$

Equation 43

$$LCI_{REMAN} = E_{reman,old} + E_{u,old} + E_{d,reman} + E_{T,reman}$$

Equation 44

The customer would be indifferent between new and remanufactured units from an energy standpoint when $LCI_{NEW} = LCI_{REMAN}$, and is expected to prefer the choice with a lower LCI if the objective is to save energy.

While the model above looks simplistic being linear in nature, estimating the energy use in each phase can be complicated. Listed below are three critical considerations:

- Conducting a comparative LCA requires equivalence of functional units. Often the function provided by a unit of the remanufactured product may be different from a unit of the new product. Examples include refrigerator volumes, washing machine volumes, tire mileage, and toner cartridge print output. In such a case we normalize the LCI with the lifetime function or service provided by the two versions such that the comparison is the energy use per unit service provided.
- Allocation of energy to the use phase can be sometimes tricky. For instance, when comparing retreaded tires with new replacement tires, one needs to carefully account for the energy used by the car / truck to the tires. This becomes a function of the rolling resistance of the different tread kinds and needs careful consideration. Provided below, as an example, is how this was evaluated.
- Remanufacturing theoretically brings a product back to 'like-new' condition, however we have reviewed extensive literature and consulted industry experts to account for any practical shortfalls to this claim. In several industries like motors, tires, and toner cartridges, there seems to be a common understanding of the degraded performance of remanufactured products and thus this was accounted for in the analysis. The impact of such degradation was found to be significant.

Example use phase energy accounting methodology

In order to quantify the use phase energy consumption of tires it is critical to first understand the sources of heat dissipation and energy losses associated with a tire in operation. More specifically, the issue to address is the impact of rolling resistance on energy performance of tires.

In this study, we take the contribution of rolling resistance on vehicle fuel consumption to be on average 15% for passenger cars, and 24% for heavy trucks [61, 62]. Furthermore, we illustrate the results based on the range for the contribution of rolling resistance on vehicle energy expenditure. We consider the range of contribution to be 10 to 20% for passenger cars and 15 to 33% for heavy trucks [61, 62]. Refer to [63] for detailed literature review of the contributions of rolling resistance losses on vehicle fuel consumption.

How can one translate the changes in tire efficiency to changes in energy consumption? Industry officials, researchers, and tire manufacturers have been studying this for decades in order to improve the energy performance of tires. The assessments encompass various testing approaches such as experimental observations using standardized testing procedures, stress-strain simulations, numerical modeling (refer [63] for more information).

One common approach for analyzing the contribution of tire rolling resistance on fuel consumption is to determine the changes in total vehicle fuel consumption with the changes in rolling resistance of tires. This is commonly referred to as 'return factor', or 'return ratio', or 'energy return'.

$$Z = \text{Return Factor} = \frac{\left(\Delta E_T / E_T\right)}{\left(\Delta F_{RR} / F_{RR}\right)} = \frac{\left(\dfrac{E_T^{'} - E_T^{o}}{E_T^{o}}\right)}{\left(\dfrac{F_{RR}^{'} - F_{RR}^{o}}{F_{RR}^{o}}\right)}$$

Equation 45

where E_T^0 , $E_T^{'}$, F_{RR}^{o} , $F_{RR}^{'}$, and Z are the vehicle fuel energy consumption with initial set of tires (taken as the reference), modified vehicle fuel energy consumption due to modified tires, rolling resistance of initial set of tires, rolling resistance of the modified set of tires, and the return factor.

In this study, E_T^0 is computed based on the following equation,

$$E_T^o = \frac{\text{Distance Travelled [Miles]} \times \text{Fuel Heat Content [MJ/Gallon of Fuel]}}{\text{Vehicle Fuel Efficiency [Miles per Gallon of Fuel]}}$$

Equation 46

Return factor provides a relation between the change in rolling resistance and its corresponding impact on vehicle energy consumption. Rolling resistance is the energy loss per unit distance travelled (J/m or N), where the higher the value the more vehicle fuel input required for overcoming tire energy losses.

In this study, we are interested, however, in the impact of change in coefficient of rolling resistance on vehicle fuel energy consumption. Coefficient of rolling resistance is a dimensionless measure of tire efficiency that is defined in terms of rolling resistance force generated per unit load applied. Therefore, coefficient of rolling resistance is linearly correlated to rolling resistance as expressed below (refer to [63] for detailed information)

$$C_{RR} = \frac{F_{RR}}{W}$$

Equation 47

where C_{RR} and W are the tire coefficient of rolling resistance and vehicle load on tires. Based on this relation, we can show that fractional changes in coefficient of rolling resistance is equivalent to fractional changes in rolling resistance,

$$\frac{\Delta C_{RR}}{C_{RR}} = \frac{C'_{RR} - C^{o}_{RR}}{C^{o}_{RR}} \cong \frac{F'_{RR} - F^{o}_{RR}}{F^{o}_{RR}} = \frac{\Delta F_{RR}}{F_{RR}}$$

Equation 48

where C^{o}_{RR} and C'_{RR} are the coefficient of rolling resistance of the initial set of tires (reference case) and the modified set of tires. Based on this, we can re-write Equation 45 as follows,

$$Z = \text{Return Factor} = \frac{\left(\Delta E_T / E_T\right)}{\left(\Delta C_{RR} / F_{RR}\right)} = \frac{\left(\frac{E'_T - E^{o}_T}{E^{o}_T}\right)}{\left(\frac{C'_{RR} - C^{o}_{RR}}{C^{o}_{RR}}\right)}$$

Equation 49

The equation above can be re-arranged to solve for the modified vehicle fuel energy consumption, E'_T, as a result of utilizing the modified set of tires,

$$E'_T = E^{o}_T + Z.E^{o}_T.\left(\frac{C'_{RR} - C^{o}_{RR}}{C^{o}_{RR}}\right)$$

Equation 50

The total energy consumption of a vehicle, E^{o}_T, consists of a combination of energy expending components. In this study we break them into energy losses due to rolling resistance of tires, E^{o}_{RR}, and losses due to all the other components $\overline{E^{o}_{RR}}$ (i.e. engine losses, transmission losses, aerodynamic losses).

$$E^{o}_T = E^{o}_{RR} + \overline{E^{o}_{RR}}$$

Equation 51

We assume that the changes in rolling resistance of the tires do not change the energy requirements of other vehicle components. In other words,

$$\overline{E^{o}_{RR}} = \overline{E^{'}_{RR}}$$

Equation 52

In addition to the assumption above, we take a range of values for return factor in order to compensate for potential variations in other vehicle components due to changes in rolling resistance. Based on the given assumption we can show that the energy required for overcoming rolling resistances of all tires on a vehicle can be expressed as,

$$E^{o}_{RR} = Z.E^{o}_{T}$$

Equation 53

where E^{o}_{RR} is the use phase energy consumption of all tires operating on a vehicle.

In addition, based on the above assumption, we can compute the use phase energy cost of a new set of tires by taking into account the following expression,

$$E^{'}_{T} = E^{'}_{RR} + \overline{E^{'}_{RR}}$$

$$E^{'}_{RR} = E^{'}_{T} - \overline{E^{'}_{RR}} = E^{'}_{T} - (1 - Z).E^{o}_{T}$$

Equation 54

Using Equation 50, we substitute for $E^{'}_{T}$ to come up with the following equation,

$$E^{'}_{RR} = Z.E^{o}_{T}.(\frac{C^{'}_{RR} - C^{o}_{RR}}{C^{o}_{RR}} + 1) = E^{o}_{RR}.({C^{'}_{RR}}/{C^{o}_{RR}})$$

Equation 55

where E'_{RR} is the energy requirement for overcoming rolling resistance energy losses of the modified set of tires on a vehicle.

Note that details of each such methodology are available through the Appendix of the thesis.

Material demand analysis

Framework objective: To assess market demand[2] trends as well as drivers/actors of material demand, and compare their influence across different materials and geographies

Broadly speaking material demand has been analyzed using two approaches in the last few decades – using econometrics, and using what is called the "intensity of use" approach. The former entails estimating the demand function econometrically. Since the materials considered here are simply inputs to manufacturing of products, the demand drivers considered are those of end demand including factors of production, material price, and substitutes and complements. One may also factor in technology, policy, and some macroeconomic factors. Within these kind of models are also included the economic input-output models that link various sectors of the economy with each other. The intensity of use approach on the other hand analyses what is called material intensity or material intensity of use, given as the ratio of material demand and GDP (or some indicator of development). Using projections of GDP and population, and that of intensity of use, the material demand into the future is estimated. Labys and co-workers provide a thorough review of different models for the mineral market including econometric modeling for markets with various kind of competitive landscapes, engineering models that use engineering principles to link outputs and inputs, optimization models for selecting best operating parameters, system models involving dynamic relationships between the variables, and input-output models that can be used to conduct a more aggregated analysis encompassing macroeconomic variables of the economy [64]. For more information refer to [65-69].

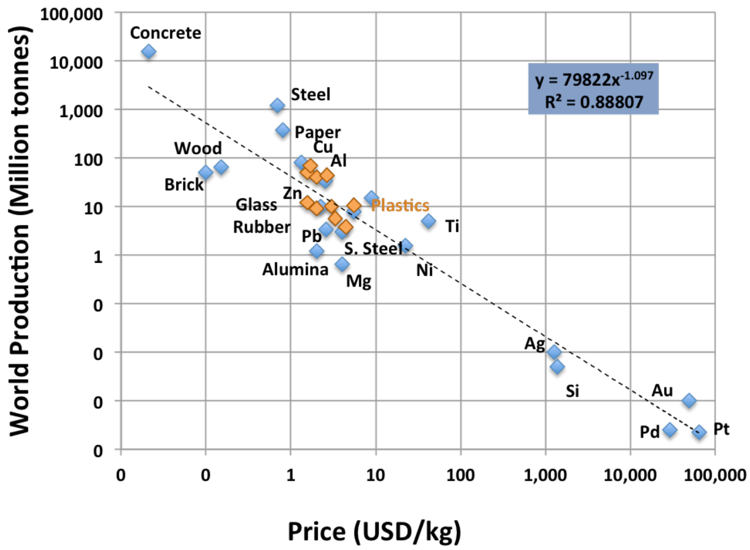
[2] In this chapter, material demand is represented through 'apparent consumption' as defined by the USGS. See end of subsection for limitations associated with this choice.

In this thesis the goal is not to forecast demand but to analyze the historic trends and interpret what it might mean for the future. This research borrows from both the econometric methodology as well as intensity of use methodology to use a new approach to studying material demand. The formulation is shown below:

$$Demand\ per\ capita\ (d) \quad = \quad \frac{Income\ per\ capita\ (a)}{Material\ Price\ (p)}\ X\ Choice$$

Equation 56

Similar to material intensity, it also adds the crucial factor of material price to it. Income per capita over price connotes the capacity of consumers to buy the material and thus the residual multiplier is practically the choice of the consumer on how much to buy. The motivation to include material price as a key actor stems from three reasons – (1) the observation of a strong (inverse) correlation between material price and production across different materials as presented in Figure 15 Part (a); (2) a similarly strong correlation between embodied energy and material price or material production presented in Figure 15 Part (b) and (c); (3) it's direct comparison between the demand of materials and the consumer's choice to purchase the materials. Income and price are key inputs to economic production and this thesis analyzes the trends in material demand factoring in both.


World Production (Million tonnes)
Price (USD/kg)
y = 79822x^-1.097
R² = 0.88807
Concrete
Steel
Paper
Cu
Al
Wood
Brick
Zn
Glass
Plastics
Rubber
Pb
Ti
S. Steel
Ni
Alumina
Mg
Ag
Si
Au
Pd
Pt
100,000
10,000
1,000
100
10
1
0
0
0
0
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0
1
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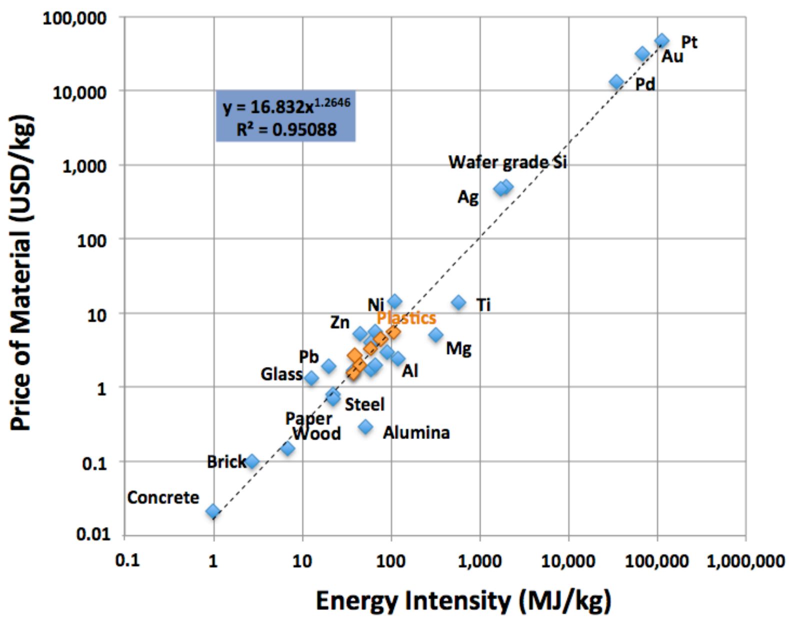
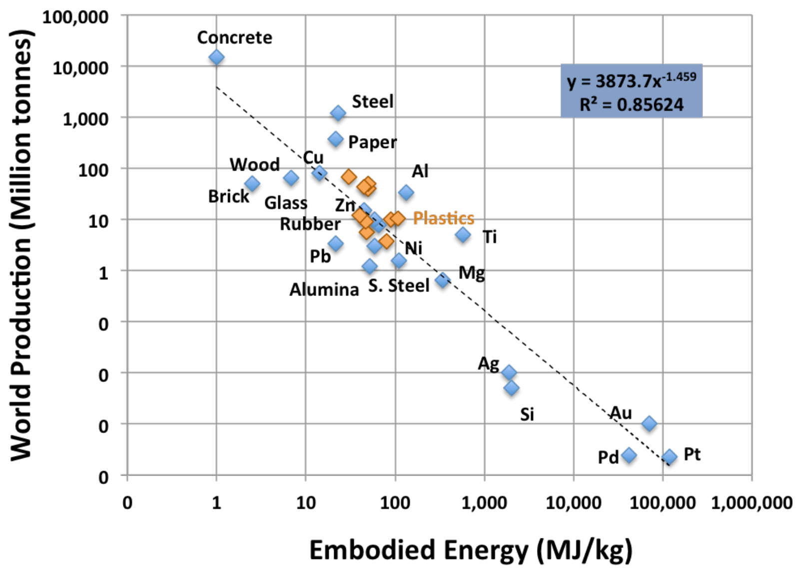
(a)


Price of Material (USD/kg)
Energy Intensity (MJ/kg)
y = 16.832x^1.2646
R² = 0.95088
Pt
Au
Pd
Wafer grade Si
Ag
Ni
Ti
Zn
Plastics
Mg
Pb
Glass
Al
Steel
Paper
Wood
Alumina
Brick
Concrete
100,000
10,000
1,000
100
10
1
0.1
0.01
0.1
1
10
100
1,000
10,000
100,000
1,000,000

(b)



(c)

Figure 15: Relationship between material price, embodied energy, and world production for different materials [4, 5].

This formulation has never been used to study materials before, but was recently presented and applied by Tsao et al. for an energy-economic analysis of solid-state lighting [70]. Their data covers over three centuries of lighting technologies for different geographical scopes (Figure 16). It spans 8 to 10 orders of magnitude and startlingly shows a strong linear relationship between the two, meaning that in spite of increasing use efficiencies of lighting technologies, the usage per capita exhibits no diminishing or saturation signs. In other words, the use of lighting has stayed directly proportional to the consumer capacity to purchase lighting given by the ratio of income per capita and price of lighting. Note that lighting is consumed directly by all sectors of the economy and thus buying capacity in this case is the GDP per capita over price. Tsao et al. show this both in terms of consumption of lumens of light as well as associated energy of lighting. This comes as a big surprise especially with regards to environmental Kuznets curves and dematerialization theories though they do not specifically target lighting. However, lighting proves to be special in two regards – (1) it renders no substitutes, a rare quality amongst common consumables and services, (2) the expenditure on lighting as a fraction of GDP has remained more or less constant over the years, fluctuating by less than a factor of two. This factor (called β by Tsao et al.) is the proportionality constant or the slope of the trend, thereby explaining the linear trend in Figure 16.

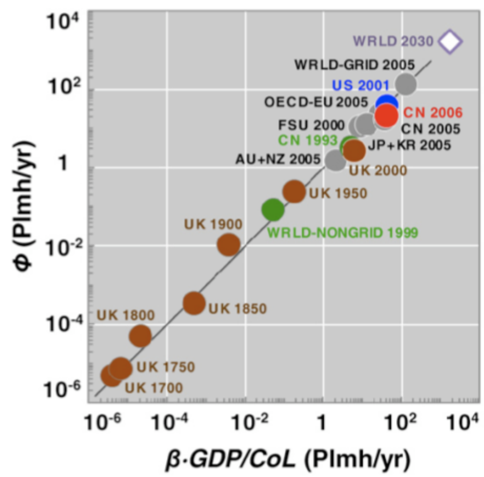


Figure 16: Consumption of light against (*βGDP)/CoL taken from Tsao et al [70]. '*β*' is a constant and thus the chart presets consumption per capita [y-axis] vs. consumer capacity [x-axis] as defined above.**

A result like this instantly motivates testing if demand of materials shows similar trends or otherwise. This method gives new insight different from that obtained by 'material intensity' such that it better represents consumer choice trends by relating quantity demanded to the buying power of consumers. Assuming a positive correlation between the two, a 'diminishing' or 'saturating effect' would present itself as a convex curve with decreasing slope as values on the axes increase. On the other hand an exponential trend would present itself with the slope increasing as the two variables on the axes increase. A third result could be that shown for lighting where industry continues to demand the amount of material proportional to its buying capacity. In the different materials studied a negative correlation between the two has usually only been observed when an external factor has influenced it like regulation influencing the consumption of lead.

Analyzing demand from this new perspective reveals some interesting trends and inferences, which are shared in the *Results* section in Chapter 3, but only partly caters to the goals of the work, which are to dig deeper and understand the reasons behind the trends. Whether a material exhibits a saturating effect or not, it's important to understand, at least to some extent, what is driving it to do so. For this the IPAT formulation is used, given as [71, 72]:

$$Impact\ (I) =\ Population\ (P) \times\ Affluence\ (A) \times\ Technology\ (T)$$

Equation 57

IPAT is a popular formula for assessing the effects of human activities on the environment. It emerged out of the Ehrlich-Holdren/Commoner debate in the early 1970s on deciphering the drivers of human impact on the environment. It has been used in various assessments in different forms in the last few decades [71-77].

The Technology factor in Equation 57 is like the residual term encompassing all the other actors. The key strength of this method is the simplified specification of the key driving forces behind climate change. The multiplicative structure makes it clear that all of the forces do not influence the impact independently of one other, and thus no one factor can be held responsible for the impact. A couple of limitations of the same are the often misinterpreted proportionality between the impact and each actor such that a 1% change in the actor leads to a 1% change in the impact (overlooking the cross elasticities between the actors), and that it has limited scenario testing capabilities [77].

For analyzing demand of materials we utilize the following modified formulation of the IPAT equation:

$$Demand\ (D) =\ Population\ (P) \times \frac{Income}{Population}\ (A) \times \frac{Demand}{Income}\ (M.I.)$$

Equation 58

The above equation indicates the relevance of population P, affluence A, and of studying material intensity, *M.I.*, as is usually done to assess material demand. However, further disaggregation can allow the extraction of insights about what causes material intensity *M.I.* to change. This is shown in the equation below.

$$Demand\ (D) = Population\ (P) \times \frac{GDP}{Population}\ (A) \times \frac{Industry\ Income}{GDP}\ (S) \times \frac{Material\ Sales}{Industry\ Income}\ (F) \times \frac{Demand}{Material\ Sales}\ (\frac{1}{p})$$

Equation 59

This equation is an identity with each term representing an actor influencing materials demand. All actors are well known accounting metrics commonly recorded and reported. This also makes the equation more intuitive. For example P or population refers to the total consumer base (in numbers), A or affluence refers to the average consumer income, S or industry share of GDP (income) relates to the consumer type – material buying or not, F is the fraction of income of material buying user that is spent on the material, $(\frac{1}{\mathrm{p}})$ the inverse of price refers to the amount of material obtained by the consumers for every dollar they spend on it. Note that, amongst different economic sectors, there is only one kind of consumer type for the kind of materials (metals and industrial minerals) considered here - industry, as other sectors of the economy, namely Services and Agriculture, consume these materials indirectly in the form of final products and goods. Thus the total demand is dictated by total demand or consumption by industry. This is why S in Equation 59 relates directly to the consumer type. This is not the case for lighting or fossil fuels or biomass, which are consumed directly by all sectors of the economy and thus accounted for in the GDP of each economic sector. Also, each of the factors is Equation 59 are transient and can change over time, and since total demand for a material depends on each of them, it is also influenced by their transience.

Taking a logarithm on both left and right hand side of Equation 59 gives the following:

$$\log(D) = \log(P) + log(A) + log(S) + log(F) - log(p)$$

Equation 60

For small changes, Equation 60 can be converted to the following expression by differentiating both sides of the equation:

$$\frac{\Delta D}{D} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta S}{S} + \frac{\Delta F}{F} - \frac{\Delta p}{p}$$

Equation 61

In other words small changes in demand, D, are simply the sum of the small changes in the actors of demand. This way the individual forces from each of the actors can be estimated using the percentage change and assessed for how they influence the change in material demand. Equation 61 should not be misinterpret as a 1% change in any of the above actors causes a 1% change in demand, meaning the elasticity of demand to any of them is 1 (-1 for price). This is not true and should not be understood so since the different actors are usually interrelated (cross-elasticities are non-zero) meaning that a change in one is likely to create some change in another factor. Researchers have tried to include this through methods that essentially use exponential fitting (regression analysis) or stochastic modeling of consumption on the variables (actors) making the process less simple [77, 78]. The usage of the simple formulation of IPAT is quite popular and as long as it is used to indicate the magnitude of the different actors and not necessarily their independent final influence on the impact, which requires elasticity estimations ([77] call this 'ecological elasticity'), it provides vital information with great confidence as well as ease.

Methodological limitations

It is crucial to highlight some of the limitations of the above methodology for material demand analysis. Taking these into consideration as implications are drawn from the results shown in the next chapter is utmost. Broadly speaking, the limitations are associated with the scope of material demand, and the interpretation of a decomposition analysis like IPAT, as used here.

Material demand in this section of the thesis is represented through 'apparent consumption' as defined by USGS [9]. Provided below is their definition of apparent consumption for the US [79]

"*Published statistics on mineral apparent consumption are limited to estimates of consumption of raw materials forms (ore, concentrate, and [or] refined metal). Apparent consumption is defined as mine production + secondary refined production + imports (concentrates and refined metal) – exports (concentrates and refined metal) + adjustments for government and industry stock changes. These estimates do not account for the amount of mineral commodities contained in manufactured products that are imported to the United States, nor do they deduct the amount of these mineral commodities contained in manufactured products that are exported from the United States*."

Statistics on total consumption (including import and export of materials through that of manufactured products) are less commonly available given the lack of records. However, some studies that have attempted to estimate this. Some of them have published results significantly different from apparent consumption. For instance USGS published two case study reports elaborating on this difference, one of lead consumption in the US, and the other on lead acid battery. They report that in 2004 U.S. apparent consumption of lead is reported as 1.44 Mt, however, total consumption is 1.78 Mt, 24% higher. In 1993 the difference was 14%. This difference can be attributed to the rise in the total lead usage for lead-acid batteries from 50 to 84% of all lead end-use and the rise in lead-acid battery imports into the US after 1997 [79, 80]. Similarly Professor John Barrett at the University of Leeds has used input-output tables to show that steel consumption in the UK results in more production outside the country than domestically [81]. Also, Graedel and coworkers have contributed extensively to national material flows for several materials and geographies including exports and imports through semi-finished and finished products [82]. Their efforts prove to be one of the most extensive in this respect.

Note that this doesn't present itself as a problem when the analysis is done at the global scale, as in Chapter 3 global analysis, and in Chapter 4. However in Chapter 3, when the demand for materials in USA, China, and India is analyzed, this can prove to be a big limitation to this study. This thesis uses apparent consumption as indicative of total consumption, just like most other studies do, however this may not be true. This opens up a valuable opportunity for future research to contribute.

Regarding application of a decomposition analysis like IPAT, one must be careful not to mistake the actors as forces. For example a change in 1% population refers to a change in 1% magnitude of the actor. However the resulting force on the material demand, which defines how much material demand changes, has to do with multiple other factors including how this change influences a change in the magnitude of other actors. For example a change in population doesn't mean no change in affluence. One example of this could be the rise in population resulting from the lower-income segment of the population, potentially due to lack of education. This could result in lowering of the per-capita income. Similarly, it may lead in an increase in average income as well. How a change in affluence results in a change in material demand can be equally complicated. Thus the force, or overall change in material demand, resulting from a change in an actor warrants further analysis than presented in this thesis. The goal of this thesis is primarily to correlate material demand changes with changes in actors by decomposing the change into the change of different actors using IPAT analysis. This provides useful insight into which actors may have dominated material demand trends, guiding future demand projections and analysis.

Prior Work

This thesis has benefitted from numerous literature studies providing insight into various aspects of the research. This is because of the topic's significantly high interest across numerous stakeholders over several decades, broad scope covering the global industry, and time dependent nature of the assessment meaning that most of the data and calculations correspond to a specific time stamp and can very well be repeated over time to improve upon the representativeness. In general most literature has either focused on a particular material, or geography. Only recently, in the last 5 to 10 years, have a few research teams undertaken global level multi-material scopes, the best of which include work from IEA, IPCC, and our research collaborators Allwood and team. IEA serves as a central data collector and aggregator for energy intensities of different sectors and thus provides a good estimate of the best available technologies (BAT) and current average technologies. While they use this information for their own estimate of energy savings through BAT, this thesis leverages their data and other's to calculate the same in evaluating BAT as one potential strategy. IPCC and Allwood focus on CO_2 emission abatement with the former being a central organization for climate change, and the latter being an upcoming leading research group from the University of Cambridge (in collaboration with our team, the Environmental Benign Manufacturing Lab at MIT) spearheading this kind of research [3, 6, 7]. This thesis complements prior work by putting together data and information scattered through several studies and databases, and collecting more to answer the question – *can the materials sector halve its energy through 2050?* In this process this thesis also significantly contributes to the assessment of material demand trends and the actors driving its change, as well as a detailed analysis of remanufacturing as an energy saving strategy. To our knowledge, this is the only work that comprehensively evaluates the materials sector for energy savings, through both technical and demand side strategies. Provided below in Table 5 and Table 6 is a detailed list of literature studies in the space along with their contribution to this research. Wherever necessary the scope of the reference as well as how research in this thesis distinguishes itself from it is also described. The scope tries to address the materials, geographies, time periods, and impacts analyzed. References corresponding to the sections of production energy efficiency (Chapter 4), remanufacturing of products (Chapter 5), and material demand analysis (Chapter 3) are highlighted in orange, blue, and green respectively. Every corresponding Chapter further elaborates on the corresponding prior work and lessons learned to guide the research presented in this thesis.

Table 5: Summary of key prior work and comparison to contribution of thesis. Solid filling refers to a more comprehensive contribution of reference (row) to area of research (column), hatched refers to partial contribution.

	BAT energy savings	Cutting-edge energy savings	Recycling energy savings	Reman energy saving	IPAT analysis of material demand	Material efficiency analysis	Cross-country mat'l demand comparison	CO_2 emission reduction	Other materials/sectors	Other EoL analyses (except recycling)	IPAT Analysis of other impacts	Investment estimates	Policy Analysis
Thesis							P						
IEA [6,11]		Partially (P)					P						
Allwood [7,82]	CO_2 savings												
Worrell [18, 83-86]	Only US		P					Only US				Only US	
IPCC [12]													
McKinsey [87-90]	Not materials specific (NMS)					NMS		NMS					NMS
Lund [91,92]													
Intlekofer [93]													
Ausubel [94]													
Behrens [52]													
Ruth [96,97]													
Wernick [98]													
Waggoner [72]													

Table 6: List of prior work, their scope of work, their contribution to this research, and additional contribution by this thesis

Reference	Scope of Work / Contribution to thesis / Thesis contribution
International Energy Agency (IEA) [6, 11],[99], [100], [101]	Scope: • Steel, aluminum, paper, cement, plastic, and chemicals • Global and national averages • Current (2005) and historic data • Energy and CO_2 emissions Contribution of reference to this work: • Industry energy and CO_2 emission breakdown into different sectors, and fuel types • Global BAT information for steel, aluminum, paper, cement, and petrochemicals • Projections of material demand through 2050 • Projections of electricity grid mix and energy mix of industry through 2050 • Estimates of energy and carbon reduction through 2050 using BAT • Cutting edge technologies in industry including hydrogen powered engines, black liquor gasification process, engine operation, etc. Additional contribution by thesis: • Repeat BAT energy saving potential through IEA and other data to validate IEA estimates • Extend evaluation to include other strategies of cutting edge primary and secondary production technologies, maximum recycling energy saving potential

	• Assess material efficiency strategies including a detailed assessment of remanufacturing. IEA reports do not address material efficiency adequately • Investigate drivers of material demand to draw perspective of material efficiency potential to meet targets • Focus on energy as opposed to CO_2 emissions to complement work by IEA, Allwood, and IPCC • IEA estimates a 43-63% increase in final energy from industry, relative to 2005, through their conservative 'blue' scenarios which predominantly only account for BAT. In this research we estimate a potential for 20% reduction through other aggressive strategies and opportunities
Allwood et al. [7, 81, 102]	Scope: • Steel, aluminum, paper, cement, and plastic • Global averages and UK averages • Recent data for 2005-2010 with some historic data as well • CO_2 emissions Contribution of reference to this work: • Projected material flows and CO_2 emissions from the five primary materials sectors through 2050 • Assumed mix of fact-based and hypothetical scenarios of improved energy efficiency, recycling, increased material yield, carbon capture and storage, non-destructive recycling, and reduced demand • CO_2 emission reduction potential from material efficiency strategies • White paper on material efficiency listing key questions for research • Example implementation of material efficiency strategies

	Additional contribution of thesis: • Focuses on energy to complement work on CO_2 emissions by IEA, Allwood, and others, answering the question – can industry halve its energy demand through 2050? • Estimate a maximum feasible energy reduction potential as opposed to an estimate of 2050 savings through hypothetical scenarios • Detailed assessment of the material efficiency strategy of remanufacturing • Investigate drivers of material demand to draw perspective of material efficiency potential to meet demand targets
Worrell et al. [18, 83-86]	Scope: • Steel, paper, and cement • Mostly US focused with some cross-country comparisons • Mid to late 1990s • Energy intensity and CO_2 intensity data Contribution of reference to this work: • BAT and cutting edge technologies for energy and CO_2 emission reduction for material industries in the US for the mid-90s • Cost abatement curves for technology deployment Additional contribution of thesis: • Aggregation of global energy savings through BAT and cutting edge across several materials • Projecting energy saving potential through 2050 accounting for recycling and material efficiency strategies
Intergovernmental	Scope:

Panel on Climate Change (IPCC) [12]	• Steel, aluminum, paper, cement, plastic, and chemicals • Global and national averages • Current and historic data • CO_2 emissions Contribution of reference to this work: • CO_2 emission reduction targets to avoid 2 – 2.4 °C temperature rise through 2050 • Energy and emission trends for industry, historic and projections, as well as some BAT data • Estimate CO_2 emission reduction potential through different mitigation options including energy efficiency, fuel switching, heat and power recovery, recycling, renewable energy, and carbon capture and storage Added contribution of thesis: • Repeats BAT energy saving potential to validate estimates • Extend evaluation to include other strategies of cutting edge primary and secondary production technologies, maximum recycling energy saving potential • Estimate a maximum feasible energy reduction potential as opposed to an estimate of 2050 savings through hypothetical scenarios • Assess material efficiency strategies including a detailed assessment of remanufacturing • Focus on energy as opposed to CO_2 emissions to complement work by IEA, Allwood, and IPCC
Ashby [5]	Scope: • Over 50 materials including basic materials • Unclear geographic, temporal, and process scopes

	• Energy, CO_2 emission, and water footprints Contribution of reference to this work: • Material profiles with global production volumes, energy intensities for primary and secondary production, recycling fractions of supply • Life cycle energy inventories of products
Bath University ICE [10]	Scope: • Over 50 materials including basic materials • Unclear geographic, temporal, and process scopes • Energy and CO_2 emission footprints Contribution of reference to this work: • Collection of energy intensities from various resources of primary and secondary production of materials
Ayers et al. [103]	Scope: • Iron and steel, aluminum, copper, lead, and zinc • US average • 1993 Contribution of reference to this work: • Exergy analysis of metal production
US Department of Energy [20, 22, 24, 25],[104]	Scope: • Steel • Data for early 2000s • US average • Energy intensity Contribution of reference to this work: • BAT and cutting edge opportunities for energy reduction in

	the US steel industry, including both primary and secondary steel production • Investment analysis for implementation of strategies • Estimation of theoretical minimum, practical minimum energy requirements (details in Methodology section) • Comprehensive overview of US steel energy use for different production steps in 1998
de Beer, and Worrell [21]	Scope: • Steel • US average • Energy intensity • 1993 Contribution of reference to this work: • Comprehensive analysis of energy reduction, short term and longer term technologies, in the US iron and steel industry including theoretical minimum analysis using exergy modeling (details in Methodology section)
US Department of Energy (DOE) [105]	Scope: • Aluminum • Data for early 2000s • US average • Energy and CO_2 emission Contribution of reference to this work: • Comprehensive analysis of energy use in the US Aluminum industry broken down into different steps • Historic analysis of energy and material use • Theoretical minimum energy requirements for each step using exergy and Gibbs Free Energy calculations

World Business Council on Sustainable Development (WBCSD) [106],[107],[108]	Scope: • Cement • Most data for 2006 • Global and national average • Energy and CO2 emission Contribution of reference to this work: • Detailed reporting of global state of the art energy use and CO_2 emissions as well as assessment of numerous technological options on reducing them across the supply chain in cement making • Use of GNR and ECRA reports to predict CO_2 emission projections through 2050 for the global cement industry
McKinsey & Company [87, 90], [89], [88]	Scope: • Aggregated estimates of all sectors of economy – do not explicitly bring out work on the 5 material sectors • Global scope • 2005-2010 and projections through 2030 or 2050 • Energy and CO_2 emissions Contribution of reference to this work: • Analyzed the potential for energy efficiency from a business perspective focusing on costs • Declared that energy efficiency offers a vast and low-cost energy resources for the US, with the potential of saving 23% of their projection of energy demand by 2020 • Highlight that largest opportunities in the industrial sector are in the energy intensive industries like refining, pulp and paper, bleaching, hydrocracking, etc. • 42% of the savings have a payback period of less than 2.5

	year • Specifically the US can reduce GHG in 2030 by 3-4.5% using tested approaches and high-potential emerging technologies with abatement marginal costs of less than $50 per ton • For the US, industry does not show up in the top 10 abatement strategies • For the US, top two industrial abatement strategies are process improvements and combined heat and power Additional contribution of thesis: • Focus on energy savings from the five material sectors specifically (details on these are not available through public reports by McKinsey and Company) • Technical analysis as opposed to focusing on business cost savings • Evaluation of other strategies of cutting edge primary and secondary production technologies, maximum recycling energy saving potential • Estimate a maximum feasible energy reduction potential as opposed to an estimate of 2050 savings through hypothetical scenarios • Assess material efficiency strategies including a detailed assessment of remanufacturing. • Investigate drivers of material demand to draw perspective of material efficiency potential to meet demand targets. McKinsey and Company seems to follow work of Allwood in their estimates.
Lund	Scope: • US remanufacturing industry

[91, 92]	• 1995 thru 2008 • All sectors Contribution of reference to this work: • Estimate the market size and the profile of the companies practicing remanufacturing • Comprehensive profile of the US remanufacturing industry including number of firms in different sectors, basic tactics and operating practices of the industry, strategies, and markets • Claim 50-80% energy savings from remanufacturing products and 40-60% price discount, relative to replacing with new Additional contribution of thesis: • Life cycle energy saving from remanufacturing products as opposed to only those from the materials production and manufacturing phases
Intlekofer [93]	Scope: • Residential appliance and computer industries Contribution of reference to this work: • Comparative energy of leasing products as opposed to buying new, where products with high use impacts and technological improvements can benefit from leasing because of decreased lifetime Additional contribution of thesis: • Focused on remanufacturing and analyzed products across 8 different sectors including appliances and computers
Kiatkittipong et al.	• Life cycle optimization for minimizing energy consumption from computer monitors, induction motors, refrigerators, and

[109]	light bulbs Added contribution of thesis: • Focused on remanufacturing and analyzed products across 8 different sectors including appliances and computers
Geyer et al. [110]	• Cost modeling of remanufacturing operations realizing focus on collection rate, component durability, and others
Ijomah et al. [111]	• Surveyed remanufacturing companies to highlight key challenges and requirements for remanufacturing operations • Suggested a generic remanufacturing model to account for interactions between the various remanufacturing activities
Ausubel & Waggoner [94]	Scope: • Intensities[3] of CO_2 emissions, energy use, food consumption, and fertilizer use • Global, US, China, India, Indonesia, Brazil, France Contribution of reference to this work: • Used IPAT formulation to study trends in material intensity, energy intensity, and CO_2 emissions intensity to understand dematerialization • Determined underlying reasons for decrease in intensities as well as persistence of the trends Additional contribution of thesis: • Focused on key materials of steel, aluminum, copper, zinc, and cement

[3] In the green section of the table 'intensities' refer to quantity per unit of GDP or GNP in that geographic and temporal scope

	• Brought in the key actor of price • Assessed the trends and actors of demand through an IPAT analysis
Ayres et al. [112, 113]	Scope: • Material intensities of various materials, various geographies, and various time periods Contribution of reference to this work: • Explains dematerialization (decrease in material intensity) through improvements in resource conversion efficiency defined as the ratio of useful work output and exergy input • Recommends use of useful work as a part of the production function almost filling in for Solow residual
Behrens et al. [95]	Scope: • Cross-regional analysis of resource extraction including fossils, metal ores, industrial and construction minerals, and biomass Contribution of reference to this work: • Metal extraction exhibits the highest growth • Resource extraction per unit GDP has decrease by 25% between 1980 and 2002 Additional contribution of thesis: • Focused on key materials of steel, aluminum, copper, zinc, and cement • Brought in the key actor of price • Assessed the trends and actors of demand through an IPAT analysis • Compared developed and developing economies

Cleveland and Ruth [114]	Scope: • Material intensities of various materials, various geographies, and various time periods Contribution of reference to this work: • Contests that the observed decline in material intensity and its interpretation for dematerialization is not necessarily robust. Argues that little is known about several industries and that there is limited macroeconomic evidence to support the theory of dematerialization • Provides a summary of literature analyzing material intensity trends and inverted-U phenomenon
European Commission [115]	• Comprehensive assessment of domestic material consumption, direct material input, and other material flow indicators for EU-15 from 1980 to 2000, with a comparison with economic indicators, as well as a comparison with Japan and US
Graedel et al. [35, 37-41, 45, 82, 116-120]	• Global, regional, and national material flow analysis for several metals including steel, copper, zinc, nickel, etc.
Krausmann et al. [121]	• Global material use analysis along with material intensity analysis for biomass, fossil fuels, construction minerals, and industrial minerals and ores
Rogich, Williams et al. [122], [123]	• US material consumption and production trends as well as material intensity trends
Ruth [96, 97]	Scope: • Copper, lead, zinc, aluminum, and iron • US focused

	Contribution of reference to this work: • Modeled material demand to estimate energy and emissions from materials production and potential dematerialization Additional contribution of thesis: • Compared developed and developing economies • Brought in the key actor of price • Assessed the trends and actors of demand through an IPAT analysis
USGS [2, 9]	• Material production and consumption over time in the US • Global and international production and consumption quantities of materials over time • Material price data • Material flow analysis of primary and secondary material in the US • Analysis of material supply and demand economic drivers
Wernick et al. [98]	Scope: • Material intensity trends for many materials including plastics, aluminum, potash, phosphorous, paper, timber, copper, steel, and lead • US focused • 1900-1990 Contribution of reference to this work: • US material consumption and production trends as well as material intensity saturation trends Additional contribution of thesis: • Compared developed and developing economies

	• Brought in the key actor of price • Assessed the trends and actors of demand through an IPAT analysis
World Bank [124]	• Cross-country material (and energy) consumption, production, and price trends with focus on China and India
Layke et al. [125]	• Trends in various material flow indicators like domestic processed output, domestic hidden flows, total domestic output, and net addition to stocks, across industrialized countries
Xu and Zhang [126]	• Trends in various material flow indicators like domestic extraction used, domestic material consumption, direct material input, domestic processed output, and others, in China
Müller et al. [35, 127]	• Steel stock and flows analysis for USA and global
Hatayama et al. [128]	• Comprehensive stock and flow diagram for steel in 42 countries from 1980 through 2050
Luo and Soria [129]	• Comprehensive overview of world aluminum industry including consumption, energy use, technology distribution, as well as modeling for future projections
ICSG [130]	• Comprehensive global material flow modeling of copper scrap
Spatari et al. [131]	• Copper stock and flows analysis for North America
Waggoner et al.,	• Comprehensive literature review on IPAT analysis and its

Chertow, Schulze, York et al., Kowalski et al., Dietz et al. [71-77]	variants • Example applications of IPAT to difference systems (not material systems, as used in this thesis)

Chapter 3: Evolution of a materials society

Abstract

This chapter analyzes the evolution of material demand with societal development, by comparing trends in the final material demand with the buying capacity of the consumers, defined as income (industry revenue per capita) divided by the material price. Using this demand of key materials - Steel, Aluminum, Copper, Zinc, and Cement - is analyzed at the global level as well as for the developed economy of USA, and the developing economies of China and India. The trends are starkly different. The US shows strong signs of saturation while; both developing economies of China and India do not (yet). The trends at the global scale seem to be dominated by the developed world and only in recent years does the influence of growing Chinese demand start showing up. To determine what is driving the differences this research analyzes the actors of material demand and determines how each of them contributes to the different materials, in the different economies. Results show that consumer income and population have been consistently increasing, but in the second half of the 20th century, the US industry has demanded less material per dollar output, while the US industry output has continued to grow. Collectively they tend to cancel each other, presenting a material saturation phenomenon where percentage changes in demand are equivalent to that in population, or in other words, the percentage changes in demand per capita are close to zero. For China and India the case is the opposite where not only is the industry and industry share of GDP growing, for each unit increase in value addition, industry has continued to demand more and more material, driving up demand, and avoiding saturation effects. This paper goes beyond analyzing material intensities and determines what actors play a role in material demand and to what extent. A key conclusion derived from the analysis is of focusing on measures that reduce the material intensity of industry, i.e. looking for ways

to reduce material demand into the future without reducing the services demanded from them.

Introduction

In Chapter 1 we discovered how the material demand[4] trends over the last 5 decades have been significantly different between the US and China or India. This includes not only the total quantities but also the respective CAGR. The reasons for the different demand rates can relate to a broad range of characteristics, some specific for the individual materials, but eventually correspond to the final utilization of these materials in providing the services demanded. Barring environmental concerns, continued demand growth can indicate signs of development. For example Graedel and co-workers show a strong correlation between material use and GDP and HDI [82]. However, if going forward, we aim to reduce material demand as one potential strategy to mitigate the energy and carbon impacts, without hampering any kind of development, we must first understand what drives material demand, and what are the different actors we can influence or should target to implement this strategy. This chapter addresses this with first understanding the historic evolution of a materials society from a new perspective, and then a decomposition of the trends into the corresponding actors. Like Chapter 1, this is done for key materials and for the geographic and economic scopes of USA, Global, China, and India.

Prior work

Interest in material demand trends has been high and growing for several decades now [112, 113, 132]. Several technical and political propositions have been made on reducing impact intensities of materials [6, 12]. Demand trends have been analyzed across different boundaries and different temporal scopes. Included in this is the empirically observed 'delinking' of material demand and economic development, one form of relative dematerialzation [76, 98, 112-114, 121-123, 126, 133, 134]. This is commonly

[4] In this chapter, material demand is represented through 'apparent consumption' as defined by the USGS

measured through a ratio indicator called "Material Intensity" or "Intensity of Materials" given as:

$$Material\ Intensity = \frac{Material\ Demand}{GDP\ or\ GNP} = \frac{Material\ Demand\ per\ capita}{GDP\ or\ GNP\ per\ capita} \quad [\frac{kg}{USD}]$$

Equation 62

Material intensity is the amount of material needed to produce one unit of net value addition or GDP or GNP. The inverse of this is sometimes called productivity of material use [95]. The higher the material intensity, the greater the material demand to produce the same GDP. Thus a reduction in material intensity without compromising on final services provided has a sustainable connotation. Other metrics like material intensity per unit service (MIPS) have also been proposed but not yet used as popularly as material intensity [114]. Along these lines is also the hypothesized environmental Kuznets curve phenomenon, where material intensity (or equivalent metrics) is expected to exhibit an 'inverted-U' shape curve (convex) such that as an economy develops, the material intensity first increases, peaks, and then eventually reduces. As a result several researchers have investigated the trend in material intensity over time or with economic development (GDP or GNP). Wernick et al. presented increasing US material intensities over several decades between 1920 and 1990 for plastics, aluminum, potash, and phosphorus; a constant intensity for paper; and decreasing intensities for timber, copper, steel, and lead, during the same period [98]. Timber exemplifies the material substitution effect, while the trend for lead is driven by regulation. Williams et al. conducted a similar analysis for the US consumption of steel, cement, paper, ammonia, chlorine, aluminum, and ethylene, and showed how in the second half of the 20^{th} century, the first three have either decreased or remained flat, while the rest have increased [123]. They also fit the steel trend to a bell-shaped 'inverted-U' curve revealing the peak to be around 1920 (potentially influenced by the World War). They highlight four interesting reasons to the maturing of basic materials use in the United States – increase in material use efficiency, material substitution, saturation in use, shifts in high income consumer preferences to less material intensive goods and services. For an aggregated material analysis (agricultural, forestry, organics, metals, and minerals), Rogich et al. reveal a reduction in material intensity in the US from 1970-1990 by approximately 30% [122]. Similar is their result for the aggregate of plastics, wood, paper, and metals. On the other hand, at the global level, a recent report by Krausmann et al. shows that the aggregated material intensity for minerals had remained constant around 1 kg/$ GDP for the first half of the 20th century, increasing slightly then after, and then decreasing after 1970 [121]. To complement this, Behrens et al. draw a regional comparison of material intensities for aggregated material use (including fossil fuels, biomass, metals, and industrial and construction minerals) and show the fastest decrease for North America, a flat trend for Oceania, Latin America, and Caribbean, and a slower decrease for the rest at approximately the aggregated rate for the World [95]. For a country-by-country analysis, Xu et al. show a decrease in aggregated material intensities for the developed economies of USA, Japan and the Netherlands, while a constant trend for China and the Czech Republic [126]. Overall, due of boundary inconsistencies, its not easy to compare across these reports, but for many developed countries, the common result has been that of reducing material intensity indicating a so called 'delinking' or 'decoupling' between material dependence and economic development, where as for developing or transition countries the results vary – sometimes increasing, sometimes decreasing, and sometimes flat.

Analyzing the trend in material intensity is indicative of productivity, but by no means defines material demand completely. For example, in most of the work cited above, though material intensity might be decreasing, overall demand and demand per capita have increased. Also material intensity trends are simple and intuitive but limitedly informative. A decreasing, increasing, or constant material intensity, over time can result from various causes and drivers, and though understanding each one precisely can be a monumental task, one definitely needs more clarity to draw inferences more confidently. For example, a decreasing material intensity could mean an absolute dematerialization, or a more rapidly increasing GDP, or decreasing economic industrialization, or perhaps a more efficient use of materials (or others). Plus material intensity alone conceals the role of population, which cancels out in the ratio [114] . The goal of this paper is to better understand the demand trends for key materials. First, following similar intentions to that behind material intensity, this paper proposes a newer formulation that assess consumer choice of material demand defined as the ratio of demand and income over material price. Income over material price relates to the maximum a consumer can demand, which we call 'buying capacity' and thus this ratio is indicative of consumer choice of demanding the particular material. Second, this paper goes beyond mere indicator-trend analyses to shed brighter light upon the different actors that influence material demand, and understand the extent to which they do so (actors refer to the different actions taking place in society that eventually force material demand like population change or income increase. Some reports call them *forces* [72], however, the understanding followed in this paper defines *forces* as the influence Actors have on the *impact* which may entail estimating the elasticities of these actors on the final impact or understanding the interdependence of the actors). To augment this understanding, different economic scopes of USA (developed), Global, as well as China and India (developing) are considered. Using this knowledge it explains why demand for some materials in some economies is exhibiting a saturation phenomena, and why it is not for others.

Materials and methods

The methodology followed is as described in Chapter 2. The materials chosen for this study are key metals – Steel, Aluminum, Copper, and Zinc and the most consumed ceramic – Cement. Not enough credible data was found for paper and plastics to include them, especially for price given the wide variety of paper and plastics consumed. The data for this study has been acquired from credible sources and often crosschecked with other sources, especially in case of any inconsistency. Data for apparent consumption quantities are mostly taken from [2, 9], GDP and population from [135], prices from [9], and industry share of GDP from [136]. However details of data and sources for each material, and each geography, is available in the Appendix.

Results

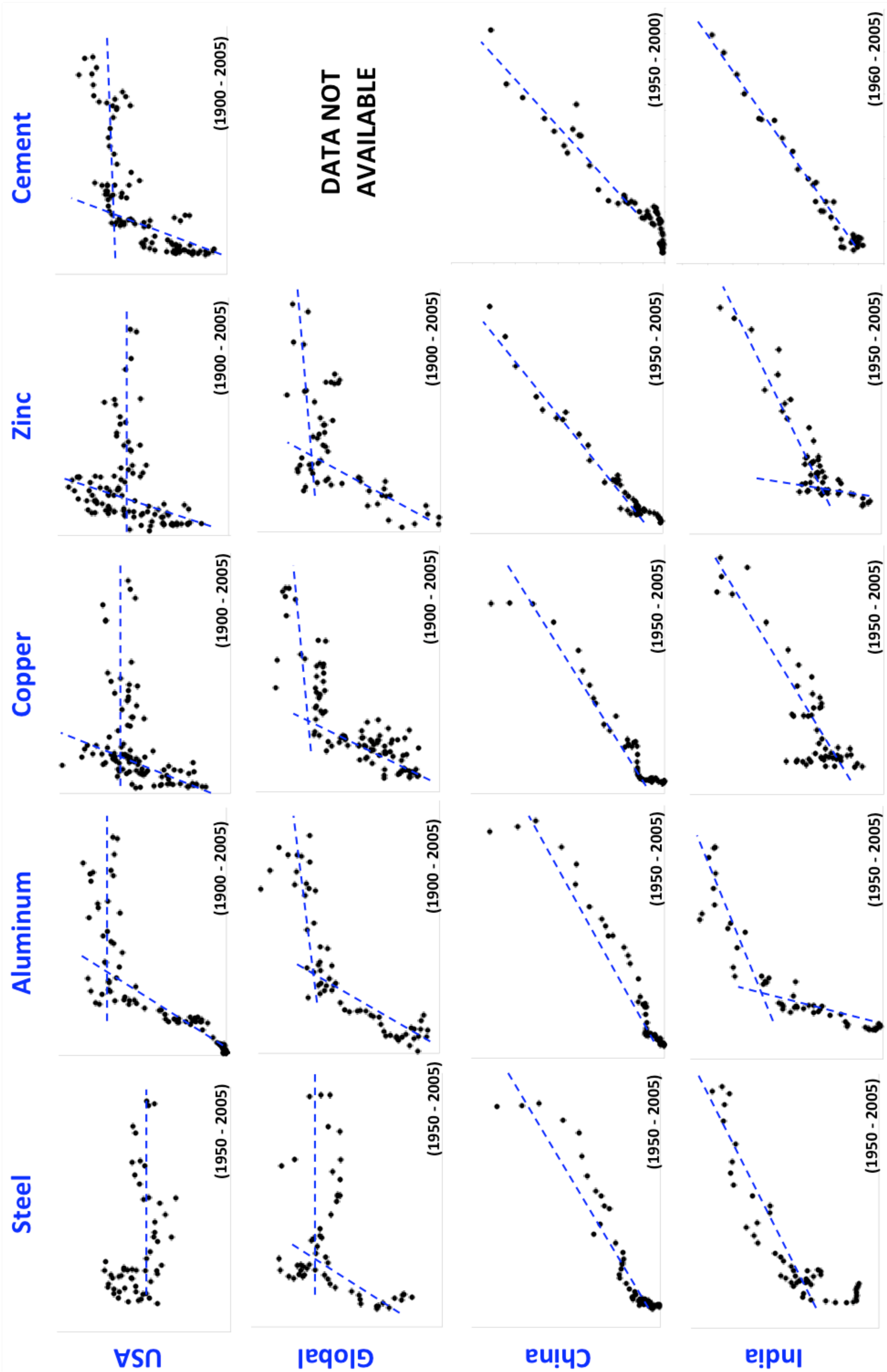
Following Equation 56 demand per capita [y-axis] Vs. industry income per capita over material price trends [x-axis] are generated for Steel, Aluminum, Copper, Zinc, and Cement, for the geographic scopes of USA, Global, China, and India. These are shown in Figure 17. Only the trends are presented along with the coverage years (in parenthesis), and not the data values to keep the presentation simple. All axes are on a linear scale. Also shown in broken 'blue' lines are the inferred trends for the different charts. These are not regressed but the author's rendition inferred from regression lines. The results are interesting and partially comforting. Interesting because of the difference in the trends between developing (China, India) and developed (USA) economies. For all materials, China and India show a proportional increase in demand per capita with increase in income over material price. In some cases (like steel and aluminum demand in India) a change in slope is apparent referring to a change in choice, however the slope never turns to zero like in the case of USA. On the other hand, the developed economy of USA shows clear signs of saturation[5]. For each of the materials, a plateau phase is observed in the second half of the century where material demand increases relatively slowly. This result is comforting as a proportional (like for lighting in Figure 8) or exponential trend can be more threatening to resource depletion and environmental degradation, as discussed before. The trends on the Global scale are fairly similar to USA or the developed economy in general, given the dominance of the developed world on both demand and industry income at least up until 2000. Post 2000 demand in China picks up at faster rates (see Figure 6 in Chapter 1) impacting global trends more significantly. If China continues to demand more and more and increases its dominance on global demand, and if the developed countries continue to exhibit a relative saturation, the global trends would soon move away from mirroring the saturated trends of the developed world to proportionally increasing trends of China and the developing economies. Note that these results and trends presented in Figure 17 include the conclusions previously drawn from material intensity trends reported before. Müller et al have explained how the trends in demand can be explained by analyzing stocks. Materials stocks are the total quantity of the materials currently being used by society, and material

[5] as defined in the Methodology section in Chapter 2

flows (demand refers to the annual flow) are the annual inputs or flows of materials to society. In studies of iron and steel used in industrialized countries it has been observed that these stocks tend to plateau after a certain level of per capita income. The general idea is that society has adequate supplies of durable goods and infrastructure and, in fact, adding more might be difficult. Müller et al. found this plateau level for iron and steel stocks to be about 10t/cap. After this level is reached, society maintains a certain level of material production required to replace and maintain this stock level. This level is estimated to be in the vicinity of 500 kg/cap/yr. For comparison, current global average per capita iron and steel stocks are estimated to be about 2.7t/cap, and global average iron and steel flows are about 200kg/cap/year [35, 81, 127].

Though relative magnitudes of per-capita demand of the materials are not shown in Figure 17, they are interesting to compare as well. For example, a USA based consumer, on average, demanded 380 kg of steel in 2005, almost double of global and Chinese levels, and close to 10 times the per-capita demand in India. On the contrary, US per-capita demand of cement in 2005 was roughly 430 kg, approximately half of Chinese demand, but more than the global average of 360 kg. India on the other hand demanded only 100 kg/capita in 2005. The story for Aluminum and Copper is similar to that for Steel, with USA demanding 20 and 8 kg/capita respectively, roughly 5-6 times Chinese and Global levels which are equivalent, and 20-30 times Indian levels. With Zinc, USA demanded 3.6 kg/capita in 2005, again 10 times the Indian level, where as China demanded 2.2 kg/capita and the global average was 1.5 kg/capita. Given one primary difference between the geographic scopes is the economic structure; the results set a strong basis to deeper analyze the economic aspects for them over the years. To do this the IPAT formulation with actors of material demand as presented in Equation 59 and described in Chapter 2 is used. Further Equation 61 is utilized to breakdown the rate of demand change into the different (not independent) actors for each material, and each geographic scope, over the last 50 years from 1955 to 2005 (the economic slowdowns of 2007-09 are avoided). The results are shown in Figure 18, in a similar arrangement to Figure 17. For each chart the vertical axes and scales as well as the horizontal axes and scales are the same and are shown on the boundary charts. Along with the six variables of

Equation 59 and Equation 61 (total demand plotted as the solid line), also shown are the percentage changes for 'mass of material used over industry income' referring to the quantity of material required by industry to provide the respective value addition. This is like the material intensity of the industrial sector and referred to as 'M' in this paper. All percentage changes are CAGR calculated between the labeled year and 5 years back.



Steel
Aluminum
Copper
Zinc
Cement
USA
Global
China
India
(1950 - 2005)
(1900 - 2005)
DATA NOT AVAILABLE
(1950 - 2000)
(1960 - 2005)

Figure 17: Demand (y-axis) vs. buying capacity (x-axis) plotted for the different materials and different geo-economic scopes. Buying capacity is defined as the ratio of industry income for the particular economy and the corresponding material price. Each data-point corresponds to a particular year, and the temporal range is given in parenthesis.

Figure 18 provides a lot of information both at the high level and at the level of each material, actor, or geography. The questions of interest for this chapter, arising from Figure 17, are essentially at the high level of each geographic scope. Hence, the analysis is presented in a top down approach. First to note is that for all geographies or countries (including global scale) the population has been continuously but slowly growing (~1-2%). The growth rates for India are marginally higher than others. In terms of GDP per capita (affluence), China exceeds others significantly (5-10%) followed by India, and then Global and USA. For all years across all scopes GDP per capita has continuously risen. A factor that is commonly discussed in a cross-country analysis (especially between developing and developed) is the level of industrialization calculated as the fraction of GDP that corresponds to Industry. Diminishing material intensity trends are often attributed to 'deindustrialization' of economies where the less material intensive service sectors start dominating. Its observed that industry share has indeed shown growing trends for China and India, and recently diminishing trends for USA as well as Global scopes, however, the year to year percentage changes are quite small, usually only a couple of percent or lesser (positive or negative). Thus contrary to common belief of the large impacts of economic structure changes, it in fact appears to play a relatively meager (direct) role. Also interesting is how total demand *D* and *M* trace each other rather closely for USA, which is not the case for China and India. This potentially indicates that the industry demand for material quantity per unit dollar output has a more dominating effect on material demand in the US, while in China and India they are separated meaning that other actors play an influential role as well. Another interesting point to note is that both *D* and *M* have reduced in the last year for all materials, except cement, in the US, while the case for China and India is the opposite. On a global scale the trends for *D* and *M* appear to be more stable, especially with M closely fluctuating around the *zero* line and *D* positive and around the 5% CAGR level. A dip in demand changes to the level of population is apparent for the years of 1975-2000 corresponding to the plateau/saturation effects observed in Figure 17. Prices and share of industry output spent on materials *F* seem to fluctuate a lot, quite inversely, at least much more than *M*. This firstly means that material prices tend to dominate changes in *F*, and secondly that *M* is relatively less elastic to material prices, at least in the short-term.

On a material-by-material level, the demand trends of Figure 17 appear in their percentage change form just as expected. For example for Steel in the US, the rate of demand change is close or fluctuating around the population change explaining the plateaued or saturating effect. On the other hand, for China and India the demand trends have largely been positive. For China there is increasing growth in recent decades relating to the exponential trend for Steel and Aluminum, while for India the growth rates seem to fluctuate around a flatter trend. The soaring demand in the initial years around 1950-1960 for China and India indicate the industrial transition when these industries started picking up. At the global scale 1975 onwards the growth of steel demand was close and fluctuating around that for population making the demand per capita trend in Figure 17 plateau. Similar is the case for other materials. The increasing impact of demand in China on global trends is clear with the rise in demand in 2005. Aluminum is equally interesting. The declining CAGR for US is apparent and explains saturation, while for the others it has been usually positive and even growing for China. Similar trends are observed for Copper and Zinc except at a global scale for Zinc where demand seemingly plateaus between 1975 and 1995 and then picks up again in recent years, and Copper for India shows large fluctuations apparently due to fluctuating *M*. Cement demand in the US and at the global scale also show much slower demand growth as compared to China and India, where increasing affluence in recent decades seem to dominate in promoting demand growth, along with the decreasing cement price in India.

As an example, the case of global steel is elaborated. The global analysis presents the added benefit that the considered demand or apparent consumption is also equal to the total consumption as the import and export quantities are internal to the boundary. The observed saturation trends at the global scale are hence that of total consumption and provide some confidence of using apparent consumption as an indicator of total consumption. For the case of global steel, the trend observed in Figure 17 is of an initial rise, followed by saturation starting the mid 1970s. Also one can observe a slight rise in the recent years around 2005. Figure 18 explains this. Population and Affluence have consistently increased during the observed period. Also, 's' the fraction of industrial GDP has changed rather slowly. What seems to have changed dramatically, causing the demand trend to also change, are 'F' and 'p', the fraction of global industry income spent on steel, and the price of steel. Prior to the mid 1970s 'F' and '1/p' changed positively driving demand, but after this period they changed negatively pushing back on demand. In fact 'F' and '1/p' seem to move quite proportionately meaning that the quantity demand from industry is less elastic to industry steel price. That's why 'M', at least in this case, proves to be a good indicator for the analysis over 'F' to study consumer choice supporting the use of material intensity as an indicator for analyzing demand saturation, as it has been in the past. One can also notice how 'D' and 'M' tend to closely follow each other post 1975, which was not the case before then when other factors seems to play a relatively more influential role. This hints that the reason for saturation-like-trends in global steel demand is primarily a function of the choice of industry to demand less material in spite of increased industry revenue, consumer base, and affluence, as well as decreased material price. Reasons for the change in choice are discussed in the next section. In the recent years choice coupled with a decrease in price, seems to result in the rising trend in demand. This may be closely related to the rising influence of China on the global market.

Steel
Aluminum
Copper
Zinc
Cement
USA
Global
China
India
30%
20%
10%
0%
1955
1965
1975
1985
1995
2005
P
A
S
F
1/p
D
M

Figure 18: YtY changes in demand per capita and the corresponding actors mentioned in Equation 59. Also plotted is the change in 'M', material intensity of industry, which is the product of F and 1/p.

Discussion

Disaggregating demand into the various IPAT components and studying them in Figure 18 sets the foundation for the intended analysis. This section presents the high-level understanding towards answering the question about what causes the contrast in trends discovered in Figure 17.

Actor / *Country*	*Population (P)*	*GDP per cap (A)*	*Industry Share (S)*	*Kg/industry (M)*
USA [1955-2005]	*	**	**	*
Global [1955-2005]	**	**	*	*
China [1955-2005]	**	****	*	*******
India [1955-2005]	***	***	**	**
Global [1975-2000]	**	*	**	*
USA [1905-1955]	*	*	**	***

Colors are comparing different actors for same country -> darker is larger magnitude, green is positive, and red is negative

** are comparing different countries for same actor with more '*'s referring to a larger magnitude*

Increasing Darkness ------->

Positive change

Negative Change

Figure 19: Simplified representation of conclusions drawn from Figure 18. Colors are comparing different actors for same geo-economic scope. Darker is larger magnitude, green(ish) is positive, and red(ish) is negative. '*'s are comparing different geo-economic scopes for same actor with more '*'s referring to a larger magnitude.

To do so the paper utilizes the results presented in Figure 18 and takes total averages of each of the actors. To present the results however *F* and material price are combined, given their strong correlation (as observed in Figure 18), and *M* is used. These averages are then ranked through color-coding and symbols as shown in Figure 19. The actors are ranked for each geographic / economic scope through colors - green indicates a positive force by the actor (to increase demand) and red indicates and negative force (to decrease demand). The darker the color, the higher the magnitude of the force. Also shown are the relative magnitudes of each actor across the different geographic scopes. This is indicated through the symbol '*' with more '*'s meaning a higher magnitude. Each actor follows its own independent scale and so the '*' cannot be used to compare different actors (the color coding serves that purpose).

The results are clear and directly answer the questions raised about understanding the trends of Figure 17. Lets neglect the last two rows for now, and come back to them later. Its strongly stands out that consumer affluence has been a strong and consistent driver of material demand, one with a high magnitude on average. Similar is the growing population though the intensity is lower. Both of these actors strongly promote increased demand for all materials across all geographic scopes. The affluence growth in China is the highest (as observed in Figure 18 and presented in Figure 19 with '****') followed by India, and then USA and Global scale, which have the affluence growth at similar average rates between 1950 to present. With regards to population, India exhibits the fastest growth and USA the slowest, while China and Global averages are intermediate and similar. Industry share, which is Industry output as a fraction of the GDP (*S*) is different for the different scopes. China and India have grown slowly, while for USA and Globally this has decreased on average. However the magnitudes are small (given by the lighter colors) but highest for USA (decreasing faster than at Global scale), similar in magnitude to that for India, while at China and Global scales the trend is slower. The last actor given by the material intensity for Industry or *M* also shows significant variation across the different geographic scopes. It's growing for all but USA, with strong growth for India and fastest growth for China (3-4 times faster than India). At the global scale *M* is growing at moderate rates, while for USA it is declining at moderate rates.

Reviewing the charts on a geography level (row by row) explains the trends observed and conclusions drawn earlier from Figure 17. It's realized that China and India continue with strong growth given that all the actors are driving it in this direction. For China *M* and *A* are the biggest actors. However for the US, though *A* and *P* are driving up demand, both *S* and *M* are reducing it, decreasing the final demand for the market and causing the observed saturation effect. On the global average the reducing *S* and slightly weaker effect of the actors keeps the demand growing between 1955-2005. Looking specifically at the period of 1975-2000 at the global scale (second-last row) it is clear that both *S* and *M* counteract the demand promoting actors of *P* and *A*, leading to the observed saturation at the global scale. This is very similar to the saturation observed for the US. So overall, Figure 19 is able to inform which actors are driving demand, in which direction, and in what capacity, for the different geographic scopes.

The last row of Figure 19 traces back the same calculation for the US, but for the first half of the 20^{th} century as opposed to the second, as for all other rows. At this time, the US by itself was developing rapidly with economic structures more like what China and India are today (to some extent). The results directly inform the same. We note that the rapid growth in material demand during the first half of the 20^{th} century in the US was driven by all the actors promoting demand. Affluence and *M* increased most followed by population and *S*. In fact the increase in *M* was the dominant factor, indicating the increasing industrial dependence on material for generating the desired profits. However from then to the second half of the century, the service sector has begun to dominate (especially with industrialization moving overseas) and the reliance of industry on materials to create economic value has begun to decrease. This is why we see the saturation effects for the developed economy of USA, and not (yet) in the developing economies like China and India. Similarly we see that for the last quarter of the 20^{th} century the global drivers are playing a similar role to the second half of the 20^{th} century for the US. Hence the similar trends observed in Figure 17.

Comparing the relative magnitudes of the different actors for US demand in the first and second half of the 20th century, it's evident that population and income played similar roles, and the key change is in the industrial material intensity (and also economic share but to a smaller extent), i.e. quantity (mass) of material demand to produce the industrial income. Two broad reasons for this decrease could be (1) a relative decrease in the 'numerator' i.e. a slowing down in the increase of material demand by industry while industry revenue continues to grow at the same rate; (2) a relative increase in the denominator, i.e. industry revenue has grown faster while growth in material demand by industry has remained the same. The final effect is likely to be caused by a combination of both. For example, industry by its construction could be changing, such that it is relying on other sources of income that are not necessarily heavily material dependent, at least for that material. Material substitution could be one reason. Another could simply be a saturated demand for the primary materials studied – for example industry gradually moving towards products (material end-use) that have a relatively longer life, and as a result require replacement less frequently, diminishing demand. In this case the demand for products by new customers can continue to grow, but the replacement demand will diminish. In such a case industry now adjusts to the changing demand and caters to other services that perhaps require lesser or other materials. Another plausible reason could be that industry has become more efficient with the use of material, with lower losses, as well as optimized material input for the desired service. This is definitely true for the steel industry [6, 11].

Regarding increasing use life of the material (demand side changes), [35, 45] has shown that from the earlier decades of the 20th century to the late 90s, the fraction of all steel used in North America for building and construction (long residence life) has doubled from 20% to 41%. Hatayama and co-workers project the fraction of end-use to buildings is going to continue to increase to over 50% on a global scale, after which it tends to reduce and stabilize around 45% [128]. Similarly for Copper, ICSG shows that the US end use of copper was 51% in building and construction in 2006, up from 24% in 1980 [130]. The increasing fraction of longer lifetime applications directly transforms into diminishing growth in demand. It is interesting to note, that research also reveals that for Asian countries the lifetime of steel in buildings is around 33 years roughly half that of developed countries like USA [128]. If this were due to the building reconstruction rate being higher in Asia, then this would add to higher demand growth rates for cement, aluminum, and zinc as well. Specific examples of material substitution include composites and plastics substituting metals or the substitution of timber explained before. An example industry moving to less material intensive sources of income includes electronic products that help generate a larger fraction to industry value addition per unit material consumed given that their relative prices are higher. With regards to more efficient use of materials (supply side changes), one of many examples is of reducing material per kilometer of long-distance telecommunication cables at roughly (-9%) CAGR over the last century [134]. Similarly known is the reducing coke input to produce one ton of steel, which directly relates to predominant energy savings as well [134]. Of course there can be rebound effects associated with such improvements if prices decrease, which negate some or all of the material savings [4, 137]. Unfortunately, data scarcity and modeling complexity does not permit a simplistic analysis on how each of these comes into play, beyond observing specific examples.

A crucial question out of the work is whether China and India, and the rest of the developing world will also exhibit signs of saturation in to the future, at what levels of demand, and when. A simple estimate would be to assume that they follow the US and saturate at similar levels growing at the existing rates until then. This would require the global demand of steel and zinc to more than double, of aluminum and copper to roughly quadruple, and that of cement to increase by 20%, keeping the population levels the same. However, the story for these countries could in fact be very different. The United Nations 'medium' scenario estimates for population growth up until 2050 are at a CAGR of 0.02% for China, 0.9% for India, 0.8% Globally, and 0.7% USA [135, 138]. These are significantly lower than historic growth rates and achieving such control will be challenging but also rewarding in terms of reducing material demand. Combining these with the projected 'Constrained growth scenarios' by PwC, affluence is expected to exhibit a CAGR of 3.1% for China and India each, 1.8% Globally, and 1.4% for the US

[139]. These are again much lower numbers for China and India compared to historic statistics of the previous few decades. Also both of the above estimates are of the conservative cases, especially the ones for affluence, and have associated negative impacts because of slower economic growth. However, even if conservative, both population and affluence will continue to drive up demand and if saturation is to be experienced by the developing world, significant changes in industrial material intensity would have to be incurred through either or combination of the factors listed before. The industry share of the economy will also contribute in this regard, however historically these have been significantly lower than the driving push from population and affluence. Such a result emphasizes the role of material efficiency in society and its ability to alleviate burdens associated with material demand. Allwood and co-workers provide a comprehensive discussion on such strategies [81, 102, 140].

Summary and next steps

In summary, this chapter uses a new way to study evolution of material demand through societal development by comparing material demand to the ratio of income divided by the material price referred to as 'buying capacity' in this thesis. 'Saturation', as referred to here, is when such a plot shows a convex trend with demand growth diminishing with increasing income over material price. Contrasting trends reveal saturation phenomena for the developed economy of USA, and not for the developing economies of China and India. Global trends appear to mirror the developed world, however the increasing influence of the developing world has begun to show up in the recent years. The use of an IPAT like formulation helps determine the key role of population and affluence in growing demand (stronger for China and India), while diminishing industry material intensity and deindustrialization help contain material demand for USA. The robustness of M revealed the price inelastic nature of industrial demand to materials, making it a worthy indicator for material demand modeling. For China and India, all the actors, on average, promoted demand, and while affluence and population are projected to continue drive up demand, it is to be seen what material efficiency strategies can we deploy to reduce industrial material intensities and alleviate the growing pressures of material production.

Chapter 4: Energy efficiency of materials production

Abstract

In this chapter we review the energy requirements to make materials on a global scale by focusing on the five structural materials which dominate energy used in materials production: steel, cement, paper, plastics and aluminum. We then estimate the possibility of reducing absolute materials production energy by half, while doubling production from the present to 2050. The goal therefore is a 75% reduction in energy intensity. Four technology based strategies are investigated without regard to cost: 1) widespread application of best available technology (BAT), 2) BAT to cutting edge technologies, 3) aggressive recycling, and finally, 4) significant improvements in recycling technologies. Taken together these aggressive strategies could produce impressive gains, on the order of a 56% reduction in energy intensity, but this is still short of our goal of a 75% reduction. Ultimately, we face fundamental thermodynamic and scrap availability constraints on our ability to improve the energy intensity of materials production. A strategy to reduce demand by providing material services with less material (called “material efficiency”) is outlined as an approach to solving this dilemma.

Introduction

We have learnt and understood the enormity of the anthropogenic demand for materials. The energy required to make these materials and their associated products, and the carbon emissions associated with this production are also huge. Industry requires on the order of a third of the total worldwide energy use per year, and contributing a similarly large proportion of total anthropogenic carbon emissions [6, 7, 11].

In this chapter, we examine the determinants of these large energy requirements, and look for potential future reductions, and in particular, potential constraints on these reductions. We particularly focus on embodied energy, which is the energy required to produce a unit of material. This when multiplied with the total units consumed or produced results in the total energy needed to provide these materials.

Framework

As a point of reference we are looking to reduce our energy use in the materials sector even while we allow demand to grow. For example, sustainability guidelines for energy and carbon emissions suggest that we need to halve our energy use from 2000 to 2050. At the same time, to allow developing countries to “catch up” to the developed world, we would need to allow for a doubling of demand [[141], [3], [7]]. This is shown more discretely in the material demand projections by IEA in Figure 20 [6]. Later on we repeat the analysis for the respective high and low demand projections for each material, but as a base case we consider doubling of the demand for each material. Taken together, this would require that the energy intensity of materials production in 2050 to be only one quarter of that in 2000. In other words, we are looking into the possibility of obtaining a 75% reduction in the average energy intensity of materials production. We set aside potential complications such as price effects and rebound and proceed as if we are operating in a world where the incentives exist to encourage this goal. Also, the efficiency improvement calculations are based on final energy and thus electricity generation and grid improvement are independent of our calculations. In the sensitivity and scenario analysis, more details and alternative calculations schemes are discussed.

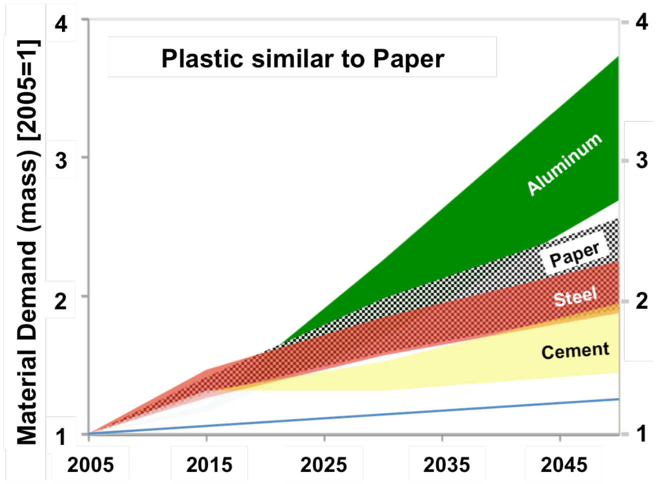


Figure 20: Forecasts of material demand by the IEA up to 2050. Both 'high' and 'low' projections are plotted as bands [6]. The 'blue-line' is explained in Chapter 6.

Embodied energy

The embodied energy is the energy required to produce a material from its raw form, per unit mass of material produced. The energy is usually measured in terms of the lower heating value (LHV) of the primary fuels used plus any other primary energy contributions. These energy requirements are dominated by two main steps. The first step involves the mining, crushing, washing and separation of the ore from the surrounding material (call gangue), and the second step is a chemical reduction process that produces the refined material from its ore, (called smelting in metals processing). Many of the important metal ores are either oxides or compounds with sulfur, which in turn are often converted to oxides during processing. The reduction step for these oxides uses a reducing agent, usually carbon, which yields a final output including refined metal and carbon dioxide gas. Hence the reduction process can produce a certain amount of carbon dioxide (on the order of one mol of CO_2 per mol of metal) in addition to the carbon dioxide associated with the energy requirements (which depends critically on the nature of the energy source). The ratio of carbon dioxide emitted by the carbon reduction reaction, to that from energy use varies by material and technology but is generally in the range of 1:1 (some cement operations) to 1:10 (some aluminum operations). In general, however, the carbon dioxide intensity of materials production is dominated by the energy intensity of production and the implied fuel usage with a very strong correlation between the two as seen in Chapter 1.

Early materials production processes were relatively simple requiring only harvesting, as for stone and timber, and mixing and heating as for bricks and concrete. These materials are still in use today, and generally produced much more efficiently than in early days, with energy intensities on the order of 1-5 MJ/kg. Newer materials, extracted from dilute ores, and involving a reduction step, are much more energy intensive. For example, the energy intensities for a variety of metals are plotted in Figure 21 versus the dilution (reciprocal of the ore grade or mass concentration "c" of the metal at the mine).

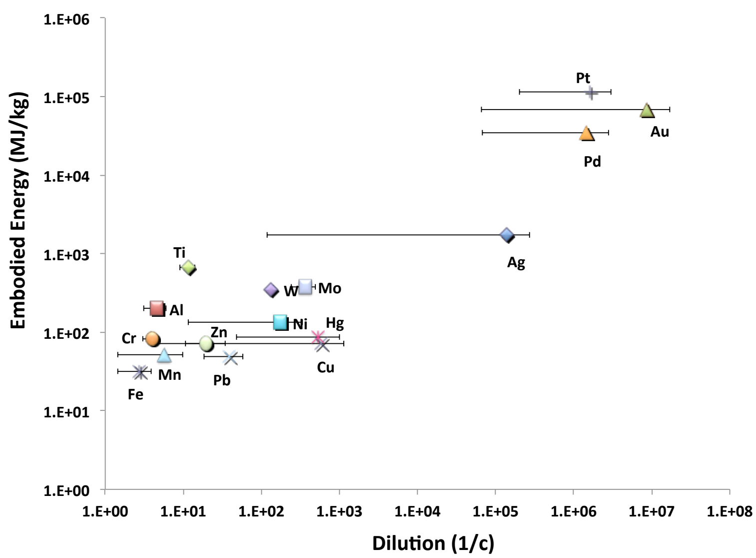


Figure 21: Embodied energy of 16 metals [5] plotted against the dilution, or inverse of concentration, of the common ores used to produce the metals [117].

While there is a considerable scatter in the plot, it does show that these materials are quite energy intensive compared to earlier materials, and that above a certain dilution, energy intensity e increases with dilution (1/c). The trend can be explained by the change in the dominating energy step. In the lower dilution range, particularly for materials such as iron and aluminum, the energy requirement for production is dominated by the chemical reduction step. At the other end of the figure, for those metals that are highly dilute (and generally less reactive), such as gold and platinum, the energy requirements are dominated by the mining and separation steps, and generally increase with increasing dilution of the ore. The scatter in the low dilution area can be explained in part by the differences in the thermodynamic requirements for the chemical reduction process. This can be estimated by looking at the magnitude of the standard Gibb's free energy of formation for the common ores used to make these metals. For example, looking in the low dilution area of the figure, the Gibb's free energy for the ores for titanium (TiO_2), and aluminum (Al_2O_3), are relatively large (17.8 and 27.1 MJ/kg respectively) compared to the Gibb's free energy for the ores used to produce iron (Fe_2O_3) and manganese (MnO2), (6.6 and 8.9 MJ/kg respectively). Other major differences, which affect the embodied energies, are the quality and availability of the ore, the ore matrix, the complexity of the smelting and production processes, the age of the technology employed, and the degree of purity required in the final output. Because these factors can vary considerably around the world, each data point in Figure 21 could actually be represented by a cluster of points around a mean value that could easily vary by ± 20% or more. See [[10],[5], Figure 7, and Table 3]. Note that unlike the engineering properties of a material, such as strength or stiffness, which can be obtained under well-specified conditions, the embodied energy is a function not only of the material itself, but also of a larger system that surrounds the material and is often not well defined. Hence this level of uncertainty is somewhat inherent to the type of large boundary analysis we are performing.

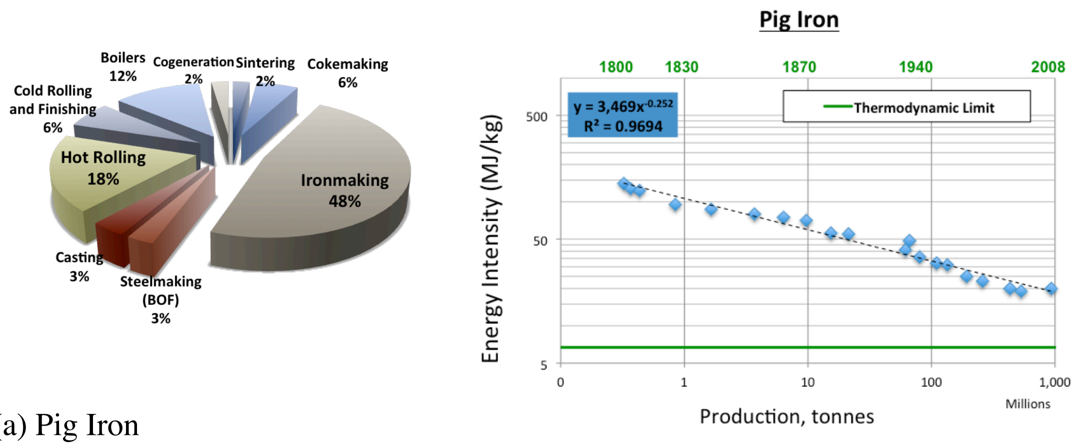
Historical data shows that industry has made significant reductions in the energy intensity of materials, particularly for those produced in high volumes.

Figure 22 gives time series data for average worldwide production of pig iron and aluminum. These data are plotted in terms of e (for the chemical reduction step only, which dominates for these two cases) versus Q, with a few dates marked to indicate the progression of time. The energy intensity data for pig iron corresponds to the coke used in blast furnaces, while the energy intensity value for aluminum corresponds to the electricity used in the smelting of aluminum (the so called Hall – Héroult process). The pig iron data shows an almost one order of magnitude reduction in the energy intensity over a time period of about 200 years. The aluminum data shows an equally impressive reduction over about a century. The average annual improvements for the energy intensity for these technologies have been in the range of 1.0 to 1.5%. The plots also show the theoretical minima for these operations. These minima are approximated using the thermodynamic models presented in chapter 2. It is readily apparent that while there is still room for improvement, new improvement will be constrained by thermodynamics. Generally as one approaches a thermodynamic limit, progress slows down and the performance levels off near to, but never obtaining the limit. **Figure 23** shows a breakdown of the energy intensity for aluminum smelting by major regions of the world over the time period 1980 to 2005. The data show the variation in the world data as well as the world average marked by the dashed line in the middle. Taken together

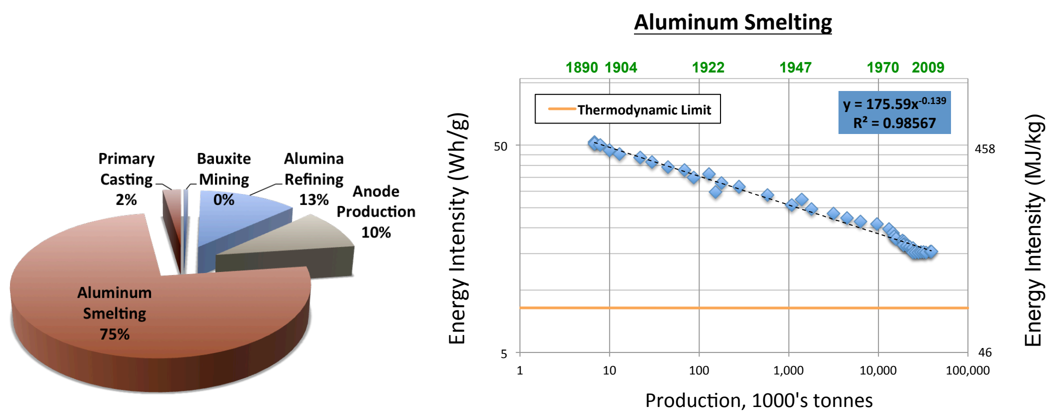
Figure 22 and Figure 23 suggest two important strategies to further reduce the world average energy intensity of materials production. The first would be to move the world average down to the best available technology (BAT) and the second would be to move further toward the theoretical minimum.

The constraints on the first strategy are primarily financial. Materials production facilities require large capital investment. Once these costs are sunk there is a large incentive to continue operation for decades. In fact, looking closely at Figure 23 reveals that some of the least energy efficient facilities are actually operated in the developed world where the installations are older, while the newer more energy efficient facilities are in the developing world. This pattern is repeated for other materials as well, see results for world cement production [6]. At the same time, it is to be noted that because materials production is so energy intensive, and materials are available on local and global markets, no one can remain competitive and be energy inefficient for long. Therefore, while there may be outliers, the bulk of production for globally competitive, energy intensive materials cannot stray too far from the best available technology. After reviewing the data for our so-called top five materials we estimate that a worldwide move from today's average to best available technologies would result in an overall energy reduction of about 18% (Best available technologies or BAT is as given by International Energy Agency (IEA). BAT in many cases can be the same as Best practice technology (BPT) that is best available and economical, but can be different when a new technology has emerged. Saygin and co-workers in their work distinguish the two for several industries [142]). This agrees with detailed estimates made by us and others, including the International Energy Agency IEA [11],[6],[7]. Some of the technologies involved in these improvements would include worldwide implementation of by-product gas recovery from steel production and thin slab casting, retrofitting of aluminum smelters and point feeders, continuous digesters and dry sheet forming for paper production, wet to dry kilns for cement, as well as fuel and clinker substitution and improvements in cracking and distillation for plastics. In addition, widespread implementation of combined heat and power and more efficient electric motors are assumed. Data used in our calculations are provided in Appendix.

Additional energy reductions can be made with research breakthroughs and by implementing cutting edge technologies. Each of the top five materials already have technology roadmaps with key energy challenges identified, and funded research and scale up on going [101]. At the same time, the major energy intensive steps for the top five materials are already in the vicinity of 60% efficient (relative to their thermodynamic limits). If we make the fairly aggressive assumption that these can be further improved to within half the remaining distance to the theoretical limit (~80% efficient) we estimate an additional overall reduction in total energy requirements for materials production of about 19%, for a total of 37% when combining both strategies. Some of the breakthrough technologies considered here include, alternative reduction technologies with fuel and feedstock substitution, black liquor gasification for paper and inert anodes for aluminum and other cutting edge technologies some of which may not have been discovered yet. Additional details can be found in [18], [86], [83], [85], [7], [11], [101],[6]. This also includes improving the yield of the material processing and manufacturing processes by decreasing in Equation 38 to its theoretical minimum of 0. The resulting magnitude of this improvement may seem smaller than expected to some. The reason is that this improvement applies only to primary production, not secondary (recycled) production, which in some cases already represents a significant fraction of supply. We discuss recycling next.



(a) Pig Iron



(b) Aluminum

Figure 22: Historic trends in global average energy requirements for production of pig iron from ore, and for aluminum smelting, versus the respective global production volumes. The corresponding years are labeled above the chart. Also

included are the theoretical minimum values for the two processes. For aluminum the primary energy is shown on the right vertical axis using global average electricity factor of 9.3 MJ/kWh. Data for iron energy intensity is obtained from [143] and that for aluminum from [105]. Production data is obtained from [9]. Pie chart data is taken from [85], [105], [21].

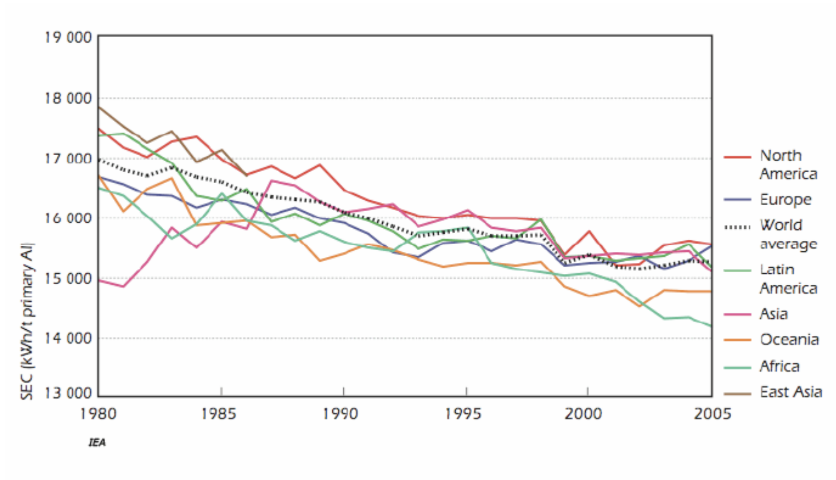


Figure 23: Historical Regional data for the energy intensity of aluminum smelting (taken as is from [6]).

Another way to reduce the energy requirements for materials production would be to look to a new material source with a lower energy intensity e. This could be to harvest the already processed materials in end-of-life products. That is, since recycling generally avoids many of the energy intensive steps in primary production (e.g. chemical reduction, mining and separation etc.) it is well known for having a lower energy requirement as compared to primary production. For example, the production of secondary aluminum may require only on the order of 10% of the energy intensity of primary aluminum. And for steel it may be only 50% of primary energy intensity [5]. The problem here is that while we know that we can generally make the energy intensity of secondary production small compared to primary production, there are serious constraints on the quantity of secondary materials that can be captured and processed. This problem is particularly apparent for emerging countries while they are building their infrastructure which adds materials to stocks rather than making them available for recycle [127].

To explore this effect, we use the model described in Chapter 2 on estimating available scrap based on material demand growth. As a reminder, we use an expression for r as given in Equation 38, with c = 0. Thus,

$$r = \frac{f}{(1+i)^n}$$

Equation 63

Table 7: Recycling parameters for top five materials. ('Cur' = current average; 'CE' = cutting edge; 'r' = Recycling rate as a fraction of supply). Details are provided in the Appendix.

Material	n [years]	r2005	r2050	$[1-e_{s,Cur}/e_{p,Cur}]$	$[1-e_{s,Cur}/e_{p,CE}]$	$[1-e_{s,CE}/e_{p,CE}]$
Steel	19	37%	69%	64%	29%	65%
Aluminum	15	30%	65%	94%	89%	95%
Cement	50	0%	0%	-	-	-
Paper	1	45%	80%	47%	34%	67%
Plastic	5	4%	28%	55%	37%	68%

If we now assume a fairly aggressive effort to increase the fraction *f* and apply estimates for relevant recycling parameters given in Table 7, we estimate a net additional reduction in the world energy intensity required to produce materials at about only 7% of current usage (increased recycling decreases the primary material fraction and thus diminishes the savings from BAT and cutting edge strategies). Note that this percentage depends on the order of implementation of our proposed energy saving strategies (current to BAT to cutting edge). If recycling were implemented before any of the other improvements (using column 5 instead of column 6) the percentage change would have been 20%. Never the less the total combined savings would remain the same, at about 44%, regardless of the order. Finally, we implement yet a further recycling improvement by assuming an additional reduction by 50% in the energy intensity of secondary materials production, e_s. Many of these secondary processes have not yet been optimized, often for practical reasons related to the collection and sorting of incoming scrap. By uniformly assuming this 50% reduction for all materials we are still quite far any thermodynamic limits, for example the melting of the metals and thermoplastics only requires on the order of 10 to 20% of our assumed values. This provides still more improvement, raising our total potential savings to 56%. Note that this improvement step appears quite large because we have already implemented aggressive increases in recycling rates in the previous improvement. This is just about as far as we can go with energy efficiency, even using very optimistic assumptions, and yet we are still substantially short of our goal of 75%.

Material substitution

Material substitution is another strategy to move towards more sustainable materials that reduce energy demand, by substituting the higher energy materials with lower energy ones. Referring to Figure 15, Part (b), this would mean moving towards materials that have the lowest abscissa, assuming that the change in required quantity of production would not undo the sought after energy savings. Looking at the same figure, this can also play out favorably from a cost perspective (for the customer that is the product manufacturing sector consuming these materials) as lower embodied energy materials tend to be lower priced. However there are at least four major problems that arise in considering material substitution as a strategy for reducing energy demand – (1) limited available opportunity as it seems that the materials with lowest embodied energy are the ones produced the most indicating that industry may already have exploited this opportunity; (2) design constraints – meaning that material quantity and type are often driven by volume / design restrictions of the end product and the technical properties of the material (be it mechanical, electrical, chemical, or other); (3) a potential increase in the quantity of the lower energy material so as to provide the same service. This could very much result in decrease in quantity. Ashby has shown that newer materials indeed provide better properties for construction materials. However, moving from natural materials (i.e. stone, timber, etc.) to these new modern materials, one sees that material strength and elastic modulus have increased by about 1-2 orders of magnitude, while the energy requirements to make these new materials has increased by about 3-4 orders of magnitude (see Figures 9.14 and 9.15 in [5]); (4) life cycle energy footprint – a material with higher embodied energy, like aluminum and composites, can return comparative energy savings in the use phase, for example, using aluminum in automobiles over steel may lead to a higher energy investment in manufacturing the car but lower gasoline requirement when in use. More examples on this can be found in [5, 144]. The next chapter on remanufacturing elaborates extensively on thinking about energy savings from a life cycle perspective. Unfortunately prior research hasn't necessarily identified the clear winners based on life cycle energy footprints of different materials as it is heavily dependent on the application and consumer behavior during and at the end of product use, as well as how the energy accounting is conducted [145, 146].

Given the complications of clear guidance based on life cycle energy footprints of materials, and that price-based material substitution has already captured a lot of the energy savings potential (of the top five; steel, paper and concrete are near the bottom of the energy intensity scale), we do not see material substitution, as a major strategy to reduce materials energy requirements. In fact the trend may be of societal movement towards more energy intensive materials. A straightforward example is Figure 20, where the higher energy intensive materials of aluminum and plastic are growing much faster than the lower energy intensive materials like cement and steel (overlooking a life cycle energy analysis).

In summary, we have looked at the possibility of reducing the energy intensity of materials production by 75% over the next four decades and found that this appears very unlikely. An analysis that includes significant new breakthroughs in production technology and recycling systems as well as deployment worldwide falls considerably short of this mark, providing only about a 56% reduction. In terms of total energy E this means a reduction of 12% in 2050 relative to 2005. The essence of this problem is that materials production energy is dominated by a small group of materials that have been in production for some time, and have already become quite efficient. Iron and steel, cement, concrete, paper and aluminum have all been in production for at least a century.

Plastics, which are newer, will be reaching a century in production just a decade or two from now. Hence, while future gains in energy efficiency for these materials are still quite likely, major improvements are restricted in part by the laws of thermodynamics.

Calculation details

The base case calculations above assumed a doubling in demand for each material through 2050. However, as we observed in Figure 20, that demand ranges for each material can be different. Obviously the higher the projected demand, the more difficult would it be to halve the total energy required to provide the materials. Thus, being conservative we show the details of the results for the 'low-demand' or lower estimates in Figure 20. This would mean aluminum growing by a factor of 2.6, steel, paper, and plastic, each by a factor of 1.8, and cement by a factor of 1.4 through 2050. Figure 24 shows the cumulative reduction in 'e' and 'E' in total and for each material through each of the four strategies considered. Note, since now the low-demand projections are used, which are different for each material, the straightforward 75% reduction goal for 'e' does not hold. However, the goal for reducing 'E' by 50% of today is shown in the green bars. Also shown in red bars is BAU 2050, business as usual, which assumes no change in 'e' through 2050, while demand grows. Key takeaways from these results:

- The total savings from adding each strategy are almost the same for the low-demand case as the base case of doubling demand. In the former we get a net reduction in 'e' of 57%, while in the low-demand case we get 56%. In fact, if the high-demand case were to be considered the reduction in 'e' is 55%. However, reduction in 'E' varies more as it factors in the demand. For the three cases of low-demand, doubling, and high-demand, the reduction in 'E' is 20%, 12%, and -6%, respectively, i.e. for the high-demand case E in 2050 is higher than E 2005 by 6%. Thus no matter what demand scenario is considered, the target is far from met, however, the strategies do yield significant savings relative to BAU 2050. This highlights the enormity of the challenge in meeting energy reduction targets of halving E by 2050.

- Looking at each material, we note that none of the individual materials meet the goal of reducing 'E' by 50% either. Steel and cement come closest with a 32% and 26% reduction respectively, while 'E' for plastics in fact increases by 14% relative for 2005. The savings are even lower for the high-demand case, in which case only steel exhibits a reduction in 'E'. This emphasizes the need to focus on demand along with embodies energy, as a means to reduce total energy.

- In general we observe steel contributing to highest to the savings relative to BAU across the five considered materials. In fact, steel provides for over half of the savings with roughly an equal split in savings from the rest. This indicates the importance of focusing on steel for energy savings.

- The order of implementation of the strategies influences the saving but the cumulative sum is indifferent. For example, if Es were deployed before RR, the net additional saving from each may be different but the sum would be the same.

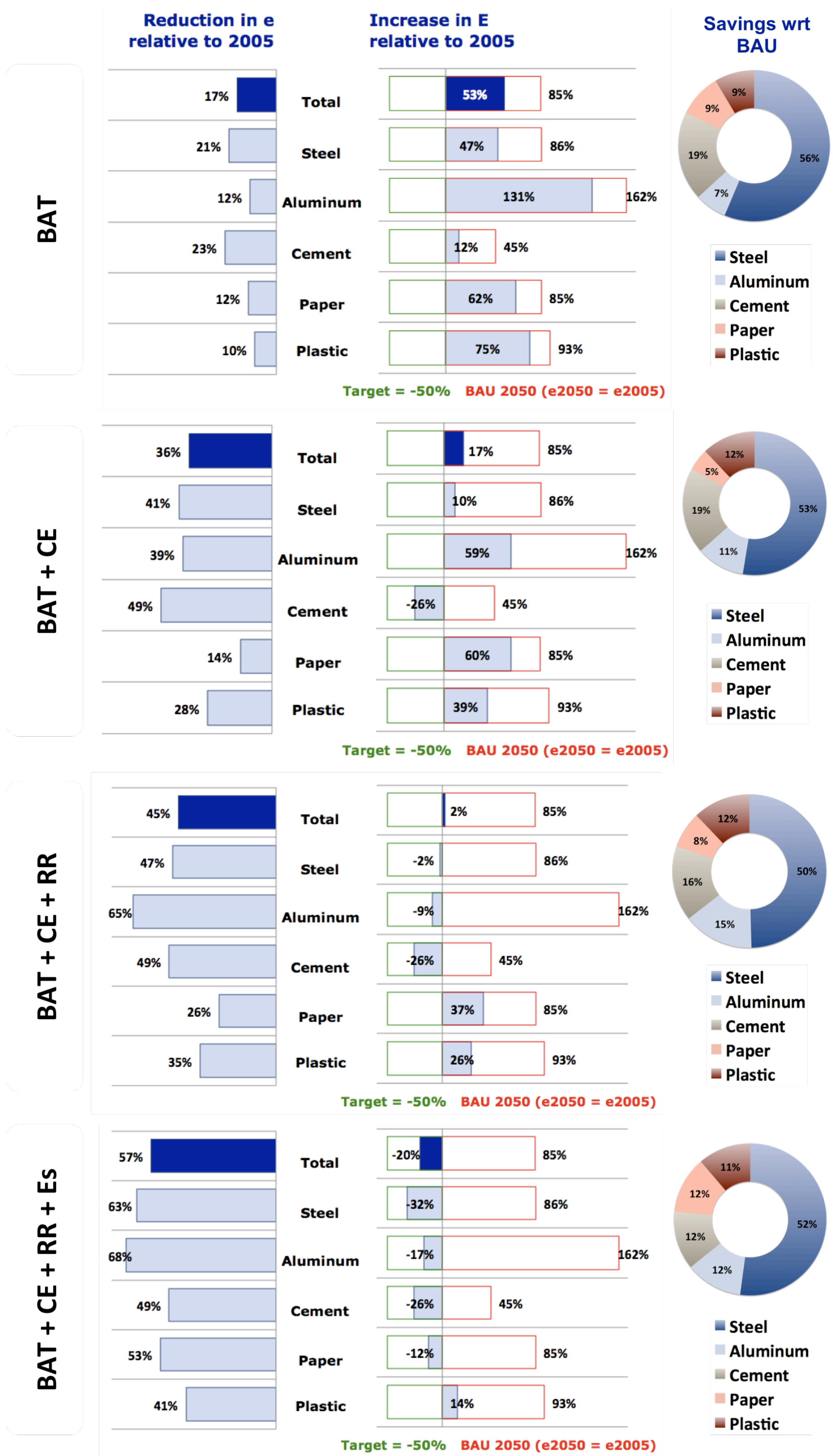

Reduction in e relative to 2005
Increase in E relative to 2005
Savings wrt BAU
BAT
17%
Total
53%
85%
21%
Steel
47%
86%
12%
Aluminum
131%
162%
23%
Cement
12%
45%
12%
Paper
62%
85%
10%
Plastic
75%
93%
9%
9%
19%
7%
56%
Steel
Aluminum
Cement
Paper
Plastic
Target = -50%
BAU 2050 (e2050 = e2005)
BAT + CE
36%
Total
17%
85%
41%
Steel
10%
86%
39%
Aluminum
59%
162%
49%
Cement
-26%
45%
14%
Paper
60%
85%
28%
Plastic
39%
93%
12%
5%
19%
11%
53%
Steel
Aluminum
Cement
Paper
Plastic
Target = -50%
BAU 2050 (e2050 = e2005)
BAT + CE + RR
45%
Total
2%
85%
47%
Steel
-2%
86%
65%
Aluminum
-9%
162%
49%
Cement
-26%
45%
26%
Paper
37%
85%
35%
Plastic
26%
93%
12%
8%
16%
15%
50%
Steel
Aluminum
Cement
Paper
Plastic
Target = -50%
BAU 2050 (e2050 = e2005)
BAT + CE + RR + Es
57%
Total
-20%
85%
63%
Steel
-32%
86%
68%
Aluminum
-17%
162%
49%
Cement
-26%
45%
53%
Paper
-12%
85%
41%
Plastic
14%
93%
11%
12%
12%
12%
52%
Steel
Aluminum
Cement
Paper
Plastic
Target = -50%
BAU 2050 (e2050 = e2005)

Figure 24: Cumulative reduction in 'e' and 'E' relative to 2050 values for the most conservative low-demand case. Target for 'E' reduction is 50% shown in green. BAU 2050 assumes no change in 'e' through 2050.

Scenario and sensitivity analysis

I. All calculations above do not include the fuel value of plastics. The table below provides the comparative results if fuel value were to be included for the three demand scenarios:

% reduction in E in 2050 relative to 2005	IEA low demand	Doubling of demand^	IEA high demand
Without Fuel Value of plastics^	20%	12%	(6%)
With Fuel Value of plastics	11%	4%	(19%)

^as presented in manuscript

( ) refers to a negative value, in this case E2050 being higher than E2005

The percentage savings are diminished because of adding the fuel value to plastics and not being able to alter it through 2050. The energy savings from each step of sequentially deploying the strategies (BAT → BAT + CE → BAT + CE + RR → BAT + CE + RR + Es) are provided below:

% reduction in E in 2050 relative to 2005	BAT	BAT + CE	BAT + CE + RR	BAT + CE + RR + Es
IEA- low demand without Fuel Value of plastics	(53%)	(17%)	(2%)	20%
IEA- low demand with Fuel Value of plastics	(58%)	(28%)	(8%)	11%
Double demand without Fuel Value of plastics	(64%)	(26%)	(11%)	12%
Double demand with Fuel Value of plastics	(69%)	(36%)	(17%)	4%
IEA- high demand without Fuel Value of plastics	(95%)	(51%)	(34%)	(6%)
IEA- high demand with Fuel Value of plastics	(104%)	(65%)	(42%)	(19%)

Notes:

1. Order of sequence matters, however net savings of BAT + CE + RR + Es are uninfluenced by the order
2. Fuel value of plastics is only allocated to primary material and not to secondary materials

II. Described below are the different scenarios considered that include testing of the sensitivity of key variable.

A	A+	Cutting edge energy requirement for primary production is ¾ in the range between BAT and theoretical minimum, closer to theoretical minimum
	A-	Cutting edge energy requirement for primary production is ¼ in the range between BAT and theoretical minimum, closer to BAT
B	B+	Cutting edge energy requirement for secondary production is 25% of current average
	B-	Cutting edge energy requirement for secondary production is 75% of current average
C	C+	Collection rate for scrap (fraction of available for collection) is 100% for each of Steel, Aluminum, Paper, and 50% for Plastic, and 25% for Cement
	C-	Collection rate for scrap (fraction of available for collection) is at average values of 2005-06
D	D+	Current average primary production energy intensities are 10% higher
	D-	Current average primary production energy intensities are 10% lower
E	E+	Current average secondary production energy intensities are 10% lower
	E-	Current average secondary production energy intensities are 10% higher
F	F+	All of the positive scenarios above combined
	F-	All of the negative scenarios above combined

The influence of varying the scenarios on the reduction in total annual energy 'E' in 2050 relative to 2005 is shown below. The target is 50% shown in the green line. The error bars correspond to demand variation with the lower end (less savings) corresponding to the IEA high demand projection, and the higher end (more savings) corresponding to the IEA low demand projections. The columns represent the base case results for assumed doubling of material demand.

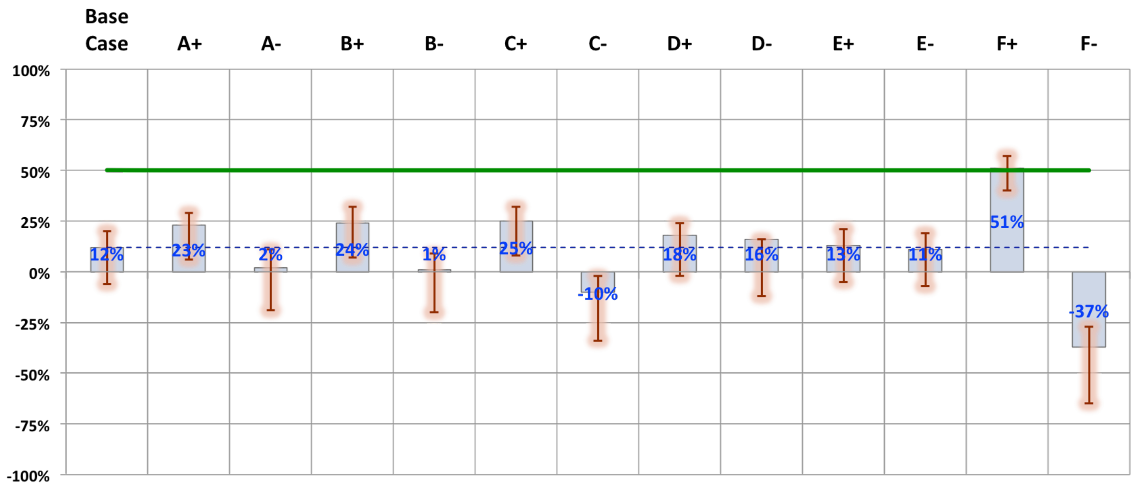


Figure 25: Total energy reduction in 2050 relative to 2005 for the various scenarios considered. The target of 50% reduction is shown as the green line.

In none of the cases, except for F+, is the target met. Also with IEA high demand, in most cases more energy is consumed in 2050 relative to 2005.

Summary and next steps

It is not our intention here to predict the future, but only to point out what we see as very likely constraints on our ability to both meet energy reduction targets and increase demand. It does not seem likely that material production (and more generally the industrial sector) can meet the dual goals we set out earlier in this paper of roughly doubling production, while halving energy use. In fact, this analysis suggests that we may only be able to halve energy with no increase in demand. Furthermore, for the strategies discussed in this paper to be implemented, significant technical breakthroughs and financial incentives are required. Currently the prices for energy and materials are too low to significantly alter the prevailing game plan, which is to substitute energy and material for labor.

Table 8: The magnitude of effect relative to price of increasing energy price or imposing a CO_2 tax. Prices same as in Figure 15. Energy fraction of cost taken from [101], and CO_2 intensities from [5].

				magnitude of effect relative to price		
Material	**Price (USD/ton)**	**Energy Frac of Operating cost**	**CO_2 (kg/kg)**	**energy price inc. by 50%**	**CO_2 is taxed at $20/ton**	**CO_2 is taxed at $100/ton**
Steel	$ 700	15%	2.5	8%	7%	37%
Aluminum	$ 2,400	30%	9.5	15%	8%	42%
Paper	$ 800	12%	1.4	6%	4%	18%
Cement	$ 100	30%	0.7	15%	15%	74%
Plastics	$ 1,985	60%	2.5	30%	3%	13%

At the same time we recognize the potential vulnerability of the top five materials to price increases, particularly those brought about by higher energy prices and potential carbon taxes. To illustrate this, we have constructed Table 8 that shows potential cost effects relative to price for our top five materials. Whether an energy cost increase would necessarily translate into a material price increase (and further to a product price increase) depends on several factors. For one, large energy intensive material producers work hard to establish long term, low cost energy sources to insulate themselves from energy price increases and fluctuation. For example, about one half of all aluminum smelted use hydropower, with long-term agreements. Never the less, these potential cost effects do indicate a certain level of pressure on these producers and the potential for price increases. These price increases on the other hand, could weaken demand and increase the effort to increase efficiency and find substitutes.

In summary then, our analysis using extremely optimistic estimates for future energy efficiency cannot deliver sufficient savings to meet our 2050 targets as outlined at the beginning of this paper. There are, however, additional strategies, which could be employed to provide material services to consumers by using materials more efficiently and there by reducing demand. We term this collection of strategies "material efficiency" [102], [81]. They include the ideas of providing equivalent materials services but with reduced materials requirements. Materials efficiency includes such ideas as extending the life of products, using materials more effectively in design, reusing materials and remanufacturing. The savings from this approach could be quite large and could allow us to meet our targets for energy and carbon. For example, conceptually at least, if we were to double the life of all current products, this could result in a maximum reduction in our demand by half. We dedicate the next two chapters in analyzing material efficiency in greater detail.

Chapter 5: Material efficiency through remanufacturing

Abstract

A popular strategy to increase material efficiency is to produce products that are used longer, there by increasing the total service provided be the product while consuming the same quantity of material and other resources used to make the product. This does not mean that we should not replace old products with new, but it essentially encourages reselling and reusing of products and potentially displacing new production. Remanufacturing can support this by bringing used products back to like-new condition. Remanufactured products that can substitute for new products are thus generally claimed to save materials and energy. These claims are made from studies that look mainly at the differences in materials production and manufacturing. However, when the use phase is included, the situation can change radically. In this chapter we first analyze the energy saving potential from remanufacturing products. 25 case studies for eight different product categories were studied, including: 1) furniture, 2) clothing, 3) computers, 4) electric motors, 5) tires, 6) appliances, 7) engines and 8) toner cartridges. For most of these products, the use phase energy dominates that for materials production and manufacturing combined. As a result, small changes in use phase efficiency can overwhelm the claimed savings from materials production and manufacturing. These use phase energy changes are primarily due to efficiency improvements in new products, and efficiency degradation in remanufactured products. For those products with no, or an unchanging use phase energy requirement, remanufacturing can save energy. For the 25 cases, we found that 8 cases clearly saved energy, 6 did not, and 11 were too close to call. In some cases we could examine how the energy savings potential of remanufacturing has changed over time. Specifically, during times of significant improvements in energy

efficiency, remanufacturing would often not save energy. A general design trend seems to be to add power to a previously unpowered product, and then to improve on the energy efficiency of the product over time. These trends tend to undermine the energy savings potential of remanufacturing. Thus overall while the strategy of remanufacturing to save materials and energy could hold a lot of potential, the caveats extracted from this analysis are critical in deriving the desired benefits.

Introduction to material efficiency through remanufacturing

One of the key conclusions derived from Chapter 3 is to develop strategies that reduce material intensity of industry 'M' = kg material needed / industry revenue. Similarly, Chapter 4 told us to focus on material efficiency to bridge the gap to achieve halving of the total energy. By definition material efficiency means reducing the ratio of material used and the service provided by it. This can be done by either using lesser material for the same service, or increasing the service extracted from the same material, or a combination of the two. Obviously reducing material content in products to provide the service has direct economic savings for the producer and is probably already optimized. Innovative designs through future research can add more. However, we believe there is great potential in being able to extract more service from the same material/product. This could be a combination of more types of services and longer service life. A popular way to do this is to extend the life of products such that the physical life of the product allows for multiple use phases of the product. By no means does this go against consumerism where we like to replace our products for new ones sooner, but in stead this means that once used, these products with residual life in them should be resold or reused (if acceptable to the owner) such that the product continues to serve the society. If this salvage life or extended service were accounted for in the material price, this would mean a reduction in 'M' as well. Another way for this to happen is for the OEMs to take back products having residual life after use and reselling them, there by extracting increased revenue from the same product. In such a case, the OEM or third party, if it may be, can refurbish the product to like-new condition, which is called remanufacturing. In this chapter we analyze remanufacturing and refurbishing as a primary strategy for material efficiency to add to our objective of halving total energy of the industrial sector. This inherently includes reselling of products thereby increasing total product use life, or total service provided by the same product.

Introduction to remanufacturing

Remanufacturing is generally seen as the most environmentally friendly of "end of life" treatments for a retired product. If the remanufactured product can be considered a substitute for a new product, then a credit is usually claimed for the avoided resource use and emissions associated with the new product production. The biggest savings is generally from the avoided new materials production, but the difference between new manufacturing and remanufacturing can also be significant. At the same time, remanufactured products generally sell for about 50-80% of the new product. Hence remanufacturing can be seen as a win-win; it saves money (for the consumer) and it saves the environment.

In the United States, remanufacturing is at least a $50 billion industry with direct employment of about 480,000 in 73,000 firms [91]. Remanufactured products include automotive and aircraft parts, compressors and electrical motors, office furniture, tires, toner cartridges, office equipment, machine tools, cameras and still others [91]. One of the primary requirements for remanufacturing is that the retired products have significant residual value at the end of life. The second is that the remanufacturing firm can effectively capture the retired product. And the third is that the product can be restored to like-new condition (in terms of product function) with only a modest investment. In terms of number of remanufacturing plants, the largest remanufacturing categories in the US are tires, followed by motors and generators and motor vehicle parts [92].

The fact that a product can have significant residual value at its end of life can present a dilemma for the original equipment manufacturer (OEM). For example, if the OEM decides to not remanufacture its own products, then it might find itself competing with its own products remanufactured by another firm. To avoid being placed in this situation, an OEM might employ a variety of strategies to defeat "third party" remanufacturing. These strategies might include making spent products inoperable, rapid (minor) design changes, using a "prebate" system, and buying back the spent products. All of these strategies have been employed by various printer OEMs with varying success in an effort to protect their ink cartridge business. For example, the prebate system employed by Lexmark, attempts to enter into a contractual agreement with the buyer to return or throw away the spent ink cartridge in exchange for a discount. However, the U.S. District Court of Kentucky barred this practice recently citing a U.S. Supreme Court 2008 decision in Quanta Vs. LG Electronics [147], interpreting it as an attempt to avoid the patent exhaustion doctrine.

An alternative position is to embrace remanufacturing and to make it part of the OEM's business strategy. A variety of firms have done this, particularly for truck tires and heavy equipment (Caterpillar, Cummins, Goodyear, Michelin). This strategy can build a strong long-term relationship with customers. As a general method for supplying products to customers however, remanufacturing presents some challenges. One challenge is to match supply and demand. The early steps in remanufacturing, which consist of recovering the spent product (sometimes called "the core"), cleaning it and testing it, all represent an investment. To capture the value of that investment and to guard against fluctuations in core supply, a remanufacturer may have to maintain a large inventory of cleaned and tested cores. A second challenge is that remanufacturing is labor intensive. The condition and variety of incoming cores can vary significantly. This means that remanufacturing must be flexible. Hence two conditions that favor remanufacturing are: 1) a relatively low wage, skilled labor market, and 2) modest inventory storage costs. In addition to this, the remanufacturer will need to have an effective way to recover spent cores.

The aim of this chapter is to test the hypothesis 'remanufacturing of products saves energy,' as popularly claimed. The research questions that motivated this study, were: 1) how big is the energy savings potential of remanufacturing, with a particular interest in identifying the products that represent the best opportunities for energy savings, and 2) how could this energy savings potential be expanded, both in terms of remanufacturing more of the usual category of products, and to expand to new product categories. While the focus is on remanufacturing, the analysis inherently includes general strategies that extend the life of products – refurbishing, reselling, reusing, etc.

Energy saving potential of product remanufacturing

While it's impossible to consider every product we use globally – consumer and industrial products – we conduct representative case studies of 8 different product categories: 1) furniture, 2) clothing, 3) computers, 4) electric motors, 5) tires, 6) appliances, 7) engines, and 8) toner cartridges, many with very high remanufacturing potential in the United States. Collectively they form 25 case studies. The analysis was framed in terms of a product replacement decision for a consumer. That is, we pose a scenario in which a consumer intends to replace a product and we examine the normative question: to save energy, should the consumer acquire a remanufactured version of the retired product, or should the consumer buy new? To give an idea of the ideal energy and material saving potential Figure 26 gives the global material savings if all units of the products considered in this study are successfully remanufactured at end of use displacing new production. We note that this can yield a significant 2% savings for iron and steel, 3.5% for copper, over 6% for aluminum, and roughly 1.5% for plastics. The estimated energy savings could be as large as 4.4 EJ, which is equal to the combined energy used today by all aluminum production globally [6]. This considers the avoided energy and materials for producing the new products, as well as the energy cost to refurbish / remanufacture the used unit. Note these estimates do not consider the already remanufactured fraction and thus are over-estimates. This is especially true for rubber, since tires on the road are predominantly retreaded tires in the US.

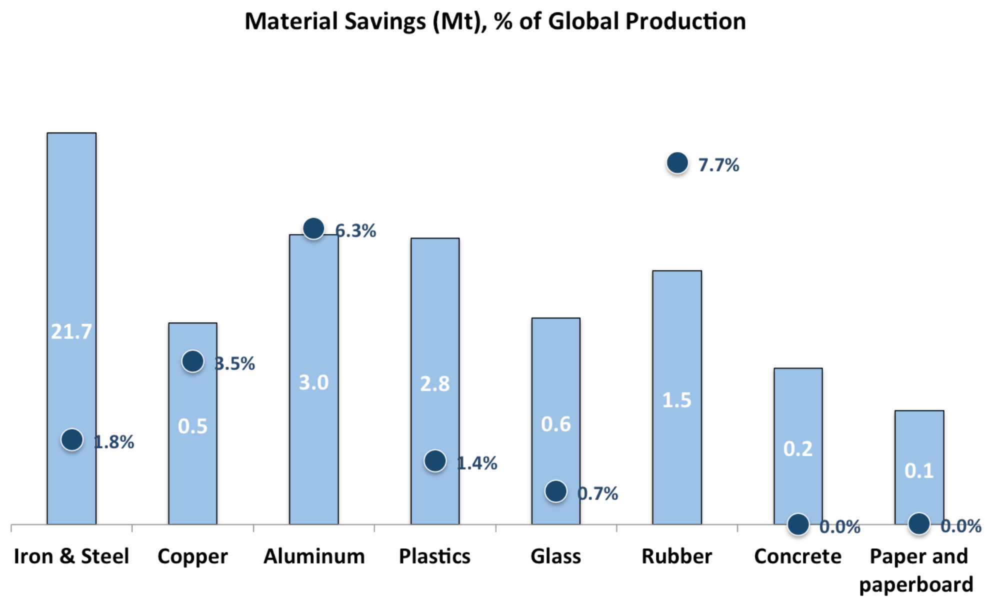


Figure 26: Expected savings for key materials (absolute in Mt (columns) and as a fraction of global production (circles)) if all units of the considered products are remanufactured successfully at end of use. Note axis for absolute savings is in logarithmic scale.

Thus extending product life has great potential to save energy and materials. However, we extend this analysis and dedicate this chapter towards presenting complications in the analysis that might make this claim untrue demanding a more careful and thoughtful assessment in the implementation of material efficiency strategies like remanufacturing.

Life cycle energy analysis of products

The above analysis of energy and material savings from increasing product life only consider the energy saved in material production and manufacturing of the products. However, to calculate the total savings potential a life cycle approach is needed so that use phase impacts are also compared. Thus the above analysis is extended, by using a life cycle energy analysis for the two product options. This means that it includes the energy requirements for materials production, manufacturing and the product use phase. We perform a sensitivity analysis to consider elements that were not included in the analysis, as well as parameter variation. Variations on system boundaries and elements beyond the life cycle of a single product are discussed at the end of the chapter. Details of the methodology are provided in Chapter 2.

The life cycle energy analysis of products is now a well-established field of study. Many studies have already been performed, many software programs are available to help in this analysis, and international standards exist to guide the practitioner. In this study, we take advantage of the analyses by others for products that fit into the general categories for remanufacturable products. In order to double check these studies, and to resolve differences between multiple studies for similar products, we developed a life cycle energy estimation tool for materials production and manufacturing [148]. The tool only requires a bill of materials (BOM) for the product and uses well known estimates both for the embodied energy in materials [5, 143], and for the energy requirements for various manufacturing processes [59, 148]. Comparisons between the life cycle energy results from others and our model helped validate the accuracy of the data used in this study.

Others have also addressed related questions in the literature such as in studies on the remanufacturing of specific products, optimum product replacement strategies, and product leasing [93, 109-111, 149-153]. An important and generally well-known result from product life cycle studies is that for most products the energy requirement for materials production dominates the energy requirements for manufacturing. In addition, observations from remanufacturing studies show that most of the original materials in the remanufactured product are saved, and the energy required for remanufacturing is almost always much less than that required for the original manufacturing [91, 154-156]

A second common observation from life cycle analysis (LCA) studies for “powered” products, which require an energy source, is that it is very common for the use phase to dominate energy use. That is, the energy requirements of the use phase can exceed the combined requirements of both materials production and manufacturing. As a result, as will be seen, even small changes in use phase energy can produce significantly different outcomes.

Based on these observations, for some products in this study we chose to ignore the energy requirements for remanufacturing. This, of course, will bias the results slightly in favor of remanufacturing; however as will be seen, the effect is generally negligible. Furthermore, this simplification opens up the interpretation of these results to include several other categories of product restoration such as repairing, refurbishing and even re-selling if the product is still in like-new condition.

Research results

We start with two representative cases, refrigerators and heavy-duty truck tires, which illustrate the methodology, and point out special issues that can arise. The analysis that follows considers a product retired in year X after a first lifetime of L years. The comparison is between a like-new, but remanufactured product of model year (X – L) versus a new product of model year X. Because of the magnitude of the use phase energy for powered products, we will pay particular attention to changes in usage patterns and changes in energy performance in the U.S. In addition, we normalize the analysis to account for improvements to the product that can be captured in the functional unit, e.g. larger refrigerators and longer lasting tires.

Refrigerators

Consider the case of a refrigerator that breaks down in year X after a first life of L years of service because of a failed compressor. All other functions for the refrigerator perform at their like-new level corresponding to their original model year (X – L). (This of course is an optimistic statement favoring remanufacturing). The options considered in this analysis are to replace the failed compressor with one that has been remanufactured and use the refrigerator for another L years, or to buy new. The analysis calculates the life cycle energy requirements per cubic meter of cooled space for the materials, manufacturing and use phases. In this case, we assume that the materials and manufacturing energy requirements to remanufacture the product are zero. The analysis is performed for four cases corresponding to new model years in 1966, 1980, 1994 and 2008. The key assumptions used in this study pertain to the use phase energy requirements, which have already been well documented for medium sized residential refrigerators used in the U.S. over the time period 1947-2008. See in particular Rosenfeld 2003 [157] and AHAM 2008 [158]; also Kim 2005 [152] gives a good review of this topic. The data show that over this time period, the electricity requirements per unit go from about 350 kWh/yr in 1947, to a peak of about 1850 kWh/yr in 1974, to about 450 kWh/yr in 2008. The early rise is due to added features (e.g. defrosting, larger freezer) and increases in size, while the decrease is due to energy efficiency mandates first in California in 1974 and later at the federal level. During this time period refrigerators grew from about 0.23 m^3 cooled volume in 1947 to 0.61m^3 in 2008. DOE sets the typical service lifetime for a refrigerator in the range of 10 -16 years. In this study we assume a lifetime of L = 14 years (also used by [159, 160]). Using these values means that a 2008 new refrigerator will use 6300 kWh electricity or (using a grid efficiency of 1/3) about 68 GJ of primary energy over its lifetime. To estimate the primary energy requirements for the materials and manufacturing of a modern refrigerator we reviewed the studies of others [152, 161-163] and using the bill of materials provided by [152] applied our model [148]. The results give a range of 4,442 to 6,847 MJ for a late 1990s era model with 0.59m^3 of cooled space. Again, to be conservative (in favor of remanufacturing) we used the higher value of about 6.9GJ and assume that it is applicable to 2008, which is argued below. Comparing this with 68 GJ one sees that the use phase energy is larger by about a factor of 10. In the 1974 case (the peak year for energy use per refrigerator) the ratio is over 40, and in the 1952 case (the remanufactured model year for the 1966 new comparison) the ratio is about 9. The upshot of this is that materials and manufacturing energy play a relatively small role in the life cycle energy requirements of a refrigerator. During the 56 years examined here, it is true that materials and manufacturing energy would have changed, but we argue that these changes were probably not much different than the original range given earlier (4.4 to 6.9 GJ). This case can be made based upon the observation that among the various changes, the two most important probably cancelled each other out. That is, among design changes one would expect more optimized use of materials (e.g. thinner sections), materials substitution (mostly plastics for ferrous metals) and most importantly larger size (a factor of 2.1 from 1952 to 2008). The size change however would probably be offset by increased efficiency in materials production. Trends given by Smil 2009 [143], Chapman and Roberts 1983 [164] and Dahmus and Gutowski 2010 [8] suggest that a reasonable estimate for efficiency improvements for ferrous metal production (the dominant material in refrigerators) would be about 1.5% per year. At this rate, over 56 years, yields a factor of improvement of about 2.3. Overall, then it appears that increases in energy due to 1) the substitution of plastics for ferrous metals and, 2) an increase in size, would be offset by improvements in design, and materials production efficiency. Improvement in parts manufacturing would also have increases (injection molding and thermoforming of plastics vs. sheet forming) and decreases due to efficiency improvements, but overall would be insignificant.

Putting this all together we show in

Figure 27 the new-product life cycle energy plotted on the Y axis, and the remanufactured-product life cycle energy plotted on the X axis. Points above the dividing line favor remanufacturing, while points below the line favor buying new. Following the points around the figure shows that in the early years when use energy was increasing, remanufacturing is favored; however, after 1974 improvements in use phase efficiency favored buying new. In the inset one can see the resulting life cycle energy for the four new model years (1966, 1980, 1994, and 2008). The life cycle energy for the remanufacturing case is essentially the earlier model year (e.g. 1966 for the 1980 comparison) minus the materials and manufacturing contribution. The figure clearly shows how small the materials and manufacturing energy is compared to the use phase energy.

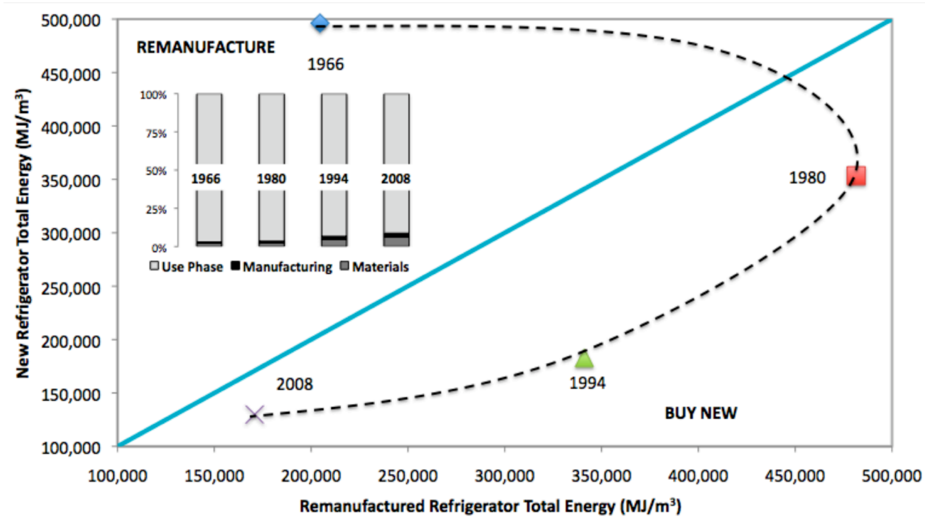


Figure 27: Comparative life cycle energy assessment between new and remanufactured refrigerators from 1966 to 2008. The insert shows the distribution of life cycle energy use across the different phases, for refrigerators manufactured in the corresponding years. The labels "Remanufacture" and "Buy New" are the decisions the consumer should make to reduce energy if the data point falls in it's respective half of the plot area.

Heavy duty truck tires

For a second illustrative example, consider the decision to replace a spent truck tire with a new or an "equivalent" retreaded tire. Retreading truck tires is a big business in the United States. According to Michelin about 44 % of all replacement tires are retreaded [165]. From a life cycle analysis perspective there are several important differences between this example and the previous example for refrigerators. The first difference is that we found fewer life cycle studies in the literature for tires and far more variation in the available data, in particular concerning rolling resistance and the tire use phase. Secondly, the life span of a truck tire is far shorter than that of a home refrigerator. Driving at 50 mph for 8 hours a day, 5 days a week for 50 weeks adds up to 100,000 miles in one year, equal to the tire lifetime. Hence historical changes in use phase efficiency are far less important than the technology options a decision maker has when he or she goes to replace a tire. Additionally, retreading adds significant new material to the old casing, and is in itself an energy intensive process. As a result, the energy requirements for materials and manufacturing for the remanufacturing of tires are included in this example.

The base case considered for this study is a class 8 tractor trailer truck (gross vehicle weight greater than 33,000 lbs. or 14,969 kg) with a fuel mileage of 5.5 mpg [166] and 18 radial tires. The life cycle inventory (LCI) for the materials and manufacturing for the radial tires relied on available data in the literature [167-170] and our estimation method [148]. We estimate the materials production and manufacturing for a new 55 kg radial tire to be 3,622 + 643 = 4,265MJ [170]. The estimate for the remanufactured tire is 1365 MJ. Hence there is a 68% energy savings if only these two phases of the life cycle are considered.

To estimate the use phase, we assume that the use phase energy of a tire is equivalent to the fraction of the fuel required to overcome the rolling resistance divided by the number of tires. Rolling resistance as a fraction of total fuel consumed for trucks however, depends on many factors including driving and roadway conditions, speed, tire pressure, tire wear and more. As a consequence, values given in the literature for the fraction of fuel required to overcome rolling resistance vary enormously from 13% up to 47% of the total fuel used [170]. The US Department of Energy (DOE) however suggests a smaller range from 13% to 33% [171]. In order to manage this variation, we identify a midpoint fraction (24%) with a specific measured rolling resistance coefficient of 0.0068 and then make comparisons to this reference case. We do this because rolling resistance coefficients can be directly measured in the laboratory under highly controlled conditions. The key assumption is that changes in the fuel required to overcome tire rolling resistance are proportional to the coefficient of rolling resistance [170] (Chapter 2 brings out more details on the methodology). To make comparisons with other tire technologies then, we use the following values of the coefficient of rolling resistance; for conventional bias ply tires 0.0097, for new improved radials (sometimes called low rolling resistance tires) 0.0061 and for new single-wide tires 0.0054 [169, 171]. New single-wide tires are now offered by a number of tire companies. They can replace a pair of conventional tires when mounted together on the axle.

An additional complication for tire remanufacturing is that because these operations can take place at many small companies, there can be significant variation in the quality of the retreading job. While it is true that a tire retreading operation can restore a tire to near original performance, from the available data there is evidence that retreading can sometimes fail to achieve like-new product performance. For example, measurements by Michelin show that the rolling resistance for retreaded radial tires can increase between 7% to 9% compared to new radials [172].

Putting this all together requires a series of assumptions often for variables that can have a large range of values. We tried to select values that represented central tendencies, or to slightly bias the calculation in favor of remanufacturing. For example, our assumption that both the new radials and the retreaded radials have the same mileage lifetime of 100,000 miles favors retreading.

For the overall use phase calculation, we assume 100,000 miles traveled at 5.5 mpg with 24% of the fuel used to overcome rolling resistance; this gives an energy value per tire of 35,640 MJ [170]. If the retreaded tire has an 8% increase in rolling resistance, this adds an additional 2851MJ for the use phase of the remanufactured tire. Now if we compare this to the savings from the difference in the materials production and manufacturing phases (4265 – 1365 = 2900 MJ) we see a potential savings of 49MJ for the retreading option. But this is only about 0.1% of the life cycle energy for the new tire. This difference is clearly within the margin of error for the life cycle energy methodology. There is no measurable increase, nor decrease, in the total energy consumed between the two options. If the lifetime of the retreaded tire is less, then more than one retreaded tire will be needed and this will favor buying new. If we assume the rolling resistance fraction is larger, say 33% instead of 24% (less starting and stopping, driving continuously at a slightly reduced speed to decrease aerodynamic drag) then this will favor buying new. If one can show that the performance of the retreaded tire is equal to the new tire then retreading can produce a maximum savings of 2900 MJ (about 7.6% reduction in life cycle energy compared to the new tire – also probably within the margin of error for the methodology). But this would be the exceptional case, not the rule. Using the coefficients of rolling resistance given earlier, one can calculate that choosing a retreaded radial ply (0.0068) instead of a retreaded bias ply tire (0.0097) will save 15,199 MJ. (This is about 28% of the bias ply tire lifecycle energy, and clearly significant). In this calculation we assumed that the material and manufacturing energy for the bias tire was the same as that for the radial. Other significant energy savings can be calculated by using the new lower rolling resistance tires listed above.

25 case studies

The results from the two previous cases, though quite different in details, lead to rather similar conclusions. In both cases the life cycle energy is dominated by the use phase, and in both cases no clear answer can be given to the simple question, does remanufacturing save energy? The answer is nuanced and depends upon many details. When we opened this study up to still more products, we found this situation occurred quite often. In fact, the answer to the question, does remanufacturing save energy? is conditional and highly dependent upon current product development trends. Furthermore, when there was a clear answer, it was just as likely that the answer was "no" as it was "yes".

The details for these case studies are given in Table 9, with relevant product and scenario data, and a reference number system (1 – 25) that is carried through to the graphical representations of the results in Figure 28 and Figure 29. Literature references and data sources are provided in the Appendix. Figure 28 is a log-log plot of the absolute values for the life cycle energy for the new (Y-axis) and remanufactured products (X-axis). Figure 29 is the percent energy savings for remanufacturing relative to the new product option in order 1 through 25.

		New						Remanufactured						
Category	**Ref # for Figure 2 and 3**	**Product Details**	**Mass New; Mass Reman (kg)**	**Year of Mfg (X)**	**Service Life**	**Emfg**	**Euse**	**Product Details**	**Year of Mfg**	**Service Life (L)**	**Emfg**	**Euse**	**Scenario**	**Normalized Unit for Energy**
Appliances	20	Dishwasher	59;59	2008	10 years	4,818	34,641	Dishwasher	1998	10 years	0	44,896	Remanufacture	MJ/unit product
	23	Refrigerator	84;84	2008	14 years	11,326	118,560	Refrigerator	1994	14 years	0	170,852	Remanufacture	MJ/m^3
	25	Washing Machine (front-load)	59;59	2008	11 years	48,391	401,027	Washing Machine (top-load)	1997	11 years	0	1,260,508	Remanufacture	MJ/m^3
Computers	7	Desktop Control Unit	10;10	2005	4 years	2,193	6,008	Desktop Control Unit	2001	4 years	0	6,341	Reuse/Upgrade	MJ/unit product
	4	Laptop	2.8;2.8	2005	4 years	1,201	2,537	Laptop	2001	4 years	0	1,867	Reuse/Upgrade	MJ/unit product
	6	CRT Monitor	14;14	2005	4 years	910	4,275	CRT Monitor	2001	4 years	0	3,763	Reuse	MJ/unit product
	8	LCD Monitor	6;6	2005	4 years	963	1,981	LCD Monitor	2001	4 years	0	2,547	Reuse	MJ/unit product
	24	Laptop	2.8;24	2005	4 years	1,201	2,537	Desktop w/ CRT Monitor	2001	4 years	0	10,104	Reuse/Upgrade	MJ/unit product
	21	LCD Monitor	6;14	2005	4 years	963	1,981	CRT Monitor	2001	4 years	0	3,763	Reuse	MJ/unit product
Furniture	2	Office Desk	122;122	-	-	3,290	0	Office Desk	-	-	0	0	Reuse	MJ/unit product
	1	Office Chair	29;29	-	-	1,350	0	Office Chair	-	-	0	0	Reuse	MJ/unit product
Textiles	5	Cotton T-shirt	0.25;0.25	-	-	47	65	Cotton T-shirt	-	-	1	65	Reuse	MJ/unit product
	3	Viscose Blouse	0.2;0.2	-	-	47	7	Viscose Blouse	-	-	1	7	Reuse	MJ/unit product
Toner Cartridge	10	Toner Cartridge	-	-	6000 pages	73	978	Toner Cartridge	-	6000 pages	6	978	Refill	MJ/fraction of usable pages
Engines	12	Passenger Car Gasoline Engine	151;151	1999	120,000 miles	11,901	556,121	Passenger Car Gasoline Engine	1987	120,000 miles	2,795	553,924	Remanufacture	MJ/unit product
	11	Combination truck Diesel Engine	1349; 1349	1999	750,000 miles	86,673	20,342,257	Combination truck Diesel Engine	1987	750,000 miles	1,850	19,309,871	Remanufacture	MJ/unit product
Electric Motors	19	22 kW Electric Motor Energy Efficient	190;166	-	6 years	18,216	4,579,302	22 kW Electric Motor Standard Efficient	-	6 years	2,222	4,784,652	Rewind	MJ/unit product
	14	22 kW Electric Motor Energy Efficient	190;190	-	6 years	18,216	4,579,302	22 kW Electric Motor Energy Efficient	-	6 years	3,080	4,628,969	Rewind	MJ/unit product
	15	22 kW Electric Motor NEMA Premium	238;190	-	6 years	19,942	4,535,505	22 kW Electric Motor Energy Efficient	-	6 years	3,080	4,628,969	Rewind	MJ/unit product
	18	22 kW Electric Motor NEMA Premium	238;238	-	6 years	19,942	4,535,505	22 kW Electric Motor NEMA Premium	-	6 years	3,674	4,584,221	Rewind	MJ/unit product
	17	200 kW Electric Motor NEMA Premium	1758; 1512	-	6 years	123,767	60,746,916	200 kW Electric Motor Standard Efficiency	-	6 years	16,400	62,499,231	Rewind	MJ/unit product
	13	200 kW Electric Motor NEMA Premium	1758; 1758	-	6 years	123,767	60,746,916	200 kW Electric Motor NEMA Premium	-	6 years	21,200	61,063,967	Rewind	MJ/unit product
Tires	22	Heavy-Duty Truck Tires Radial	55;55	-	100,000 miles	4,265	35,640	Heavy-Duty Truck Tires Bias-ply	-	100,000 miles	1,365	50,839	Retread	MJ/unit product
	9	Heavy-Duty Truck Tires Radial	55;55	-	100,000 miles	4,265	35,640	Heavy-Duty Truck Tires Radial	-	100,000 miles	1,365	35,640	Retread	MJ/unit product
	16	Heavy-Duty Truck Tires Advanced Radial	55;55	-	100,000 miles	4,265	31,971	Heavy-Duty Truck Tires Radial	-	100,000 miles	1,365	35,640	Retread	MJ/unit product

Table 9: Comparative LCI of energy use between new and remanufactured products [173]

Figure 29 clearly reveals that the answers to our question are split; there is a group of products that can provide large relative energy savings (products numbered 1 – 8), and there is a group of products that strongly favor buying new (products numbered 20 – 25) and then there is a group in the middle that are more nuanced (products number 9 – 19). The products in the first group (1- 8) include office furniture (2 cases), clothing (2 cases) and computer equipment (4 cases). They all save energy when remanufactured, resold or upgraded because there have been insignificant changes in the use phase energy over the time period considered. For the office furniture there is no use phase energy. For the computer equipment, energy efficiency improvements within the same kind of devices over the time period (2001 – 2005) are not large enough to overcome the manufacturing phase savings achieved by reusing. Similarly, (though not included in this study) the refurbishing of returned new products would fall into this category.

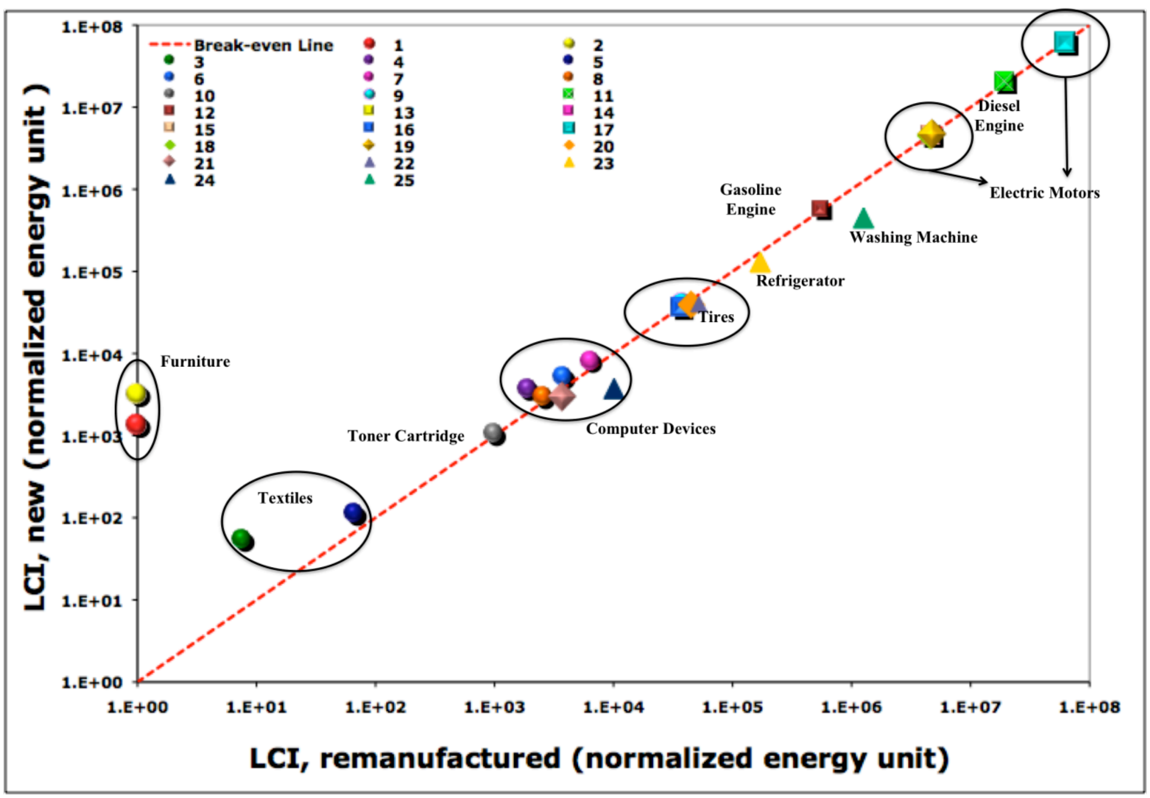


Figure 28: Comparative LCI of energy use between new and remanufactured products. See Table 9 for a legend to the case numbers.

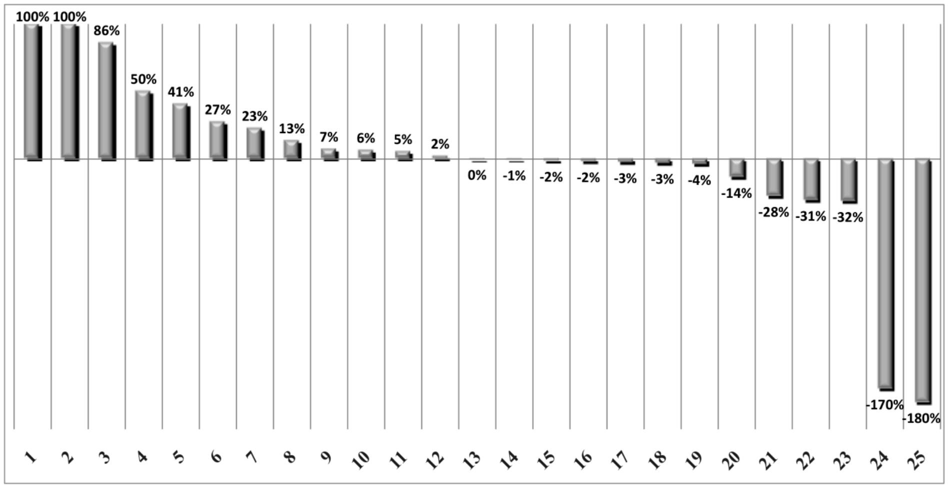


Figure 29: Percentage life cycle energy saving by choosing to remanufacture over new for the 25 product case studies. See Table 9 for a legend to the case numbers.

At the other end of the figure, products 20-25 are cases where the use phase energy has changed significantly due to efficiency mandates and/or the introduction of new efficient technologies. Case 20 compares a remanufactured 1998 dishwasher with a much more energy efficient 2008, Case 21 compares a CRT to an LCD display, Case 22 compares a retreaded bias ply truck tire to a new radial truck tire, Case 23 compares a 1994 refrigerator to a 2008 model, Case 24 compares a used desktop computer to a new laptop, and Case 25 compares a rebuilt top loader clothes washing machine to a new front loader. In each case, choosing the remanufactured product over a new will result in a significant additional energy requirement as indicated in Figure 29.

In the middle of this figure are a number of products (9 – 19) that require more explanation. It should first be pointed out however that all of these cases lie between +7% and -4% of the new product energy requirement, and we are not sure the LCI methodology can make accurate statements in this range. Nevertheless, starting with Case 9 we compare a retreaded radial truck tire to a new radial truck tire. A savings is indicated here because we have not included the potential loss in performance for the retreaded tire. As discussed earlier, this loss can be substantial, with the result that the potential savings shown would be reduced to zero.

Case 10 is for the refilling of a toner ink cartridge. The projected savings would be 6% provided the refilled cartridge functioned as new. In this area there is very little data on the performance of refilled cartridges and nothing we have found from the remanufacturing industry. However one report, commissioned by HP, suggests that it takes 101 sheets of paper to print 100 good copies with a new cartridge and 114 to print 100 with a refilled cartridge [174]. If this data were correct, the embodied energy in the extra paper and electricity needed to print the additional 13 pages would be enough to offset the projected savings. However, in order to make all assumptions in favor of remanufacturing, data and results presented in the tables and figures, for cartridges as well as other products, assume that the remanufactured products perform like-new and do not experience such degradation in performance.

Case 11 represents the remanufacturing of diesel engines. This product has been studied by Sutherland and co-workers who indicate a large potential savings due to avoided materials production and manufacturing [154]. Furthermore the energy efficiency of diesel trucks has been essentially flat at about 5.5 mpg over the time period 1975 to 2006 [166]. Hence we have calculated a potential 5% energy savings. At the same time, it is clear that even a small reduction in the fuel economy of a rebuilt engine or improvement in the new could offset this gain. For example, a change of only 0.025 mpg would be enough to undo this savings.

Cases 12 through 19 are dominated by two different sizes of electric motors. The smaller (22 kW) comes under the EPAct regulation of 1992, while the larger (200 kW) does not. The cases essentially compare different new motor efficiency ratings, with various rewound motors. The key piece of information included in these calculations is that we used the DOE recommendation to reduce the efficiency of the rewound 22 kW motors by 0.5% and for the rewound 200 kW motors by 1% [175, 176]. This difference is enough to shift the result, in terms of energy usage, in favor of buying new. Again, we state our doubts whether the LCI methodology can really make meaningful statements when the differences are so small.

All of these cases are plotted in terms of absolute energy requirements in Figure 28. Points that lie above the dividing line favor remanufacturing, while those below, favor buying new. Note that the energy resources used by motors and engines are large, and so small performance improvements, if they can be substantiated, could represent significant savings in magnitude. They would however, be small relative to the total energy resources used.

Discussion

When taken as a whole, it seems that making general energy savings claims for remanufacturing is not advisable. It happens that, historically, remanufacturing did save energy (and materials too) when products were unpowered. But current design trends of powering up products appear to have altered the energy resources usage substantially. That is, products that used to have no use phase are now powered. For example, rakes, snow shovels, and hammers, are now leaf blowers, snow blowers, and power tools. This trend brings convenience and reduces human toil, but at the same time subsequent improvements in energy efficiency could work to reduce the potential energy savings promised by remanufacturing. (In Figure 28 this phenomena would be represented by products moving from on, or very near to the Y-axis – where remanufacturing would clearly save, to the dividing line – where the outcome involve small differences between large numbers). It has often been proposed to design using a modular platform in order to incorporate new features in used products. This could be a significant advancement for remanufacturing. For the purpose of this paper, this would mean incorporating energy efficiency improvements. However, it was also observed in this study that many of the major efficiency improvements in products are not incremental but radical, with major transformations in the product architecture, inhibiting such upgrades. Examples include desktop to laptop computers, top-load to front-load washing machines, and bias-ply to radial tires. On the other hand, the upgrading of components could be accomplished if they were standardized.

At the same time, other old benefits still accrue. Remanufacturing does provide local skilled jobs, generally reduces transportation when the primary materials come from far away, and may displace some primary production if the remanufactured product is truly a substitute for a new product. Concerning transportation, in the sensitivity analysis, it became apparent that transportation could become an issue for some extreme cases such as the air transport of new laptop and notebook computers from Asia to the United States. This can add substantially to the energy requirements of new products. Under these conditions, remanufacturing can appear energy saving. The case for laptops presented in this paper (# 4 as per Table 9) shows that even if transportation is not included, the energy savings by reusing the old laptop can be close to 50% of the manufacturing plus use phase energy requirements of the new laptop. Adding international transport will increase these relative energy savings to 58% making reuse even more favorable. We also would like to point out that while there are many additional aspects of remanufacturing that could be explored, one that strikes us as particularly important is the degree to which the remanufactured products actually substitute for new. This is a research issue unto itself. Past work indicates that the relationship can be quite complex, and in some cases the two products can end up being more like complements than substitutes [177, 178]. Thus overall while the strategy of remanufacturing to save materials and energy holds a lot of potential, the caveats extracted from this analysis are critical in deriving the desired benefits. As such, the trend in powering up of products followed by improving energy efficiency diminishes the energy saving potential from remanufacturing. Coupling this with scalability challenges of driving consumer behavior to remanufacture or use remanufactured goods leads us to believe that over all remanufacturing may not play a very significant role amongst the various strategies for energy demand reduction in the materials sector.

Chapter 6: Material efficiency targets, feasibility, and future work

Feasibility of achieving material efficiency targets

We have determined that amongst the two levers for reducing E, 'e' and 'Q', we can reduce e of 2050 by 57% relative to e of 2005 (in the most optimistic case), which relates to a reduction in E by 20%, falling well short of halving E over the same period. This would happen after deploying highly aggressive energy reduction strategies including some that are not even known of today. This means that in order to achieve the halving target the other level, Q, has to contribute as well and that we cannot allow demand to double (Figure 20). In fact it would only be achieved if the aggregate demand for the materials were restricted to increasing by only 25% relative to 2005. That means the ratio of demand in 2050 to that in 2005 cannot be more than 1.25. The 25% takes into account the interrelationships between the strategies like increased savings in 'e' due to increased recycling fraction of supply as demand growth is decreased. Figure 20 shows what this increase would mean through the plotted blue line at the bottom. Clearly this is significantly lower than any of the projections, high or low, for any of the materials. Clearly the challenge we face in trying to achieve this goal is huge. Figure 30 gives a demand per capita comparison between today "2005" and IEA projections of "2050-low" and "2050-high", as well as with US current average labeled "2005-USA", and what a 25% restriction on Q increase would mean, labeled "2050-target". The enormous challenge of achieving the target is again apparent. It would mean that on average each person would demand 10% lower material than today. Relative to IEA projections, the target demand would need to be close to 40% lower, and around 70% lower than what a US national demands today (except for cement). Without even exploring material efficiency opportunities, and referring to historic demand trends around the world as shown in Figure 6, it seems like this is close to being insurmountable.

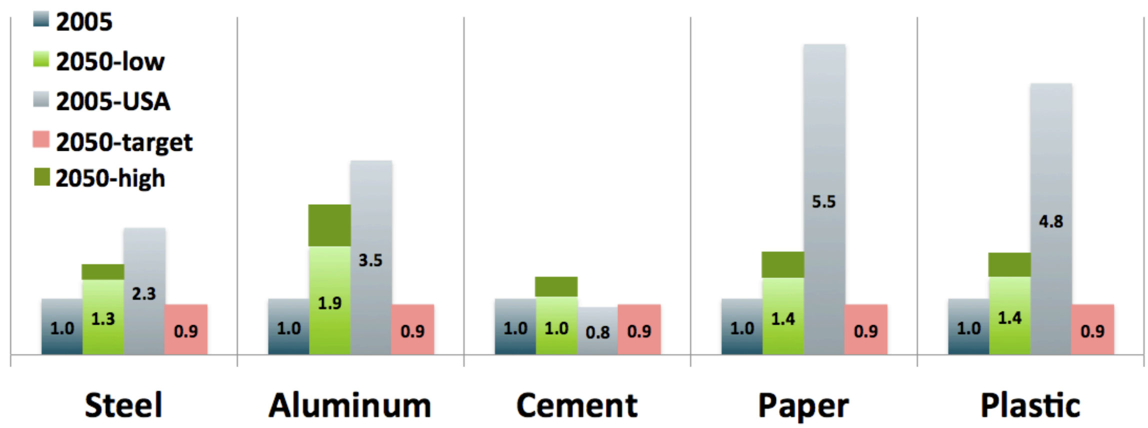


Figure 30: Demand per capita comparison between today "2005" and IEA projections of "2050-low" and "2050-high", as well as US average labeled "2005-USA", and what a 25% restriction on Q increase would mean, labeled "2050-target". The numbers in the green bar are for 2050-low.

Material efficiency options

Allwood and co-workers have conducted detailed research in analyzing material efficiency options and their potential to reducing CO_2 emissions [7, 81, 102]. Three key strategies that help reduce the material demand (input and final demand), without influencing the service-supply by materials are a) redesigning products to reduce weight; b) increasing the life of products or reusing material/components without melting (non-destructive recycling); and c) using materials more intensely by either extracting more service or more kinds of service per person or have more people use the same material, thereby extracting more overall service from the same material. Theoretically, if each were to be implemented 25%, meaning a) a 25% reduction in weight of products by optimized design; b) a 25% increase in the life of products; and c) increasing the intensity of use of materials by 25%, we can reduce the final demand of materials by $(1 - (0.75)/(1.25^2)) \sim 50\%$. In this calculation the 0.75 refers to the 25% reduction through (a) which is then divided by 1.25 for each of (b) and (c). Thus aggressive material efficiency strategies can, theoretically, help achieve the targets. The important question is if this is feasible and if so how.

Allwood and co-workers have shown a potential for reducing material content by up to 30% in construction beams, 10-30% in line pipes, and another 30% in each of car bodies, food cans, and rebars. The added benefit of saving materials by improved design is that it directly translates to cost savings for the producer (assuming other costs are unaffected), and thus becomes a natural incentive for strategy deployment. The idea of longer lasting products was discussed in detail in Chapter 5, and can lead to net energy expenditure if the life cycle energy is considered. In order to avoid this, Allwood et al. suggest following an onion skin model where in the replacement parts (that can also allow for upgrade of the older products to new state of the art) are placed in the outer skins and the rest inside. In other words, going from inner core to outer layers the expected lifetime of the products decreases. This way there is great incentive for consumers to reuse the core while replace the outer layers, easily, with state of the art replacement parts, assuming the state of the art replacement parts are compatible with the old core. A similar cost share onion skin model can be also used to provide incentive for reuse of higher cost cores. Similar to extending product life is reusing product components, given that most products fail because of the failure of a few components while the others can be reused. Here again the challenge could be that of compatibility with the new replacement parts. The third idea is around increasing the intensity of material or product usage. There are very few products out there (especially amongst consumer goods) that are used at capacity. In fact Allwood and others declare that transportation means are usually used at less than 10% capacity. Similar is the case for other metal products like domestic washing machines. We know the same for buildings, which in fact offer a much longer use life. Overall their assumptions for the degree of deployment of each strategy encouragingly shows that the targets can be met for aluminum and steel, less convincingly for aluminum given the higher projected demand [81]. We believe that the challenges in doing so are not only difficult but also too complex to solve in some cases and we discuss them in the next section.

Material efficiency challenges

While material efficiency strategies offer great opportunities in theory, their application may not be very straightforward. Provided below are a few challenges we see that need to be overcome in order to derive the desired reduction in material demand, without compromising on the services demanded through materials.

Table 10: Challenges associated with the different material efficiency strategies in consideration

	Producer Economics	Consumer Behavior	Technical
Light-weighting	• Reduced product price, driven by consumer perception • Increased price of supplied materials due to reduced economies of scale	• Consumer perceiving lighter products as inferior • Lower guaranty / warranty on product • Higher insurance premiums	• Safety protocols inhibiting light-weighting • Light-weighting can lead to shorter product lives and/or reduced intensity of use
Extending product life	• Reduced demand of product leading to decreased profits or increased product upfront price	• Consumer need for rapid performance improvement and change • Consumer education on product upgrading	• Designing for upgrade and future technology adoption in existing products
Increasing intensity of use	• Reduced demand for product leading to decreased profits or increased product price	• Consumer resistance to share	• Increasing intensity can lead to shorter product life • Monitoring equitable sharing

Clearly there are significant challenges all around. However, we do believe, that some aspects of material efficiency could be implemented quickly, and at low cost if consumers were motivated to do this. Another strong driver could be policies that encourage material efficiency. Soderhom and Tilton have suggested that given such challenges, and the lack of clear understanding for the potential of the various material efficiency strategies, political intervention should target the damage directly and let society or businesses figure out the technical strategies in reducing the damage. An added complication is the dynamic nature of the environmental remediation potential and of the feasibility of each strategy with the advent of new technologies and changes in prices. The technical analysis however guides businesses in understand how they can reduce this damage, as well as makes policy makers better informed [179].

For further information on material efficiency, refer to Allwood and co-workers who have provided detailed papers framing the key questions around this subject, as well as discussing the different challenges and mechanisms to deploying material efficiency strategies [102, 140].

Summary and future work

In summary the work in this thesis shows that achieving the set out targets of halving energy demand from the materials sector by 2050 will probably not be feasible. Three key findings that support this are:

1. Very optimistic energy intensity strategies (eventually constrained by theoretical limits) with conservative low-demand projections can reduce the total energy by only 20% of today's level. High-demand projections lead to a net increase in energy by 6% of today's energy demand
2. Savings from remanufacturing are uncertain and undermined by energy efficiency trends. With more and more products being powered up followed by increase in their energy efficiency, along with the challenge of overcoming consumer demand for newer products, deriving energy saving through remanufacturing is more complicated than previously considered
3. Material demand reduction targets to bridge the remaining gap are very challenging, restricting increase of demand to only 25% of today's quantities. This entails that by 2050 we would need to reduce demand per cap by 10% of today's level which is an

insurmountable task given the historic trends and future projections of material demand

One of the best cases to support the achievement of material demand targets is the so-called saturation phenomenon as discovered in Chapter 3. To understand the salient points of this case, one must differentiate between materials stocks; the total quantity of the materials currently being used by society, and material flows; the annual inputs or flows of materials to society. In studies of iron and steel used in industrialized countries it has been observed that these stocks tend to plateau after a certain level of per capita income. The general idea is that society has adequate supplies of durable goods and infrastructure and, in fact, adding more might be difficult. Müller et al found this plateau level for iron and steel stocks to be about 10t/cap. After this level is reached, society maintains a certain level of material consumption required to replace and maintain this stock level. This level is estimated to be in the vicinity of 500 kg/cap/yr. For comparison, current global average per capita iron and steel stocks are estimated to be about 2.7t/cap, and global average iron and steel flows are about 200kg/cap/year [35, 81, 127]. It is interesting to take these numbers and estimate the amount of iron and steel required to move the world from its current average values, to the levels of the developed world. In order to build world stocks of iron and steel to an average value of 10t/cap for a population of 9 billion, total production of at least 71 Gt of new primary material would be required, assuming that all existing stocks are recycled in a closed loop. To accomplish this goal, annual primary steel production would (if growing linearly) have to increase by a factor of 2.7 in parallel with growth in secondary steel production. This estimate underscores the enormity of the task: achieving a world-wide 'saturation' stock level of 10t/cap requires that we mine and refine most of the 79Gt of identified ore from which usable iron can currently be economically and legally extracted [127]. This is not impossible, iron is one of the more abundant elements in the Earth’s crust and we will not run out. But understandably, the potential complications involved for a task of this scale are clearly beyond what can be fully taken into account in any forecast. Note also, that the nominal growth rate shown in Figure 20 for steel (a doubling in demand) would not result in raising the current world average (200kg/cap/yr) to the current level of iron and steel consumption in the developed world (500kg/cap/yr). To accomplish this goal, steel would have to increase by a factor of 3.2 (assuming a world population of 9 billion) rather than 2.0.

Thus achieving the targets would require new thinking about how we use materials. Could the developed world work towards a goal of reducing their basic material requirements, while allowing the developing world to catch up to this new level? This is decidedly not a business as usual scenario, but is worth looking into in more detail. Material efficiency could greatly help in reducing the energy demand from the materials sector. However, it has not been explored in as much depth as energy efficiency. New thinking in this area to address not only engineering challenges but also policy challenges is sorely needed. While we see this approach as technically possible, we foresee several unaddressed technical challenges along with some major behavioral and economic challenges to large-scale deployment, requiring significant inputs from the social sciences. Overall material efficiency seems to provide an innovative extension to energy reduction strategies with potentially large untapped potential and should increasing become an important area of research in the coming decades. However, given the challenges discussed and the severity of the targets, achieving a 50% reduction in cumulative energy from the five materials studies is unlikely. This means that either or both transportation and buildings sector would have to do better than just halving their energy to make up from the shortfall from industry. At a rough glance this is not so difficult as clearly both these sectors offer a number of low hanging opportunities for reducing their energy demand. At the same time if the targets are to be assessed purely from CO_2 analysis, then the greening of the grid along with electrification of the different sectors can also play a big role. However, MacKay has shown how the low power density of most of our renewable energy sources can create a big limitation to greening of the grid, requiring infrastructures much larger than what we use today to produce our energy[180, 181]. Another potential option is of carbon sequestration, which is yet to become commercially feasible for large-scale deployment but could prove to be a significant contributor in the later years. More research on each of these can be found in [3, 99, 100, 182-188].

In closing highlighted below a few specific areas of future work from this research that directly or indirectly will drive reduction in energy demand from the five basic materials. While halving the total energy from the five basic material sectors may not be feasible it is nonetheless essential to continue to find and deploy strategies that reduce the energy demand from the materials sector. The suggestions for future work are categorized into primary production, recycling supply, policy, and material efficiency.

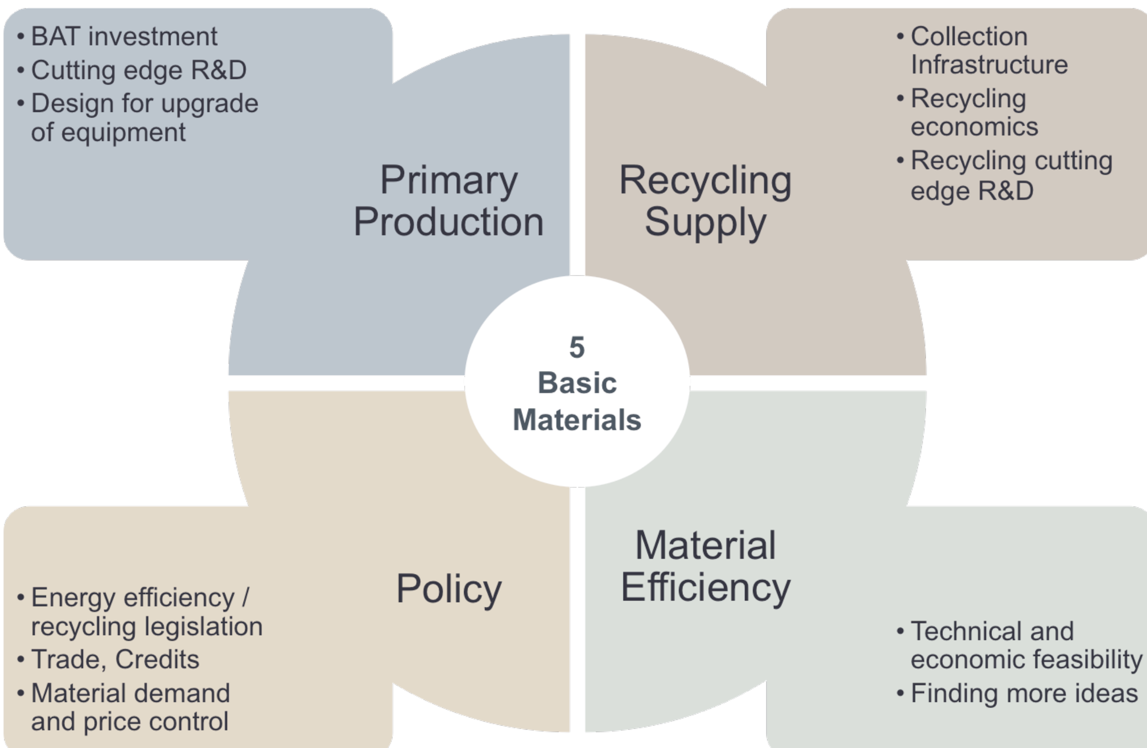


Figure 31: Potential areas of future work (research and strategy deployment) from this thesis

Primary production:

- Finding incentives for material production plants to upgrade to best available technologies. With newer installments in developing countries like those in Asia and Africa, best available technologies are already being installed. But the upfront capital costs for upgrade have deterred existing plants. It would be valuable to research ways in which the material production equipment can be redesigned to incorporate upgrades without full replacement, as more energy efficiency technologies evolves over time.

- Researching ways to (a) further reduce the energy intensity of primary production of materials beyond BAT – through cutting edge technologies; (b) making these novel technologies commercially scalable. There are several technologies in lab that hold potential into the future but more research will be needed to move the energy intensity to the midpoint between BAT and theoretical minimum.

Recycling supply

- Finding ways to enhance scrap collection infrastructure. Waste collection rates vary from being close to a 99% for products like car batteries to almost 0% for some of the plastics. Part of the reason is the poor collection infrastructure. Another major reason is the uncertain or poor economics of waste recycling. Researching ways to improve recycling profitability will automatically lead to development of collection infrastructure and recycling facilities. With the recent rise in commodity prices, scrap recycling can become much more incentivized and might spur this development.
- As the recycling fraction of supply increases into the future, especially if recycling economics and infrastructure develop, then it would be good for both the environment and bottom-line to discover or invent energy-efficiency opportunities that reduce the energy requirement for secondary production. Chapter 4 discussed some of these, but it requires more work to make the existing technologies commercially scalable, and to develop new technologies to drive further improvements. Note that the developed world, like steel in the US, already relies heavily on secondary fraction, and thus there already exists an attractive market for improving EAF or other secondary material production technologies.

Material efficiency

- Researching ways to overcome the discussed challenges to material efficiency strategies as well as determine other new strategies. Examples include, redesigning products that can be upgraded with newer technology such that a remanufactured product can potentially substitute perfectly for a new. With regards to material intensity of use, developing nations are likely to build both stable public transportation systems that encourage material sharing, as well as a need for individual vehicles with rising purchasing power. Several big cities around the world are example of the former substituting the latter through their development with increased population density and urbanization. However, there still remain challenges to derive similar motivations for material sharing in other applications like buildings, or even consumer goods, with one obvious deterrent being security.

- There needs to be greater clarity on the economics of material efficiency. Energy efficiency typically falls in line with cost savings, but material efficiency does not necessarily render its benefits directly. Making products that end up being used for longer (or resold after use) or making products that are easily shared leads to a decrease in net demand for products hurting producer profitability. Designing products with lower material content can reduce costs for the producer but can hurt the revenues if the product is perceived as being inferior. In fact the trend in the past has been to use efficiency for performance enhancement. For example, in the recent decades, in the US, there has been a greater demand for vehicle performance attributes of size, acceleration, and other amenities, over energy or material efficiency given the lower cost of energy and materials. In this particular case, the new CAFE standards and rising commodity price might in fact lead to producers focusing on energy and material efficiency, like they did after the first set of CAFE standards.

Policy

- A direct way to drive the required changes is to instate policies. Research can significantly contribute towards guiding their development. The challenge here is the lack of understanding in prioritizing amongst the various options amongst energy and material efficiency and hence lacking unanimous support for a particular policy structure. However, several ideas have been discussed in literature around ways in which policy could drive efficiency. These include carbon credits, cap and trade, emission taxing, subsidies, as well as influencing the behavior of the consumer. However policies often come with good and bad effects, and research can help provide a comprehensive analysis of each. Overall based on the research presented in this thesis, we advice policy makers to not only focus on the conventional energy efficiency goals but also consider how material efficiency can be further driven. Soderhom and Tilton have provided their thoughts on the same [179]. A simplistic approach would be for policy makers to see how to drive up net material costs or waste management costs so as to push for light weighting. Similarly finding ways to influence consumer behavior towards material sharing and extending product life (if energy saving) would play a critical role in industrial energy reduction through the coming decades.

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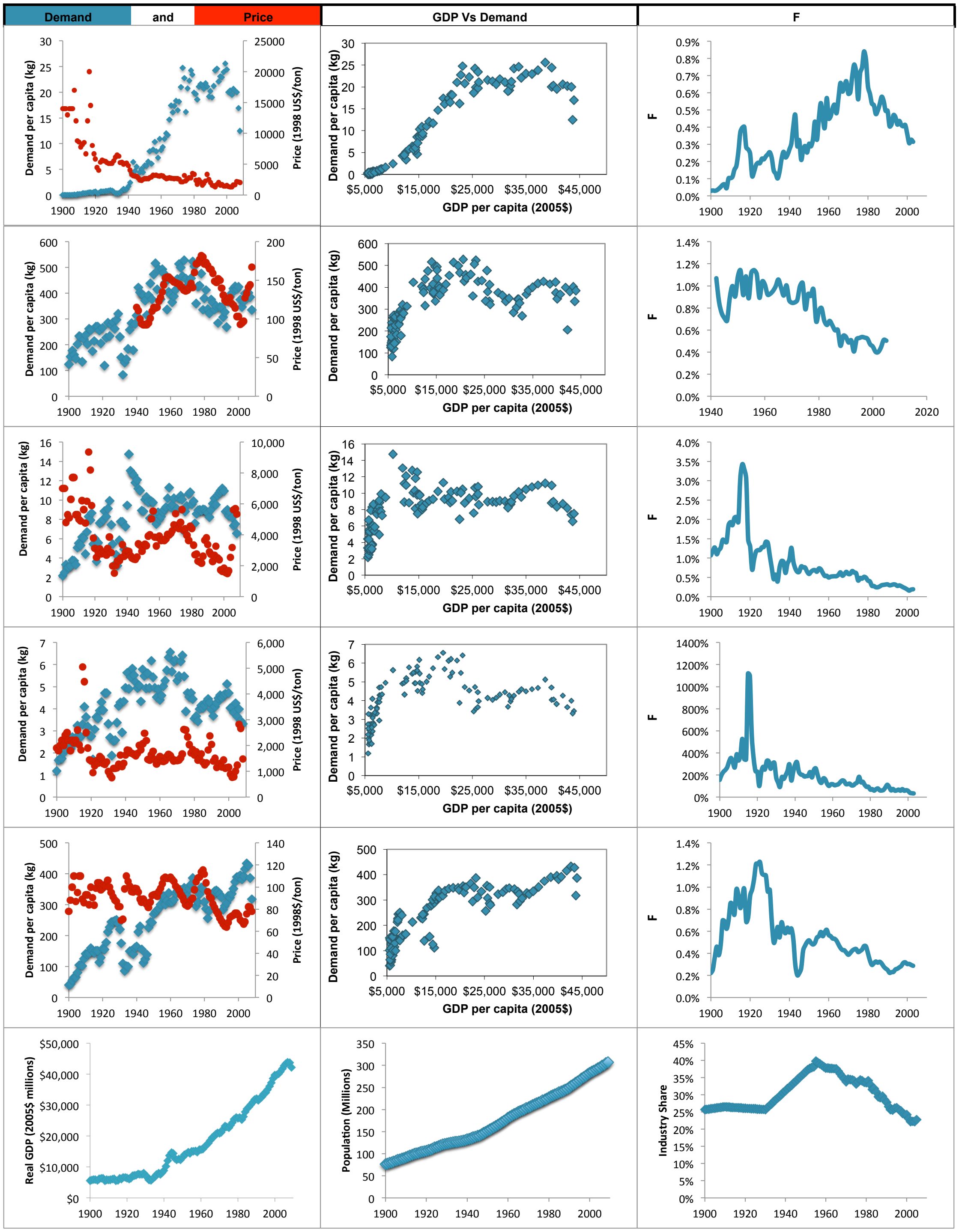
Appendix

A.1: Data used for demand analysis (Chapter 1, 3, and 6)

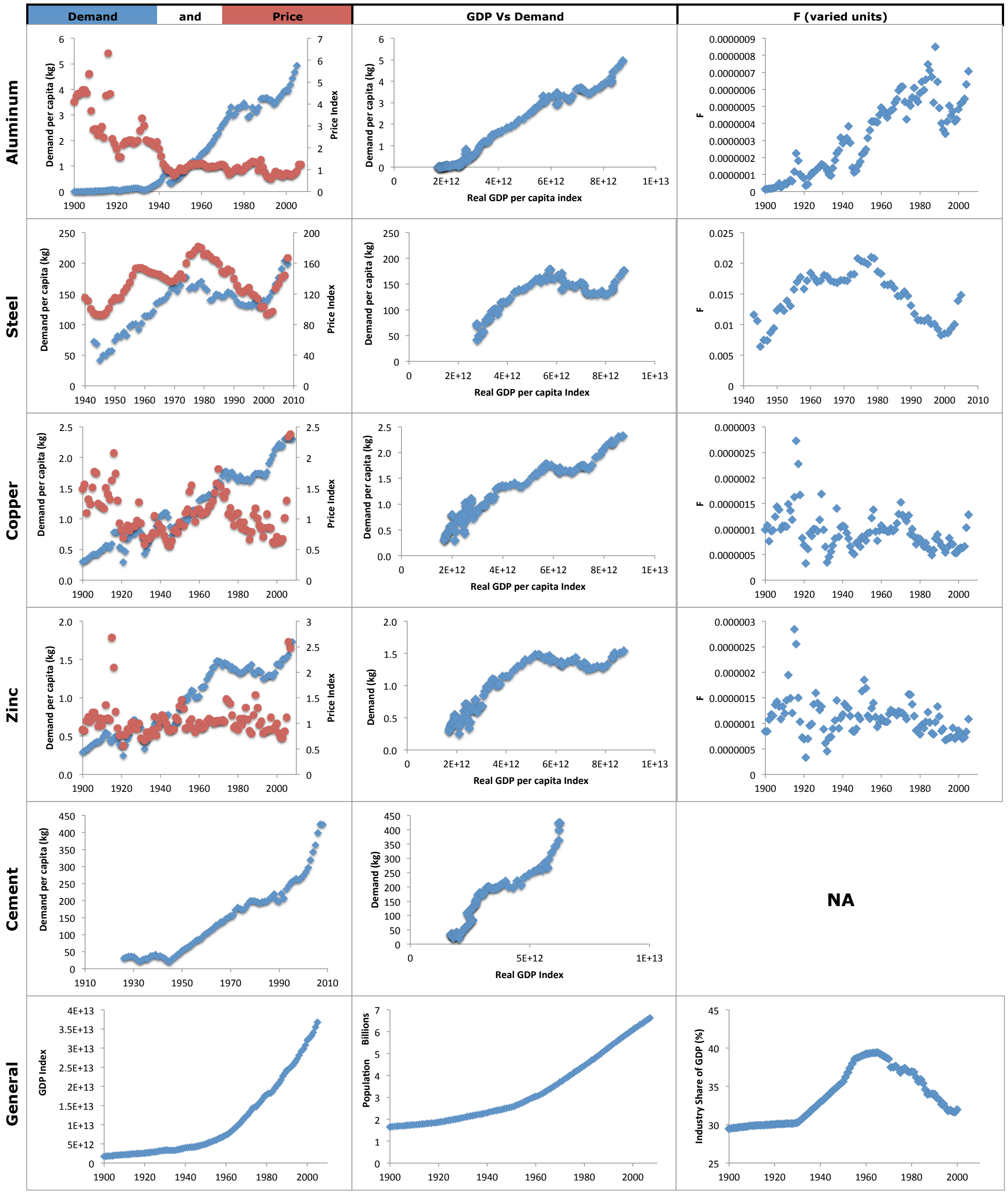
		USA	China	India	Global
Aluminum	Price	[9]	[9]	[9]	[189]
	Demand	[9]	[190, 191]	[190, 191]	[9]
Steel	Price	[9]	[9]	[9, 192]	[9]
	Demand	[9]	[190, 193]	[190, 191]	[9]
Copper	Price	[9]	[9]	[9]	[189]
	Demand	[9]	[190, 191]	[190, 191]	[9]
Zinc	Price	[9]	[9]	[9]	[189]
	Demand	[9]	[190, 194]	[190, 195]	[9]
Cement	Price	[9]	[196, 197]	[196, 198]	NA
	Demand	[9]	[199]	[200-202]	NA
GDP		[203]	[204]	[135, 136]	[121]
Population		[203]	[135, 205]	[204, 206]	[121]
Industry Share		[136]	[136]	[136]	[136]

Provided below is the raw data procured from the above resources and some additional charts used in the analysis. "F" is the fraction of industry income spent on the material, referring to 'choice' from Chapter 2 and 3.

USA

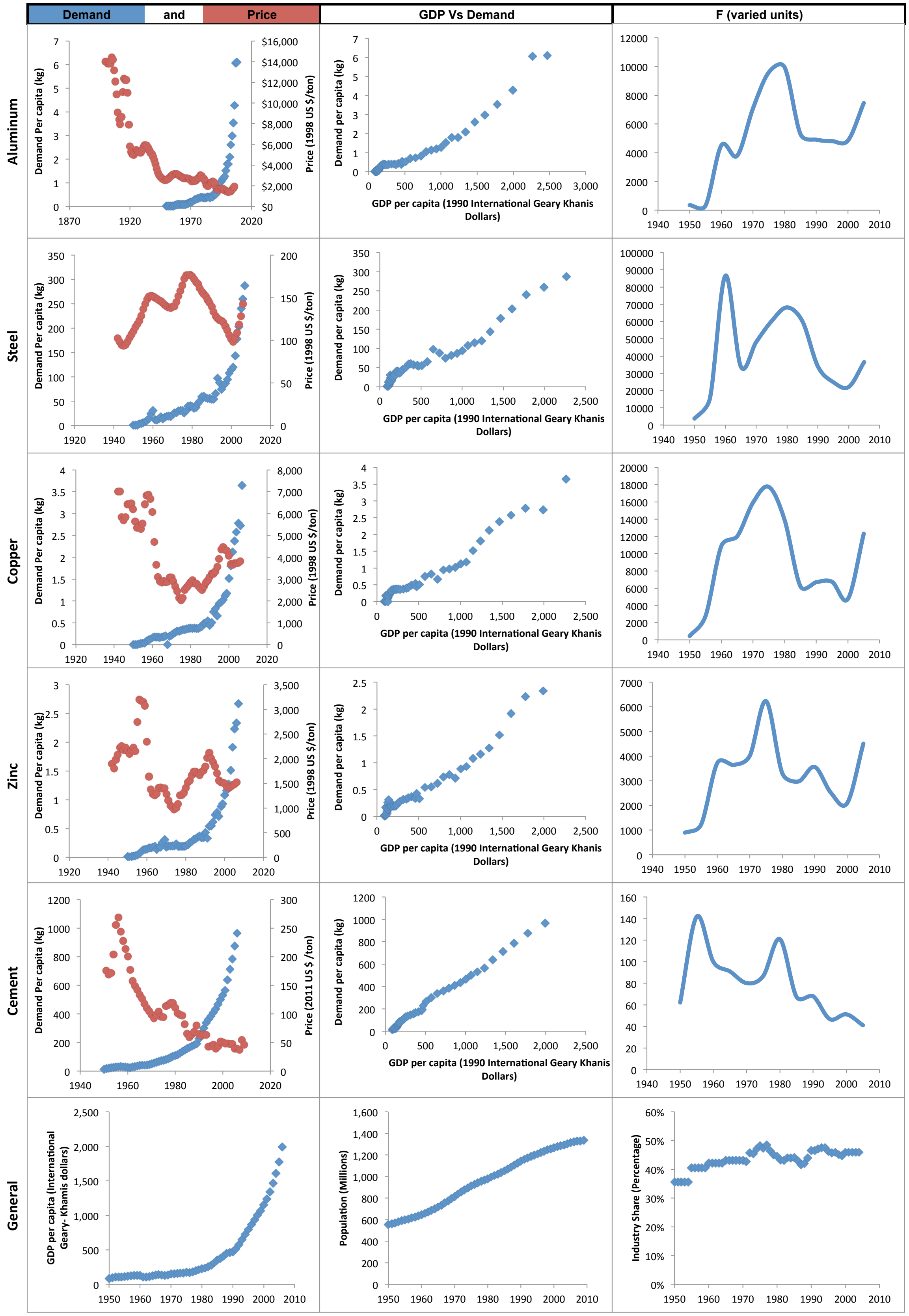

Demand
and
Price
GDP Vs Demand
F
Aluminum
Steel
Copper
Zinc
Cement
General
Demand per capita (kg)
Price (1998 US$/ton)
Price (1998$/ton)
GDP per capita (2005$)
Real GDP (2005$ millions)
Population (Millions)
Industry Share

Global



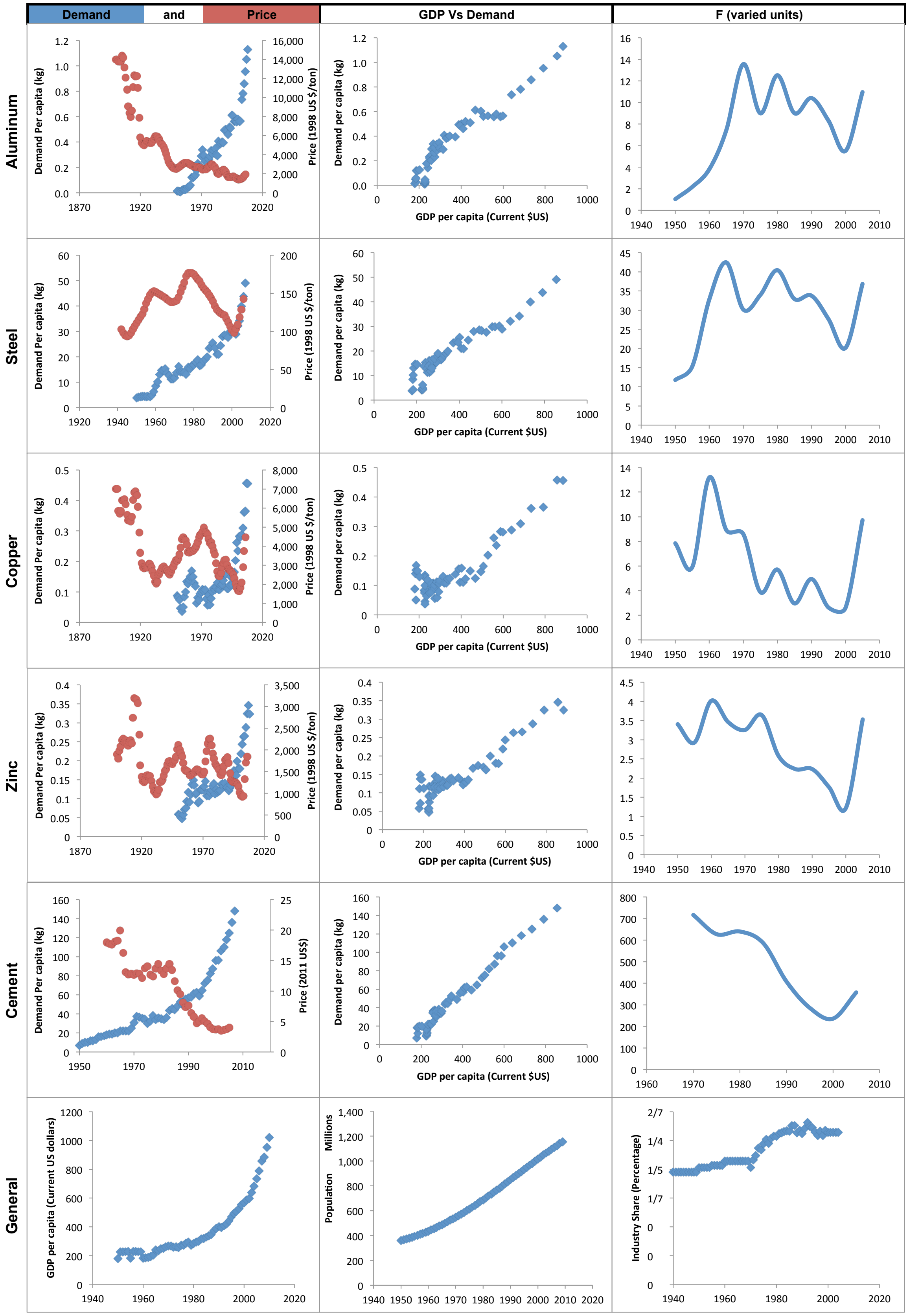
Demand
and
Price
GDP Vs Demand
F (varied units)
Aluminum
Steel
Copper
Zinc
Cement
General
Demand per capita (kg)
Price Index
Real GDP per capita index
Real GDP per capita Index
Demand (kg)
Real GDP Index
F
NA
GDP Index
Population
Billions
Industry Share of GDP (%)

China



Demand
and
Price
GDP Vs Demand
F (varied units)
Aluminum
Steel
Copper
Zinc
Cement
General
Demand Per capita (kg)
Price (1998 US $/ton)
Price (2011 US $ /ton)
Demand per capita (kg)
GDP per capita (1990 International Geary Khanis Dollars)
GDP per capita (International Geary- Khamis dollars)
Population (Millions)
Industry Share (Percentage)

India



Demand and Price
GDP Vs Demand
F (varied units)
Aluminum
Steel
Copper
Zinc
Cement
General
Demand Per capita (kg)
Price (1998 US $/ton)
Price (2011 US$)
Demand per capita (kg)
GDP per capita (Current $US)
GDP per capita (Current US dollars)
Millions
Population
Industry Share (Percentage)

A.2: Data used for energy efficiency analysis (Chapter 4)

Material	**Ep 2005 avg [MJ/kg]**	**Ep BAT 2005 [MJ/kg]**	**Ep cutting edge [MJ/kg]**	**Es 2005 [MJ/kg]**	**Es cutting edge [MJ/kg]**	**f2005**	**f2050**	**n [Years]**	**i**	**Q2006 [Mt]**	**Q2050 [Mt]**	**r2005**	**r2050**
Steel	25	19	13	9	5	56%	90%	19	1.4%	1250	2324.1	37%	69%
Aluminum	93	82	56	6	3	49%	90%	15	2.2%	55	143.93	30%	65%
Cement	4	3	2	0	0	0%	0%	50	0.8%	2550	3687.5	0%	0%
Paper	23	19	18	12	6	46%	81%	1	1.4%	370	686.25	45%	80%
Plastic	32	29	23	15	7	6%	30%	5	1.5%	243	470	4%	28%
Totals										**4,468**	**7,312**		
Notes & Definitions	Average energy required for primary production of material in 2005	Best available technology for primary production of material in 2005	Cutting edge technology for primary production, assumed half way between BAT and Theoretical minimum (calculated using exergy)	Average energy required for secondary production of material in 2005	Cutting edge energy required for secondary production of material (Calculated assuming 50% of Es 2005)	Material scrap collection rate in 2005 [quantity scrap collected/quantity exited use] (Calculated using r2005, i, n)	Material scrap collection rate in 2050 [quantity scrap collected/quantity exited use]	Average residence time in use phase	CAGR of material produced (Calculated using Q2006 and Q2050) Assumed Production = Consumption at global level	Global material production in 2005/2006	Global material production in 2050	Recycling rate of material in 2005 [material recycled/total supplied]	Recycling rate of material in 2050 [material recycled/total supplied] (Calculated using i, n, f2050)

All energy data are in final energy

Plastics energy data exclude fuel value

A.3: References used for data in A.2

C: Calculated as explained in A.2; A: assumed

Material	Ep 2005 avg [MJ/kg]	Ep BAT 2005 [MJ/kg]	Ep cutting edge [MJ/kg]	Es 2005 [MJ/kg]	Es cutting edge [MJ/kg]	f2005	f2050	n [year]	i	Q2006 [Mt]	Q2050 [Mt]	r2005	r2050
Steel	[6]	[6]	[31], [30]	[5], [6], [18]	C	C	[7]	[33]	C	[6], [11]	[6], [11]	[6], [11]	C
Aluminum	[6], [11]	[6], [11]	[31], [30]	[6], [5]	C	C	[7]	[207], [208]	C	[6], [11]	[6], [11]	[6], [11]	C
Cement	[6], [11]	[6], [11]	[31], [30]	NA	C	C	[7]	A	C	[6], [11]	[6], [11]	[7]	C
Paper	[6], [11]	[6], [11]	[211]	[6], [11]	C	C	[7], [6]	A	C	[6], [11]	[6], [11]	[6], [11]	C
Plastic	[10], [5]	[7]	[7]	[209], [210]	C	C	[7]	A	C	[6], [11]	[6], [11]	[5]	C

A.4: Data sources used for remanufacturing analysis (Chapter 5)

Category	Ref # for Table 9, Figure 28, Figure 29	Data sources
Appliances	20	[158, 162, 163, 212, 213]
	23	[152, 157-159, 163, 212, 213]
	25	[158, 163, 212-214]
Computers	7	[215, 216]
	4	
	6	
	8	
	24	
	21	
Furniture	2	[217, 218]
	1	
Textiles	5	[219-221]
	3	
Toner Cartridge	10	[174, 222, 223]
Engines	12	[155, 166, 224]
	11	[154, 155, 166, 224]
Electric Motors	19	[175, 225-228], [228], [226], [225]
	14	
	15	
	18	
	17	
	13	
Tires	22	[63, 110, 167-169, 171, 227, 229-233]
	9	
	16	

A.5: Assumptions and comments regarding remanufacturing analysis

	The energy for remanufacturing is negligible compared to virgin manufacturing	***The remanufactured product performs like-new and thus gives an equally long second life***	***Retrospective LCA conducted assuming that the Manufacturing energy remains the same***	***Performance degradation with use and maintainence neglected***	***Average age of a remanufactured product is one lifetime old***	***End-of-Life and transportation phases neglected***	***Other Assumptions / Comments***
Appliances	**X**	**X**	**X**	**X**	**X**	**X**	-
Computers	**X**	**X**	**X**	**X**	**X**	**X**	A detailed list of assumptions available in [b]
Furniture	**X**	**X**		**X**	**X**		EOL phase neglected assuming same for new and remanufactured
Textiles	**1**	**X**		**X**	**X**		The per unit energy consumed to reuse / resell / remanufacture has been assumed to be the same for the two kinds of textiles and taken from [c]
Toner Cartridge				**X**	**X**		Using [d], fraction of useful pages assumed to be 0.99 (given for new, but for Table and charts also used for Refilled). Also Emfg in Table 1 includes credit from End of Life of 39 MJ/cartridge [d]
Engines	**2**	**X**	**X**	**X**	**X**	**X**	The fuel economy of a vehicle for its entire life time is taken to be the average of all new vehicles of its class (passenger car/ class 8 truck) and model year
Electric Motors	**3**			**X**	**X**	**X**	Decrease in performance due to rewinding is assumed to be that used in MotorMaster+ [e]
Tires				**X**	**X**	**X**	The energy to manufacture radial and advanced radial are assumed equal. Assumed the same return factor for all three tire types
EXTRA COMMENTS:	**1.** Included transportation for remanufacturing; **2.** Estimate taken from [a] **3.** Included copper winding replacement	Remanufacturing is meant to entail a stringent testing stage for like-new	Due to unavailability of data and/or less than 5% life cycle energy impact of manufacturing	Sufficient Data not available	Personal conversation with some remanufacturers indicated that the cores can in fact very often be even older.	No data was found - For not "X" a sensitivity analysis was conducted	"**X**" indicates the use of the assumption while a blank indicates otherwise.

[a] = [154]; [b] = [215]; [c] = [221]; [d] = [174] ; [e] = [176]

A.6: List of publications from this work

1. T.G. Gutowski, Sahni S., Allwood J., Ashby M., Worrell E., "The Energy Required to Produce Materials: Constraints on Energy Intensity Improvements, Parameters of Demand," accepted for publication in Phil. Trans. R. Soc. A.
2. T.G. Gutowski, S. Sahni, A. Boustani, and S.C. Graves. "Remanufacturing and Energy Savings," Environmental Science and Technology Vol. 45, pp. 4540-4547, 2011
3. S. Sahni, Pamela Silva, T.G. Gutowski, "Actors of material demand," in preparation
4. S. Sahni, T.G. Gutowski, "Energy saving strategies in the materials sector: the case of aluminum", 2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST), Cambridge MA.
5. S. Sahni, T. G. Gutowski "Your scrap, my scrap! The flow of scrap materials through international trade," IEEE/International Symposium on Sustainable Systems and Technology (ISSST) 2011, Chicago.
6. A. Boustani, S. Sahni, S.G. Graves and T.G. Gutowski, "Appliance Remanufacturing and Life Cycle Energy and Economic Savings," IEEE/International Symposium on Sustainable Systems and Technology, Washington D.C., May 16-19, 2010.
7. S. Sahni, A. Boustani, T.G. Gutowski, and S.G. Graves, "Reusing Personal Computer Devices - Good or Bad for the Environment?" IEEE/International Symposium on Sustainable Systems and Technology, Washington D.C., May 16-19, 2010
8. S. Sahni, A. Boustani, T. Gutowski, S. Graves, Remanufacturing and Energy Savings, MIT Energy Initiative Report Series, January 28, 2010.
    a. Remanufacturing and Energy Savings, MITEI-1-2010.
    b. Appliance Remanufacturing and Energy Savings, MITEI-1-a-2010.
    c. Cartridge Remanufacturing and Energy Savings, MITEI-1-b-2010.
    d. Electric Motor Remanufacturing and Energy Savings, MITEI-1-c-2010.
    e. Engine Remanufacturing and Energy Savings, MITEI-1-d-2010.
    f. Furniture Remanufacturing and Energy Savings, MITEI-1-e-2010.
    g. Personal Computer Remanufacturing and Energy Savings, MITEI-1-f-2010.
    h. Textile Remanufacturing and Energy Savings, MITEI-1-g-2010.
    i. Tire Remanufacturing and Energy Savings, MITEI-1-h-2010.