PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Energy Required to Produce Materials: Constraints on Energy Intensity Improvements, Parameters of Demand

Journal:	*Philosophical Transactions A*
Manuscript ID:	Draft
Article Type:	Research
Date Submitted by the Author:	n/a
Complete List of Authors:	Gutowski, Tim; Massachusetts Institute of Technology, Mechanical Engineering Sahni, Sahil; Massachusetts Institute of Technology, Materials Science and Engineering Allwood, Julian; University of Cambridge, Department of Engineering Ashby, Michael; University of Cambridge, Department of Engineering Worrell, Ernst; Utrecht University, Copernicus Institute of Sustainable Development
Subject:	Energy < ENGINEERING AND TECHNOLOGY, Environmental engineering < ENGINEERING AND TECHNOLOGY, Materials science < ENGINEERING AND TECHNOLOGY, Mechanical engineering < ENGINEERING AND TECHNOLOGY
Keywords:	Energy, Materials, Carbon, Sustainability, Industry

The Energy Required to Produce Materials: Constraints on Energy Intensity Improvements, Parameters of Demand

Timothy G. Gutowski[a], Sahil Sahni[b], Julian M. Allwood[c],
Michael F. Ashby[c] and Ernst Worrell[d]

a Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
b Department of Materials Science and Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA
c Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom
d Department of Environmental and Innovation Studies, Utrecht University, Heidelberglaan 2, NL-3584 CS Utrecht, The Netherlands

Abstract

In this paper we review the energy requirements to make materials on a global scale by focusing on the five 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 2000 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 the constraints on improvement in energy intensity are fundamental in nature, prescribed by the laws of thermodynamics. But other options for the reduction in total energy do exist, such as material substitutions, and reductions in demand. A strategy for meeting our target by providing materials services more efficiently and thereby reducing demand is suggested, called "material efficiency".

1. Introduction

Humanity's use of materials is immense, growing, and quite unequal between the rich and the poor. For example, Graedel and Cao point out that there is a reasonably strong correlation between rates of metals usage and Gross Domestic Product (GDP) (R^2 = 0.79), with per capita metal use in the more developed countries from 10 to 100 times larger than the use in the less developed countries [1]. Our collective anthropogenic material flows are now a geological force, equaling in magnitude other natural geological phenomena [2], and often dominating or perturbing natural material budgets and cycles for many of the elements [3],[4]. The power required to make these materials and their associated products, and the carbon emissions associated with this production are also huge, requiring on the order of a third of the total worldwide primary energy use per year (~ 160 EJ), and contributing a similarly large proportion of total anthropogenic carbon emissions (~ 10 $GtCO_2$) [5],[6],[7].

In this paper, we examine the determinants of these large energy requirements, and look to potential future reductions, and in particular, potential constraints on these reductions. We approach this problem by focusing on the largest energy users among the many materials, and then on the most energy intensive operations of their production processes. We frame the problem by using a simple mathematical identity which states that the energy use for a particular material E is equal to the quantity of material produced Q times the average energy intensity for that material e.

$$E_i = Q_i \cdot e_i \qquad (1)$$

where

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

Q_i = materials production per year (mass)

e_i = energy intensity (MJ/kg)

Our total energy use then is just the sum $E_T = \Sigma E_i$.

First we look at the energy intensity of materials production, e and review the reasons for the high values and the steps that can be taken to reduce these values. Secondly, we look at the determinants of demand Q, and identify mechanisms that could be used to reduce demand.

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 [[8], [9], [5]]. Taken together, this would require that the energy intensity of materials production in 2050 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.

If one looks at the hundreds of materials that humanity produces, the associated energy requirements are dominated by just a few material categories. This is quite fortunate from an analysis point of view. Here we look at the materials used to make physical goods. Figure 1 shows a Pareto type plot rank ordering the energy requirements for these materials. The figure shows that just a few materials dominate materials production, and if we track just the "top five" (steel, cement, paper, aluminum and aggregated plastics) these alone dominate the entire world industrial sector both in terms of energy used, and CO_2 emitted [[10], [5], SI].

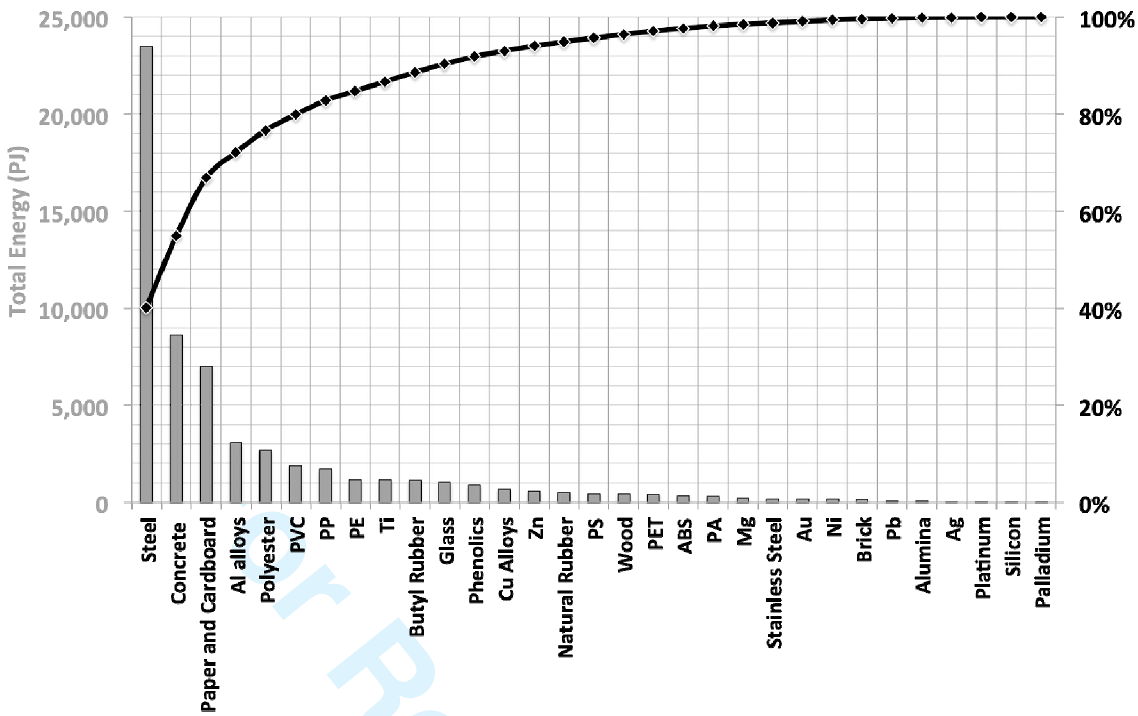


Figure 1. Total energy used for the production of 31 materials worldwide, cumulative scale on the right. [11].

2. Energy Intensity "e"

The energy intensity, or 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 shown in Figure 2.

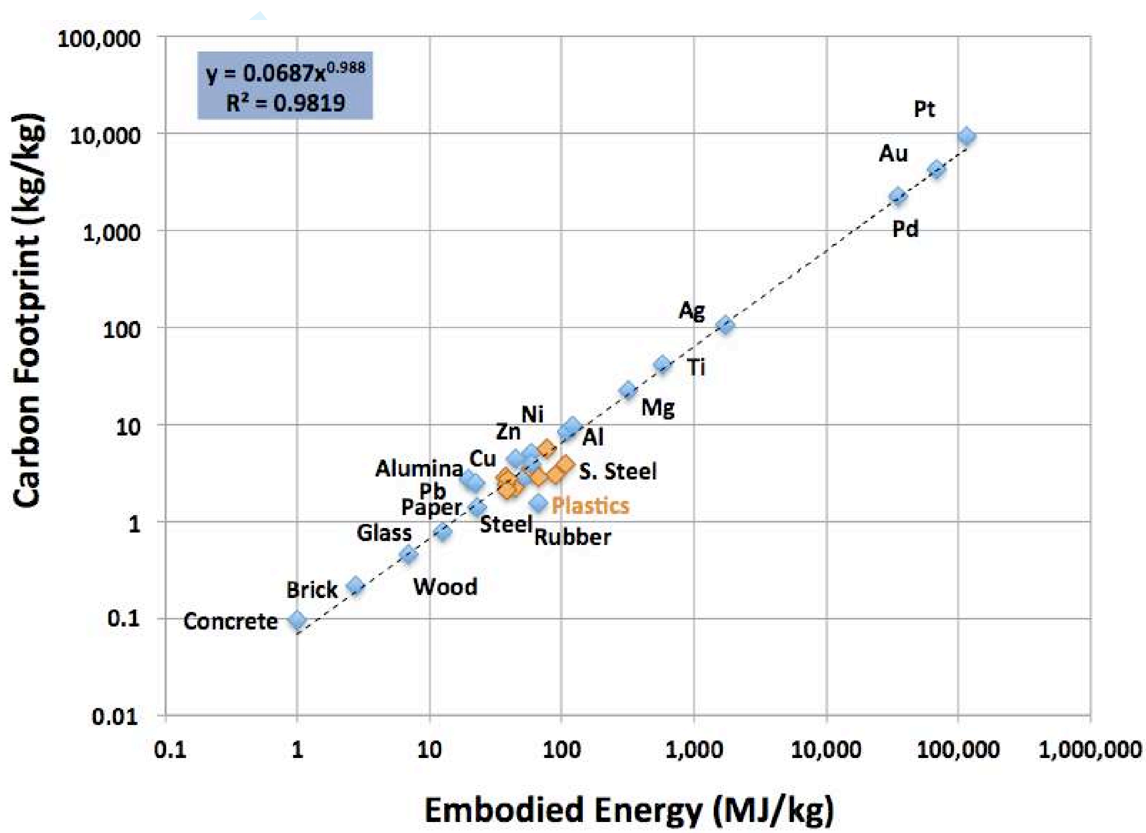


Figure 2: The carbon emission in kg CO_2 per kg of material produced versus the embodied energy. Data from [11].

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 3 versus the dilution (reciprocal of the ore grade or mass concentration "c" of the metal at the mine).

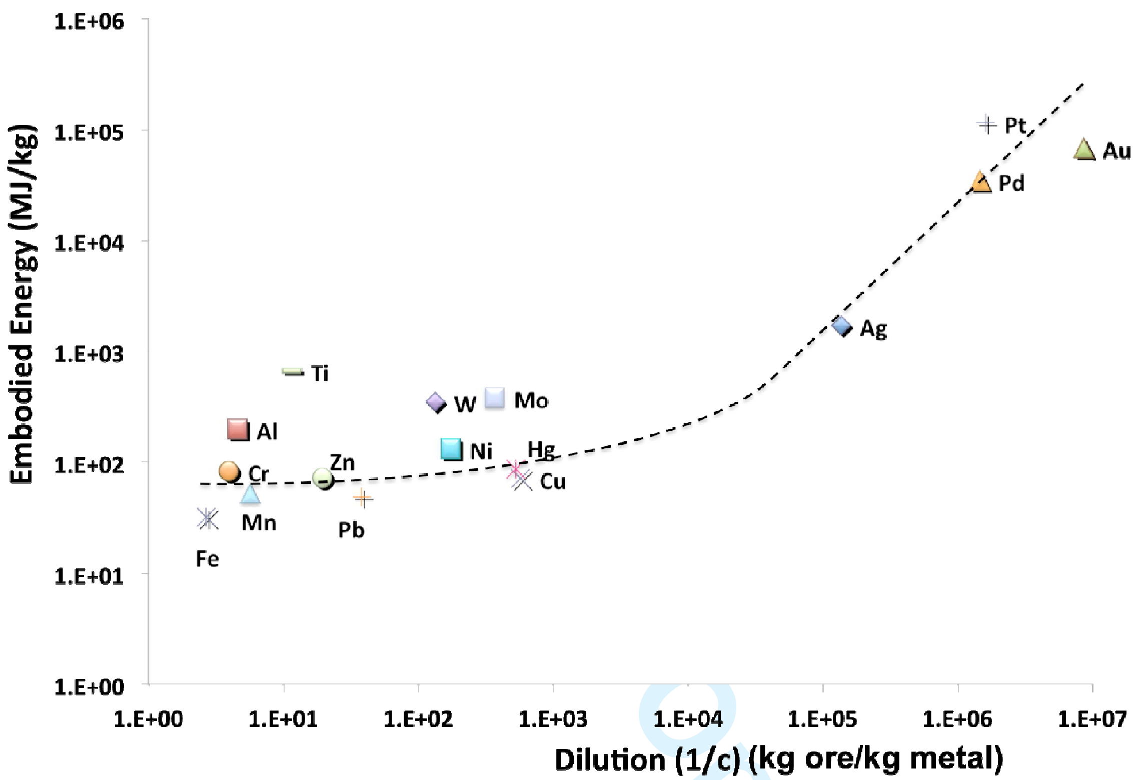


Figure 3: Embodied energy of 16 metals [11] plotted against the dilution, or inverse of concentration, of the common ores used to produce the metals [12]. See SI for more discussion of this plot.

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 shape of this curve 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 3 could actually be represented by a cluster of points around a mean value that could easily vary by $\pm 20\%$ or more. See [[13],[11], SI]. 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 4 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 by the standard Gibbs Free Energy of formation for the ores (Fe_2O_3 and Al_2O_3). 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 5 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 Figures 4 and 5 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 represent large capital investment. Once these costs are sunk there is a large incentive to continue operation for decades. In fact, looking closely at Figure 5 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 [7]. 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 can not 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[1] would result in an overall energy

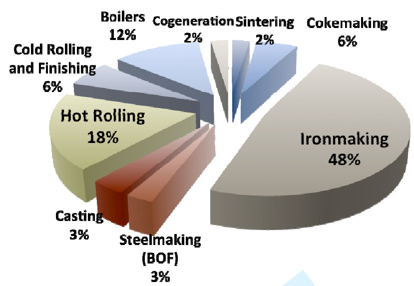
[1] Best available technologies or BATs can contain those that are available but not necessarily economically viable. BAT in many cases can be the same as Best practice technology (BPT) that

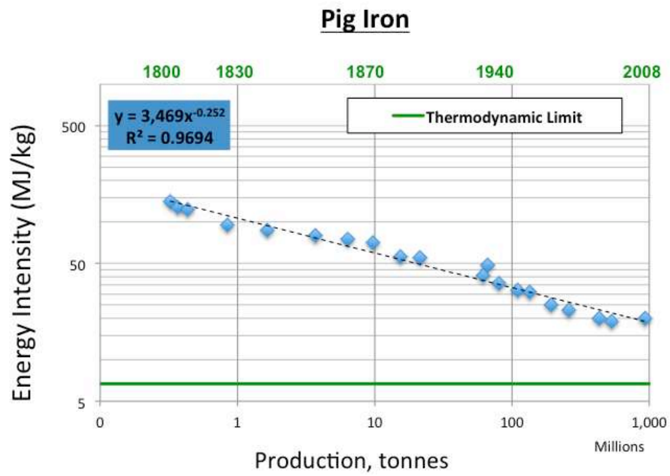
reduction of about 20%. This agrees with detailed estimates made by us and others, including the International Energy Agency IEA [[6],[7],[5]]. Some of the technologies involved in these improvements would include worldwide implementation of by-product gas recovery from steel production and thin slab 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 is assumed. Data used our calculations are provided in the supporting information document.

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 [10]. 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 17%, 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. Again additional details can be found in our work and that of others, as well as in our supporting information [15], [16], [17], [18], [5], [6], [10],[7]. The 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.

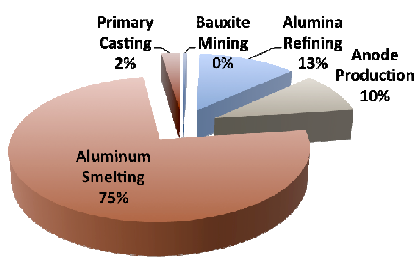
---

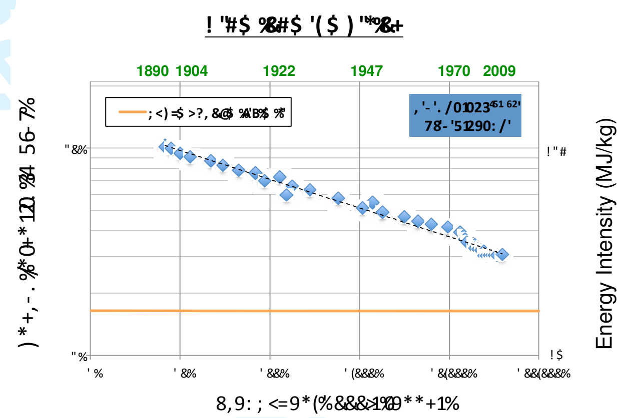
is best available and economical, but can be different when a new technology has emerged. Saygin and co-workers in their work distinguish the two for several industries [14].





4a Pig Iron





4b Aluminum

Figure 4: 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 [19] and that for aluminum from [20]. Production data is obtained from [21]. Pie chart data is taken from [18], [20], [22].

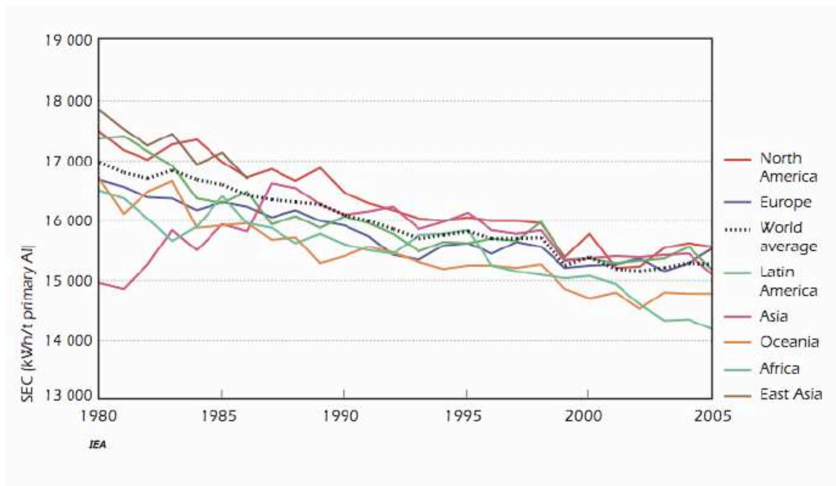


Figure 5: Historical Regional data for the energy intensity of aluminum smelting [7].

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 [11]. 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 [23].

To explore this effect, we use a relatively simple model that focuses on post consumer discards, an area with the most potential for improvement. Consider the total demand Q_T subdivided into Q_p (primary production) produced with energy intensity e_p, and Q_s (secondary production) produced with energy intensity e_s. The total energy E_T for a given material then is,

$$E_T = Q_p e_p + Q_s e_s \qquad (2)$$

$$E_T = Q_T[(1-r)e_p + re_s] = Q_T\bar{e} = Q_T e_p(1-m) \qquad (3)$$

$$m = r(1-\frac{e_s}{e_p}) \qquad r = \frac{Q_s}{Q_T} \qquad \text{(4a and b)}$$

where $\bar{e}$ is the average energy intensity, r is the fraction of secondary material in the supply and m controls our potential energy savings. Since the general situation is $r \leq 1$ and $e_s < e_p$, with $0 < m < 1$, our goal then is to make m as close to one as possible.

We state the constraints on Q_s as follows

$$Q_s < Q_{discards} < Q_T \qquad (5)$$

That is, our secondary supplies must be less than the end of life discards due to difficulties in collection, separation and losses. Let us say

$$Q_s = f\,Q_{discards} \qquad (6)$$

where $0 \leq f \leq 1$ is the fraction of discards that become available to satisfy demand. Secondly, the discards must be less than demand, because in general, the discards have come out of the system after "n" years of product life time, while demand has continued to grow at rate "i". Putting this together gives us an expression for r, as

$$\frac{Q_s}{Q_T} = r = f(1+i)^{-n} \qquad (7)$$

In other words, r is constrained by the efficiency of the recycling system as well as by the parameters of growth. Furthermore, as we move forward to improve our recycling in an effort to reduce energy use and carbon emissions from materials production, we will run into the realization that some materials such as steel, paper and aluminum are already recycled at fairly high levels. At the same time there is no known route to efficiently recycle concrete, and the recycling of plastics is difficult. The challenges plastics present to recycling, are the flip side of the advantages they provide for product design – they are almost infinitely changeable. That is we can alter their color, properties and performance by a vast array of pigments, additives and fillers, only to greatly complicate the problem of material identification and separation at the end of life. At the same time, some improvements in technology and labeling in Europe do seem to be helpful in improving the recyclability of plastics.

Table 1 Recycling parameters for top five materials. ('Cur' = current average; 'CE' = cutting edge). Details are provided in the Supporting Information document.

Material	n [years]	i	f_{cur}	f_{new}	$[1-e_{s,Cur}/e_{p,Cur}]$	$[1-e_{s,Cur}/e_{p,CE}]$	$[1-e_{s,CE}/e_{p,CE}]$
Steel	19	1.4%	56%	90%	49%	1%	50%
Aluminum	15	2.2%	49%	90%	90%	82%	91%
Cement	50	0.8%	0%	0%	-	-	-
Paper	1	1.4%	46%	81%	47%	37%	69%
Plastic	5	1.5%	6%	30%	74%	64%	82%

If we now assume a fairly aggressive effort to increase the fraction *f* and apply estimates for relevant recycling parameters given in columns 1 through 5 in Table 1, we estimate an additional reduction in the world energy required to produce materials at about only 6% of current usage. 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 6 instead of column 7) the percentage change would have been 18%. 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 in the energy intensity of secondary materials production, e_s. Here we somewhat arbitrarily assume the current value of this energy intensity is reduced by half for all sectors. 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%.

One more method to further reduce the energy requirements for materials production might be considered; to substitute materials with low energy intensity for materials with high energy intensity. This would be done at the product design stage with proper consideration of the performance requirements for the materials. For example, it would appear that timber with an energy intensity in the vicinity of 1 - 3MJ/kg, could be substituted for steel with an energy intensity around 20MJ/kg, in some building applications. As a general observation however, it can be seen that the energy intensity of materials correlates very closely with their price. This is shown in Figure 6. The close correlation is due in part, to the fact that energy shows up as a relatively large percentage of the cost to produce a material – something like 30% for concrete and aluminum and 60% for plastics [10]. As a result we can assume that materials substitution driven by price has already had some effect on reducing the energy intensity of the materials we use. For example, in Figure 7 the energy intensity, e, Vs world production, Q, for many materials of construction are plotted. The figure reveals that in general many of the high production volume materials are already the low energy intensity materials. Of the top five; steel, paper and concrete are near the bottom of the energy intensity scale. Though it is possible that some opportunities for the substitution of concrete, brick and wood for steel do likely still exist. For any particular case, however, one would need to do a life cycle assessment for the product to ensure that the overall energy requirements are reduced. This approach would be especially important when considering aluminum and plastics which have generally been substituted for lower energy materials, such as steel. For example, if the application is to vehicles such as automobiles and aircraft, the energy savings during the use phase brought about by employing lighter weight materials such as aluminum and plastic matrix composites may be (and often is) larger than the marginal increase in materials energy. In fact, it is quite likely, that when the problem of total energy reduction is approached from a product life cycle perspective that this will lead to the deployment of some materials that are actually higher in energy intensity rather than less.

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. The essence of this problem is that materials production energy is dominated by a small group of materials that has been in production for some time, and has 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. We next turn our attention to the potentially more painful option of reducing material demand. This is explored in the next session.

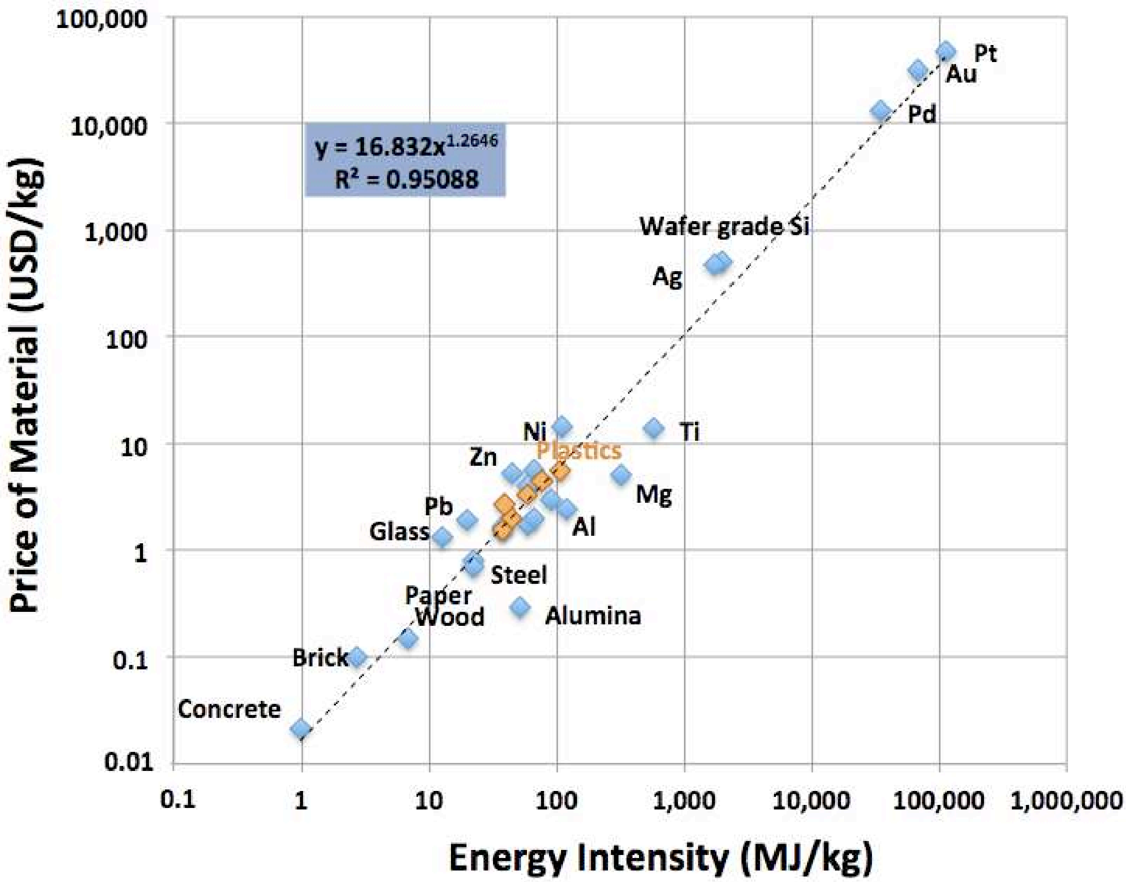


Figure 6: Price of various materials plotted against the embodied energy of the materials. The data for embodied energy comes from [11], for material prices for metals from [21], plastics from [24] and brick, wood, and glass from [11]. Plastic prices are for year 2011, and all others are for 2009.

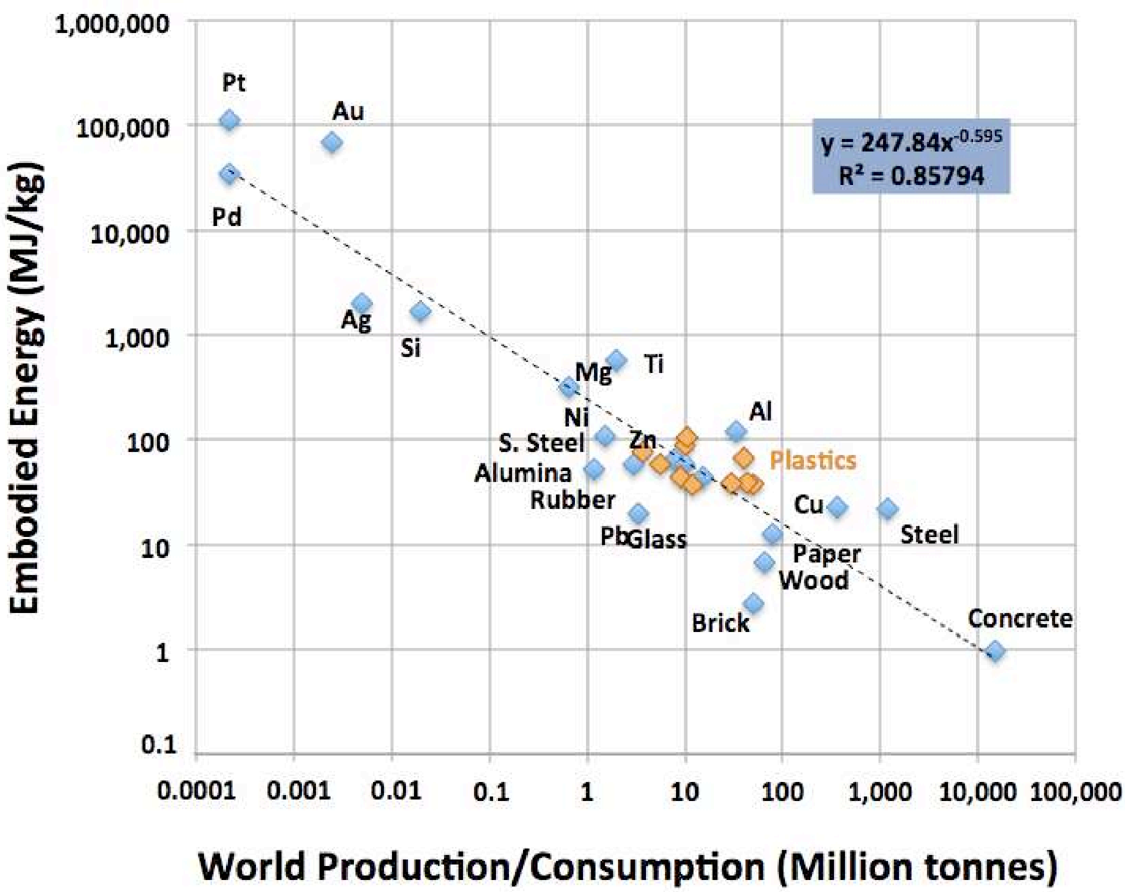


Figure 7: Energy intensity e versus world production Q for various materials of construction [11].

3. The Determinants of Material Demand "Q"

To explore the growth in materials demand, we will decompose Q into four components using a mathematical identity similar to the so called IPAT equation, or the Kaya Identity [25].

$$Q = P \cdot \frac{GDP}{P} \cdot \frac{V_{mat'ls}}{GDP} \cdot \frac{Q}{V_{mat'ls}} \qquad \text{(eq. 8)}$$

or

$$Q = P \cdot A \cdot M \cdot \frac{1}{p} \qquad \text{(eq. 9)}$$

differentiation leads to

$$\frac{\Delta Q}{Q} = \frac{\Delta P}{P} + \frac{\Delta A}{A} + \frac{\Delta M}{M} + \frac{\Delta(1/p)}{1/p} \qquad \text{(eq. 10)}$$

where,

Q	=	quantity of the material consumed[2] (usually mass)
P	=	population
A	=	affluence (GDP/P)
GDP	=	Gross domestic product (or a similar measure) of the total value of the goods and services produced in the region considered.
M	=	total market value of the material considered ($V_{mat'l}$) as a fraction of the GDP. To some extent this is how society chooses to spend its money. This component is called "choice" by Waggoner and Ausuble [28]
p	=	price, economic value of the material per unit of quantity Q.

We breakdown the quantity of materials demanded Q in terms of population P, Affluence A, relative material value M and the reciprocal of price ($1/p$). By using time series data one can show how the growth or decline in Q (i.e. $\Delta Q/Q$ given in percent per year) is related to the growth or decline in the terms on the right hand side of equation 9, as shown in equation 10. This is a process of simple addition provided that the annual changes are small (i.e. on the order of a few percent). Note that writing identity

[2] Apparent consumption used for this calculation is as defined and provided by USGS. This doesn't include material consumed as part of imported products or that lost as exported products. [26], [27].

equations does not imply that the terms on the right hand side are independent, nor that the relationship demonstrates cause and effect. But it does show correlations and allows us to identify major historical trends in society, thus provides a framework for speculating about how things might change.

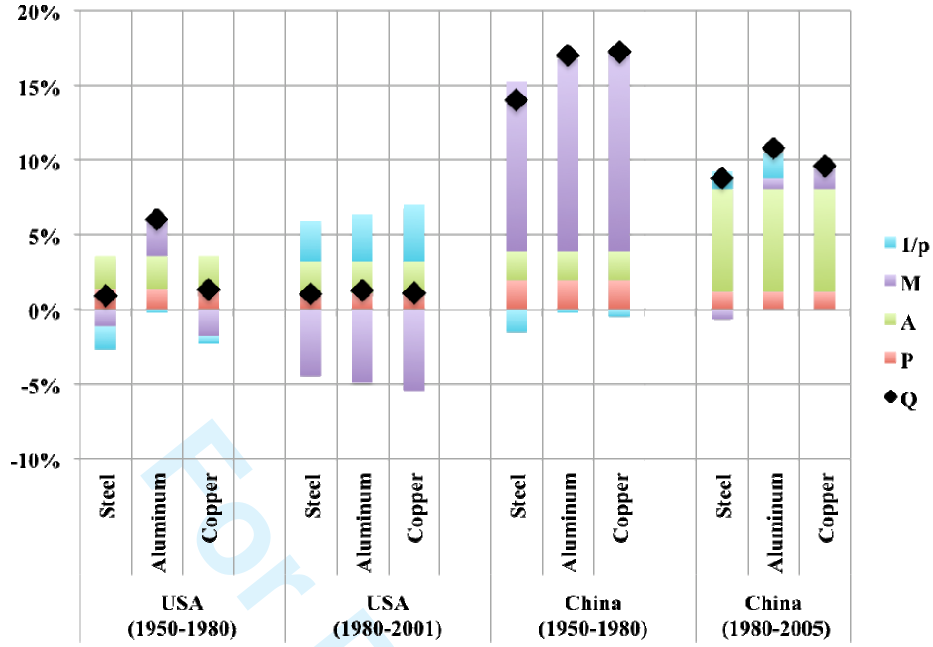
Broadly speaking, world trends for the terms in equation 10 over the last 9 decades, show that both population and affluence have been steadily increasing, the first at a rate of a little more than 1% a year, and the second at a rate a little below 2%. At the same time, material prices while subject to variation, have generally been decreasing. For example, the industrial index for materials has fallen by a little under 2% a year over this same time period [11]. In other words, three out of the four terms on the right hand side of equation 10 have mostly been going up at a combined rate of a little under 5%. The fourth term M, which represents the value of materials produced for society relative to the total value of all goods and services produced by society, has been generally decreasing but varies considerably between the rich and the poor. Generally, M increases with a high value as a country grows and builds its infrastructure, and then slows down and can become negative as growth in GDP outpaces materials use. This transition is sometimes called "relative dematerialization" and includes economic structural effects as GDP shifts from manufacturing to services. Worldwide, M has been dominated by the behavior of the developed countries leading to a decline on the order of 2% per year. Putting this together, indicates a historical trend of growing materials demand on the order of almost 3% per year. Note that 3% a year for 50 years will give an increase of more than 4 times.

To consider the different patterns of demand, consider the data for the USA and China given in Figure 8. The time periods reflect times of rising materials prices (1950 – 1980) and times of falling materials prices (1980 to 2001 or 2005). The data for three metals shows several interesting features. First of all, we see that the USA has essentially saturated in per capita demand for these metals. That is the growth in Q keeps in pace with the growth in population, in particular for the 1980 to 2001 data. This moderation in demand appears to be linked with the increasingly negative value for the change in M.

For China, on the other hand, strong demand for materials, on the order of 8 to 10% per year, has been evident for at least the last five decades, but the drivers of this demand have changed dramatically as China has changed. Currently, growth in materials demand in China is driven primarily by significant increases in affluence. But earlier data showed a pattern more like developing countries, with large values of the parameter M. In between these two time periods, the sign for M has flipped from large positive to slightly negative.

Figure 8: Historical time series data for the terms in equation 10. Quantity data for USA is obtained from [21], for China from [29], GDP and Population data from [30], price data from [21].

Region (Time)	Material	Q	P	A	M	1/p
USA (1950-1980)	*Steel*	0.9%	1.4%	2.2%	-1.1%	-1.5%
	Aluminum	6.0%	1.4%	2.2%	2.6%	-0.2%
	Copper	1.3%	1.4%	2.2%	-1.8%	-0.5%
USA (1980-2001)	*Steel*	1.0%	1.1%	2.1%	-4.5%	2.7%
	Aluminum	1.3%	1.1%	2.1%	-4.9%	3.2%
	Copper	1.1%	1.1%	2.1%	-5.4%	3.8%
China (1950-1980)	*Steel*	8.2%	1.8%	2.3%	5.5%	-1.5%
	Aluminum	8.5%	1.8%	2.3%	4.5%	-0.2%
	Copper	10.4%	1.8%	2.3%	6.5%	-0.5%
China (1980-2005)	*Steel*	8.3%	1.2%	8.6%	-2.6%	1.2%
	Aluminum	9.7%	1.2%	8.6%	-1.8%	1.7%
	Copper	8.6%	1.2%	8.6%	-1.1%	0.0%



How these patterns play out into the future is open to speculation, but several possibilities are outlined here to demonstrate the range of parameters. Perhaps the most conservative would be to extrapolate at the apparent rate of growth for the developed countries at about 1%. This gives a multiplier of 1.65 after 50 years. Alternatively we could use the estimated recent world rate of 3% and this would give a multiplier of 4.4 after 50 years. Compared to these we could posit two altruistic scenarios. In the first, we assume saturation in the developed world with no additional growth, but additional growth for the developing world up to the same per capita materials levels as the developed world. Using data from Graedel and Cao, for metals usage, one can estimate the required growth to be a little over a doubling in total demand [1]. This is similar to the estimate we used in our opening goal statement. If on the other hand, we were to attempt to meet our energy target by maintaining materials demand at the current level, but to do it equitably, the developed world would have to cut their demand by more than half, while the developing world could increase by a factor between 3 and 4.

Factors that could moderate materials demand (see equation 8) of particular importance include higher materials prices, and a weakened economy. Higher materials prices could come about by shortages in supply and/or increases in costs including energy costs and carbon taxes. Because most of our construction materials are generally quite abundant on earth, including the feed stocks for our top five, there should be no long term concerns about their availability. At the same time, as we expand our palate of materials to include nearly all of the 92 naturally occurring elements often in specialized applications, it is quite probable that some short and moderate term supply shortages could very well occur while new sources are brought into production and substitutes are developed. Several recent reports and papers identify the supply of some of the rare earth metals and other energy materials as potentially vulnerable until alternative supplies are developed around the world [31], [32]. Similarly some materials may become more difficult to access and/or may become more dilute as the best resources are depleted. These materials including copper and uranium, could then have corresponding price increases.

Figure 3 suggests how energy requirements could go up if dilution were to increase dramatically. At the same time it is to be noted that mining and separation processes are still quite far from theoretical limits and potential gains in this area are quite possible. In fact over recent history surface mining of dilute ores has actually been more energy efficient than the subsurface mining of more concentrated ores for the same metal [33]. Overall however, the problem of difficult access and dilution for materials production of our top five materials is generally not foreseen as serious, with the possible exception of plastics. The more serious problem has to do with the consequences of energy resources used and their effect on our ecosystems.

4. The Next Step

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 have it both ways. 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 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 2: The magnitude of effect relative to price of increasing energy price or imposing a CO_2 tax. Prices same as in Figure 6. Energy fraction of cost taken from [10], and CO_2 intensities from [11].

				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 2 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 uses 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” and discuss them in recent publications [34], [35]. 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[3]. Of course this would not be an attractive solution from the viewpoint of those who produce our input materials, but on the other hand, material efficiency does offer a way to provide material services for humanity while still meeting energy and carbon targets. It is clear that current price incentives are unlikely to motivate these kinds of improvements either in terms of energy efficiency as outlined in this paper, or material efficiency as just mentioned. Therefore it is necessary that we explore how we can wrap these improvements up in other benefits, and promote these improvements, as necessary, by changes in policy.

References

[1] T. E. Graedel and J. Cao, "Metal spectra as indicators of development," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 107, pp. 20905-20910, Dec 7 2010.

[2] J. R. McNeill, *Something New Under the Sun: An Environmental History of the Twentieth-Century World*: W. W. Norton & Company, 2000.

[3] R. J. Klee and T. E. Graedel, "Elemental cycles: A status report on human or natural dominance," *Annual Review of Environment and Resources,* vol. 29, pp. 69-107, 2004.

[4] J. Rockstrom, W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley, "Planetary Boundaries: Exploring the Safe Operating Space for Humanity," *Ecology and Society,* vol. 14, 2009.

[3] If we explore this idea using equation 9, we are saying a halving of M could result in a halving of Q. Of course such a dramatic intervention would require some singnificant changes from today, and would have some influence on all of the other paramaters in equation 9 as well. Further, extending product life would also affect our results from recycling per equation 7.

[5] J. M. Allwood, J. M. Cullen, and R. L. Milford, "Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050," *Environmental Science & Technology,* vol. 44, pp. 1888-1894, Mar 15 2010.

[6] *Tracking industrial energy efficiency and CO2 emission*: International Energy Agency, IEA, 2007.

[7] *Energy technology transitions for industry: strategies for next industrial revolution*: International Energy Agency, IEA, 2008.

[8] *Realizing the potential of energy efficiency: targets, policies, and measures for G8 countries*. UN foundation, 2007.

[9] *Working Group III: Mitigation of Climate Change* vol. 2011. http://www.ipcc-wg3.de/: Intergovermental Panel on Climate Change, IPCC.

[10] *International Energy Outlook*. http://www.eia.gov/forecasts/ieo/index.cfm: U.S. Energy Information Administration, 2011.

[11] M. F. Ashby, *Materials and the environment: Eco-informed material choice*. Oxford, UK: Butterworth-Heinemann, 2009.

[12] J. Johnson, E. M. Harper, R. Lifset, and T. E. Graedel, "Dining at the periodic table: Metals concentrations as they relate to recycling," *Environmental Science & Technology,* vol. 41, pp. 1759-1765, Mar 1 2007.

[13] J. Craig and G. Hammond, "Inventory of Carbon and Energy (ICE)," 1.6a ed. University of Bath, 2008.

[14] D. Saygin, E. Worrell, M.K. Patel, and D. J. Gielen, "Benchmarking the energy use of energy-intensive industries in industrialized and developing and developing countries," *Energy,* vol. 36, pp. 6661-6673, 2011.

[15] E. Worrell, N. Martin, and L. Price, "Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Industry," *Energy, the International Journal,* vol. 5, pp. 513-536, 2001.

[16] E. Worrell, N. Martin, and L. Price, "Potentials for Energy Efficiency Improvement in the U.S. Cement Industry," *Energy, the International Journal,* vol. 12, pp. 1189-1214, 2000.

[17] N. Martin, Worrell, E., Price, L.K., *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Cement Industry*: Ernst Orlando Lawrence Berkeley National Laboratory, 1999.

[18] E. Worrell, Martin, N., Price, L.K., *Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector*: Ernst Orlando Lawrence Berkeley National Laboratory, 1999.

[19] V. Smil, *Energy in nature and society: general energetics of complex systems*. USA: MIT Press, 2008.

[20] W. T. Choate, Green, J. A. S. , "U.S. Energy Requirements for Aluminum Production Historical Perspective, Theoretical Limits and New Opportunities," 2003.

[21] *Mineral Yearbooks* vol. 2011. http://minerals.usgs.gov/minerals/pubs/myb.html: United States Geological Survey (USGS).

[22] J. de Beer, E. Worrell, and K. Blok, "Future technologies for energy-efficient iron and steel making," *Annual Review of Energy and the Environment,* vol. 23, pp. 123-205, 1998.

[23] D. B. Muller, T. Wang, and B. Duval, "Patterns of Iron Use in Societal Evolution," *Environmental Science & Technology,* vol. 45, pp. 182-188, Jan 1 2011.

[24] IDES. (Jun 15th). *Plastic material prices*.

[25] K. Yamaji, Matsuhashi, R., Nagata, Y., Kaya, Y., "An Integrated System for CO2/Energy/GNP Analysis: Case Studies on Economic Measures for CO Reduction in Japan. ," presented at the Workshop on CO2 Reduction and Removal: Measures for the Next Century, Laxenburg, Austria, 1991.

[26] M. P. Hekkert, L. A. J. Joosten, and E. Worrell, "Analysis of the paper and wood flow in The Netherlands," *Resources Conservation and Recycling,* vol. 30, pp. 29-48, Jul 2000.

[27] David R. Wilburn and D. A. Buckingham, "Apparent Consumption vs. Total Consumption—A Lead-Acid Battery Case Stud," 2005.

[28] P. E. Waggoner and J. H. Ausubel, "A framework for sustainability science: A renovated IPAT identity," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 99, pp. 7860-7865, Jun 11 2002.

[29] T. Nishiyama, "The roles of Asia and Chile in the world copper market," *Resources Policy,* vol. 30, pp. 131-139, Jun 2005.

[30] "United Nations Statistical Database," United Nations, http://unstats.un.org/unsd/databases.htm.

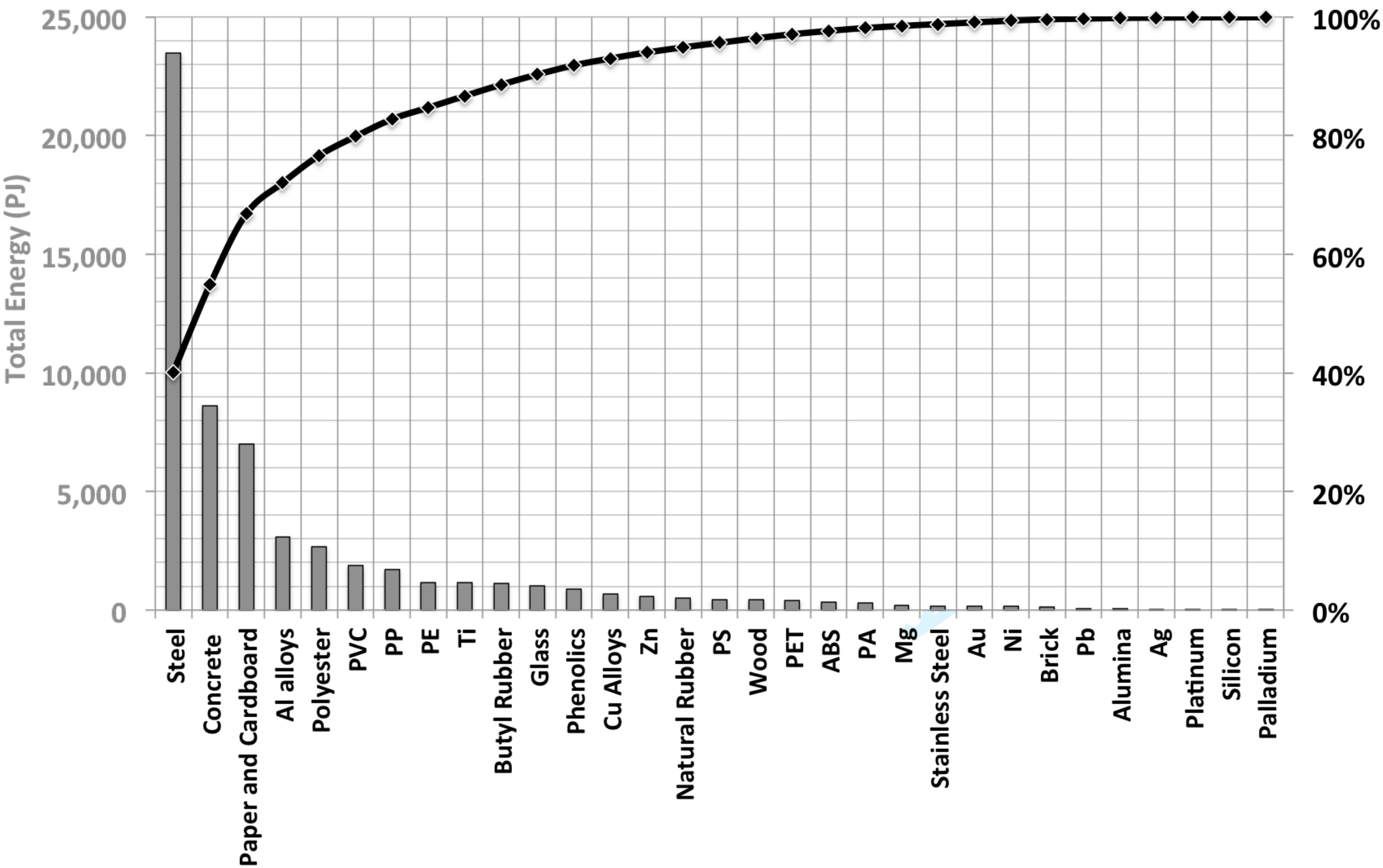
[31] *Critical Materials Strategy*. http://energy.gov/downloads/us-department-energy-critical-materials-strategy-0: U.S. Department of Energy, 2010.

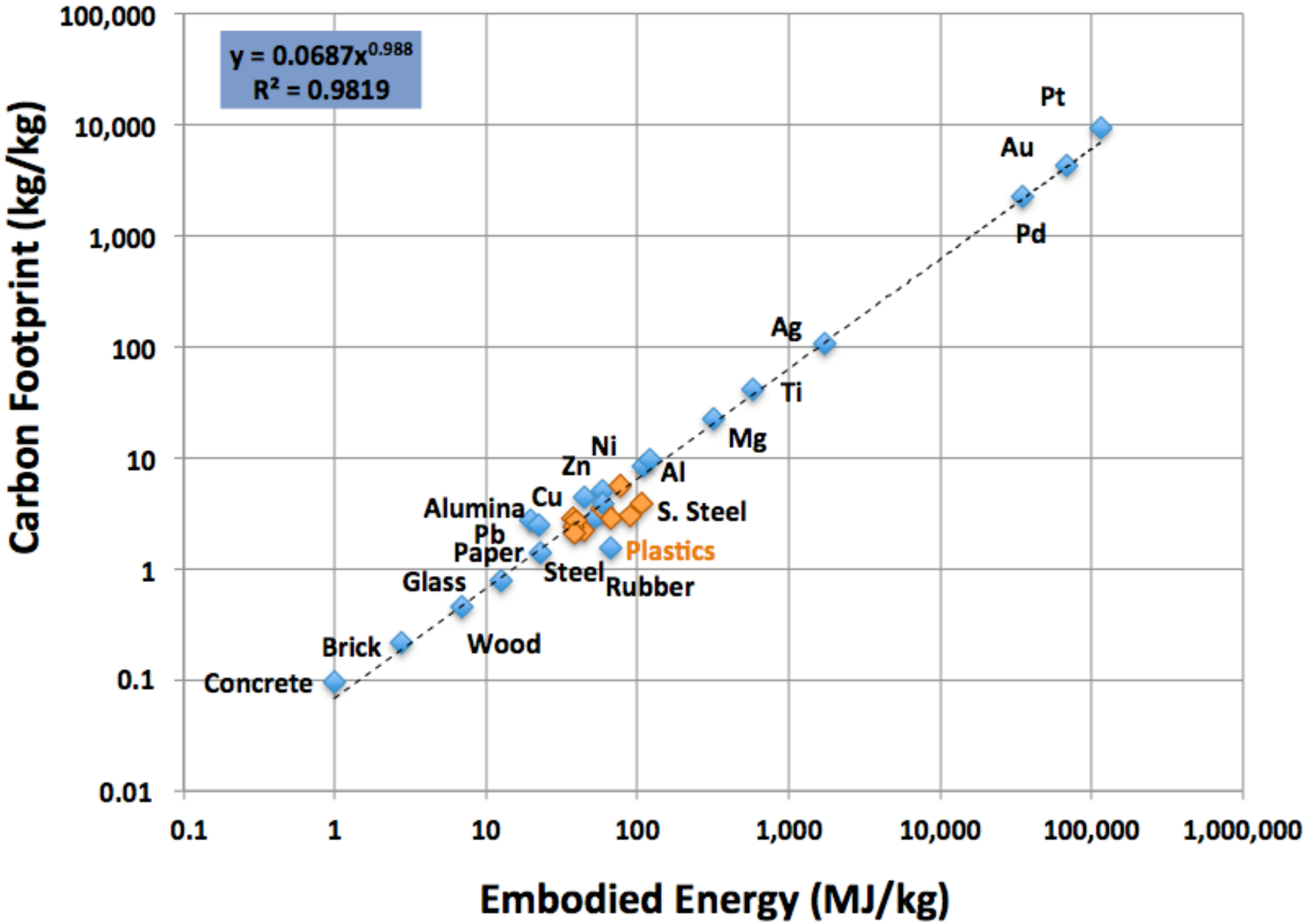
[32] T. E. Graedel, "On the Future Availability of the Energy Metals," *Annual Review of Materials Research,* vol. 41, 2011.

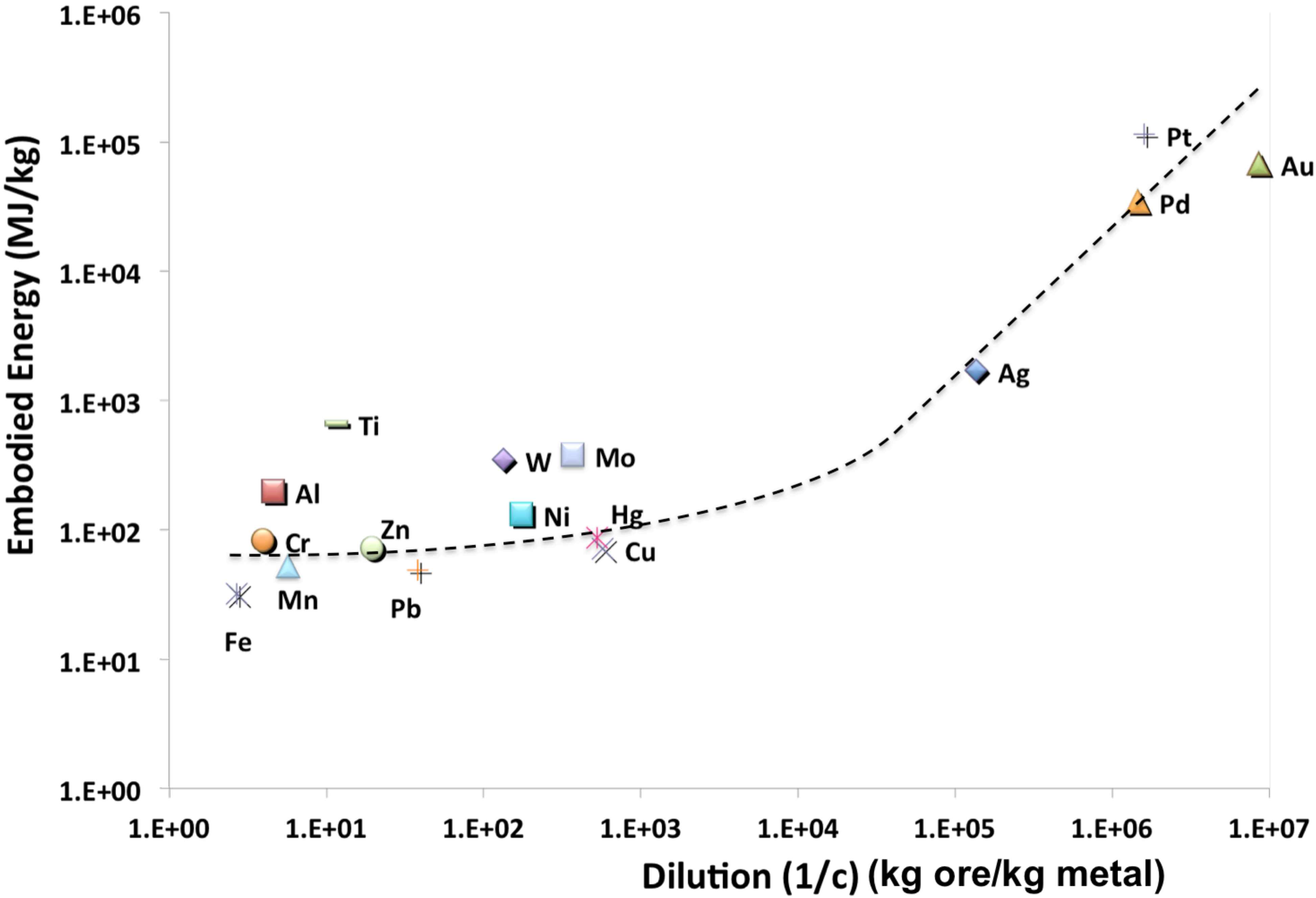
[33] P. F. Chapman, Roberts F., *Metal resources and energy*: Butterworths Monographs in Materials, 1983.

[34] J. M. Allwood, M. F. Ashby, T. G. Gutowski, and E. Worrell, "Material efficiency: A white paper," *Resources Conservation and Recycling,* vol. 55, pp. 362-381, Jan 2011.

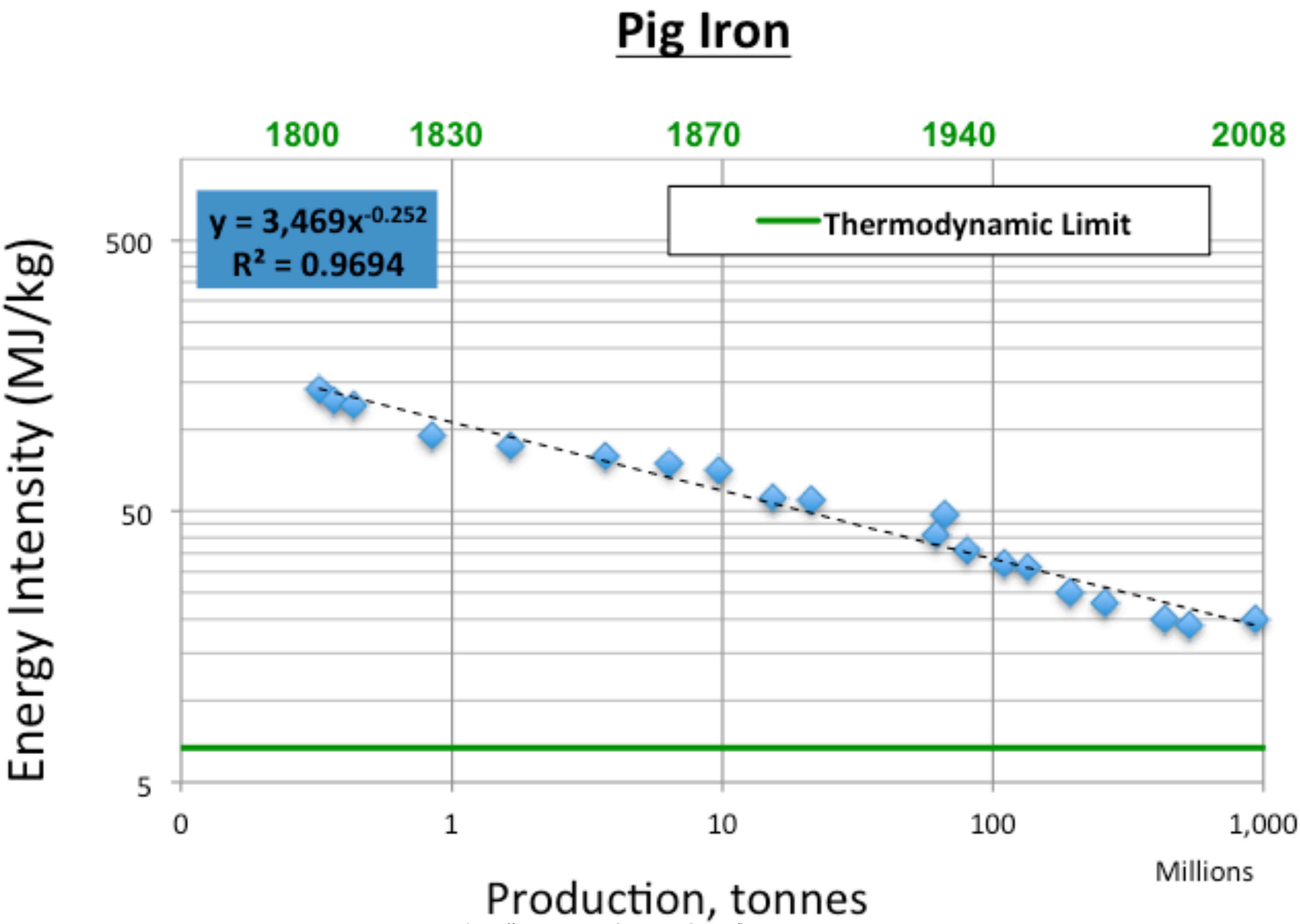
[35] J. M. Allwood and J. M. Cullen, *Sustainable Materials - With Both Eyes Open.* Cambridge UK: UIT Press, 2012.

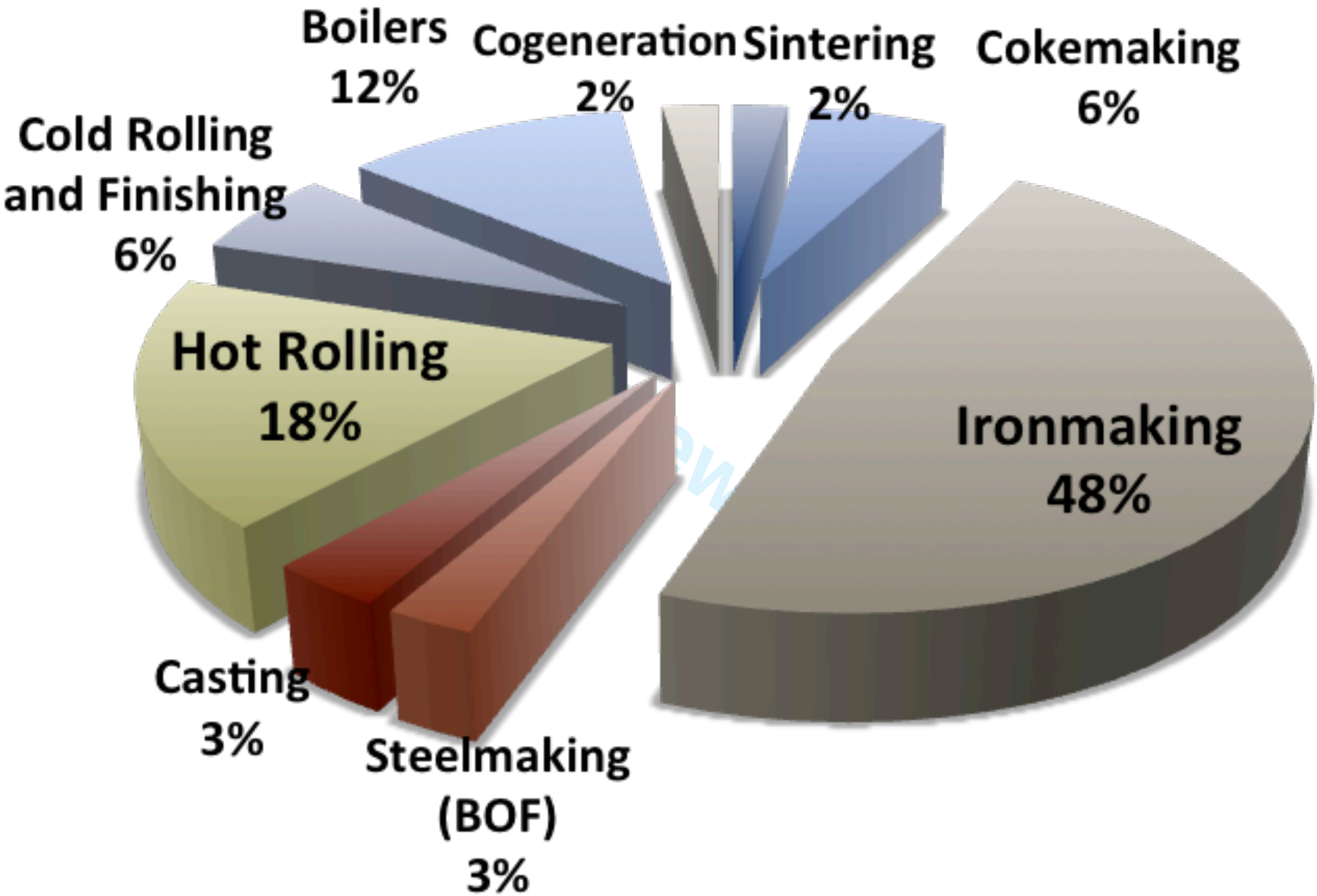

Total Energy (PJ)
25,000
20,000
15,000
10,000
5,000
0
100%
80%
60%
40%
20%
0%
Steel
Concrete
Paper and Cardboard
Al alloys
Polyester
PVC
PP
PE
Ti
Butyl Rubber
Glass
Phenolics
Cu Alloys
Zn
Natural Rubber
PS
Wood
PET
ABS
PA
Mg
Stainless Steel
Au
Ni
Brick
Pb
Alumina
Ag
Platinum
Silicon
Palladium

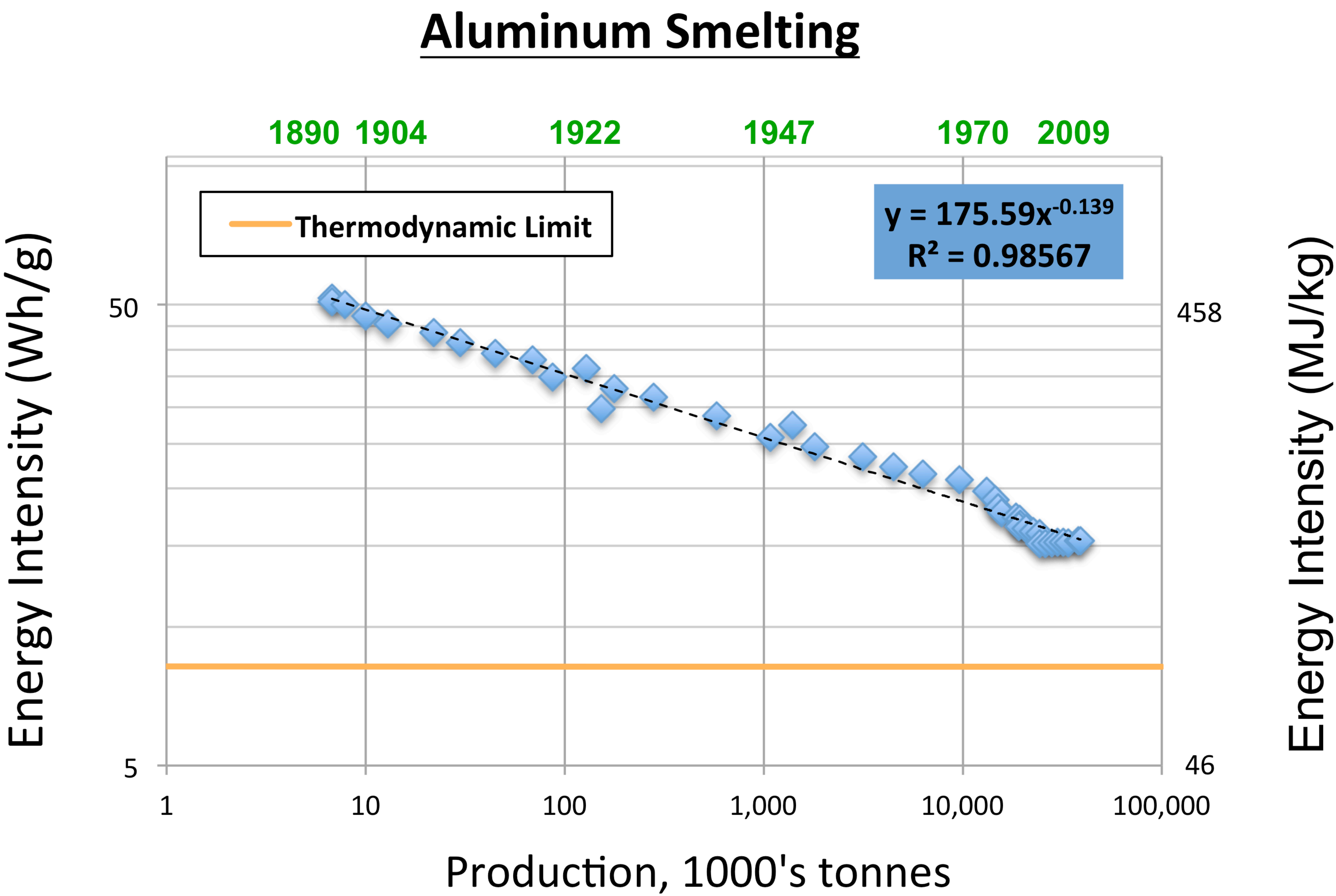

y = 0.0687x^0.988
R² = 0.9819
Carbon Footprint (kg/kg)
100,000
10,000
1,000
100
10
1
0.1
0.01
Embodied Energy (MJ/kg)
0.1
1
10
100
1,000
10,000
100,000
1,000,000
Pt
Au
Pd
Ag
Ti
Mg
Ni
Zn
Al
Cu
Alumina
S. Steel
Pb
Paper
Plastics
Steel
Rubber
Glass
Brick
Wood
Concrete

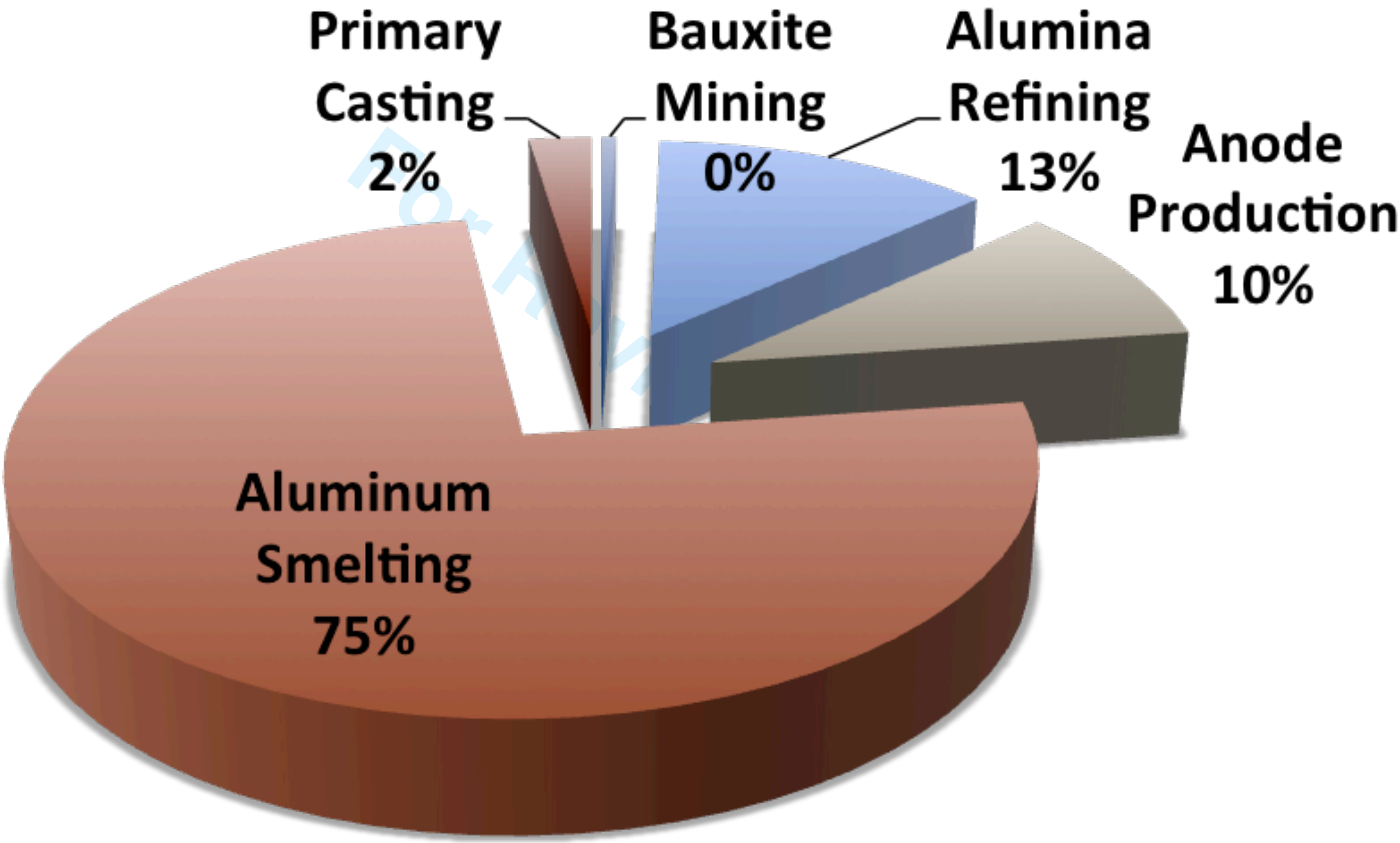


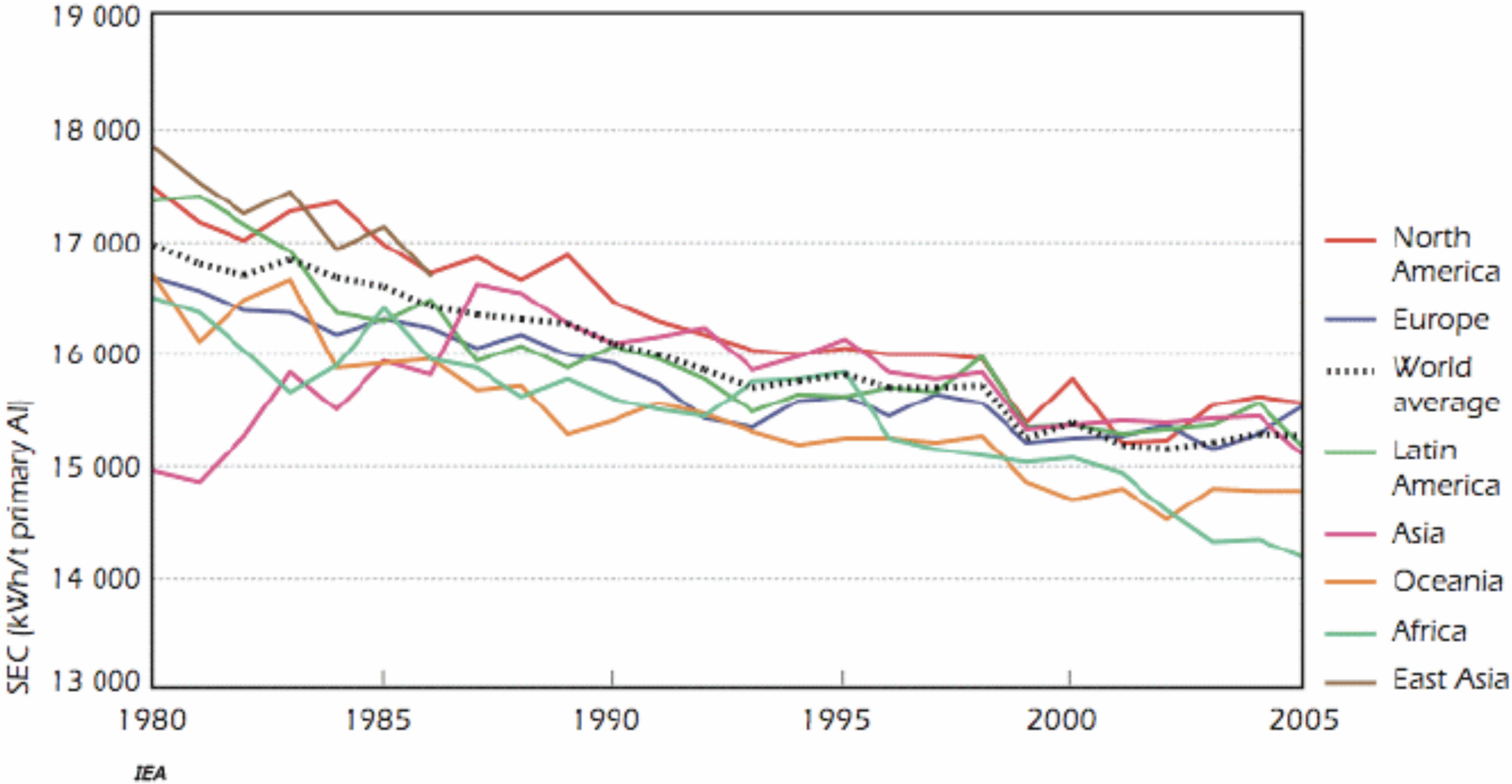
Embodied Energy (MJ/kg)
1.E+06
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
Dilution (1/c) (kg ore/kg metal)
Pt
Au
Pd
Ag
Ti
W
Mo
Al
Ni
Hg
Zn
Cr
Cu
Mn
Pb
Fe

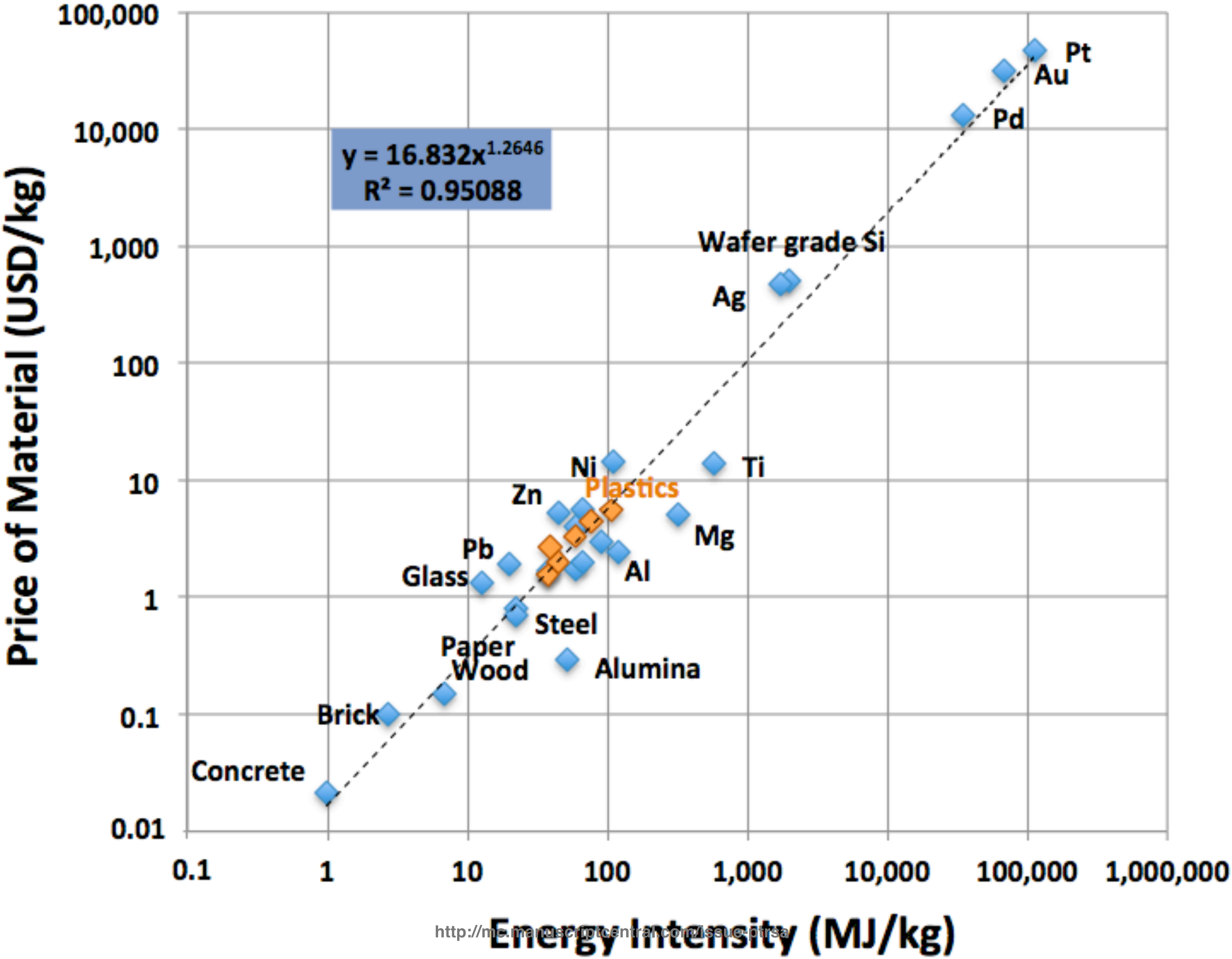

Pig Iron
1800
1830
1870
1940
2008
y = 3,469x-0.252
R2 = 0.9694
Thermodynamic Limit
Energy Intensity (MJ/kg)
500
50
5
0
1
10
100
1,000
Millions
Production, tonnes


Boilers
12%
Cogeneration
2%
Sintering
2%
Cokemaking
6%
Cold Rolling
and Finishing
6%
Hot Rolling
18%
Ironmaking
48%
Casting
3%
Steelmaking
(BOF)
3%

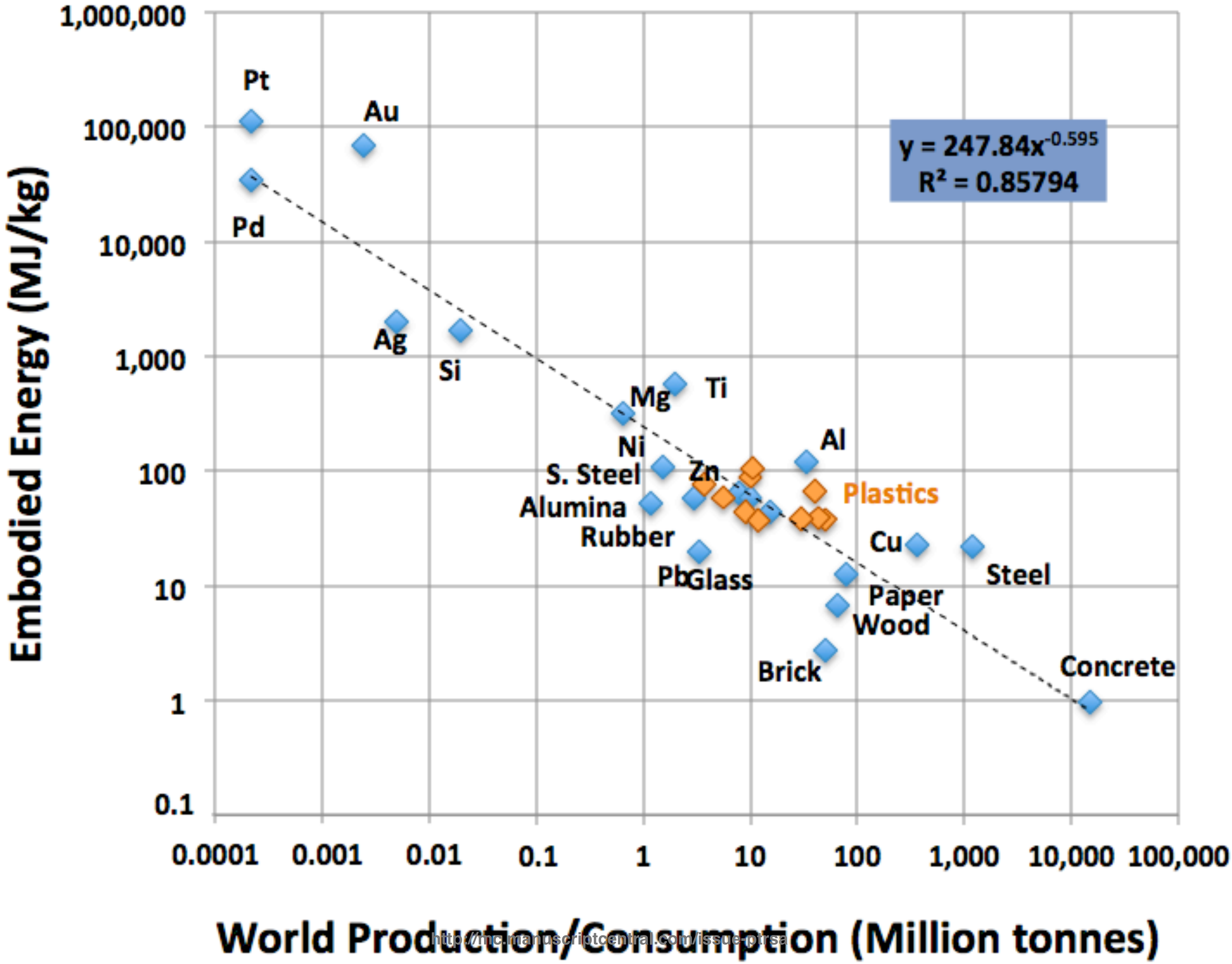

Aluminum Smelting
1890
1904
1922
1947
1970
2009
Thermodynamic Limit
y = 175.59x^-0.139
R² = 0.98567
50
5
458
46
1
10
100
1,000
10,000
100,000
Energy Intensity (Wh/g)
Energy Intensity (MJ/kg)
Production, 1000's tonnes


Primary Casting 2%
Bauxite Mining 0%
Alumina Refining 13%
Anode Production 10%
Aluminum Smelting 75%

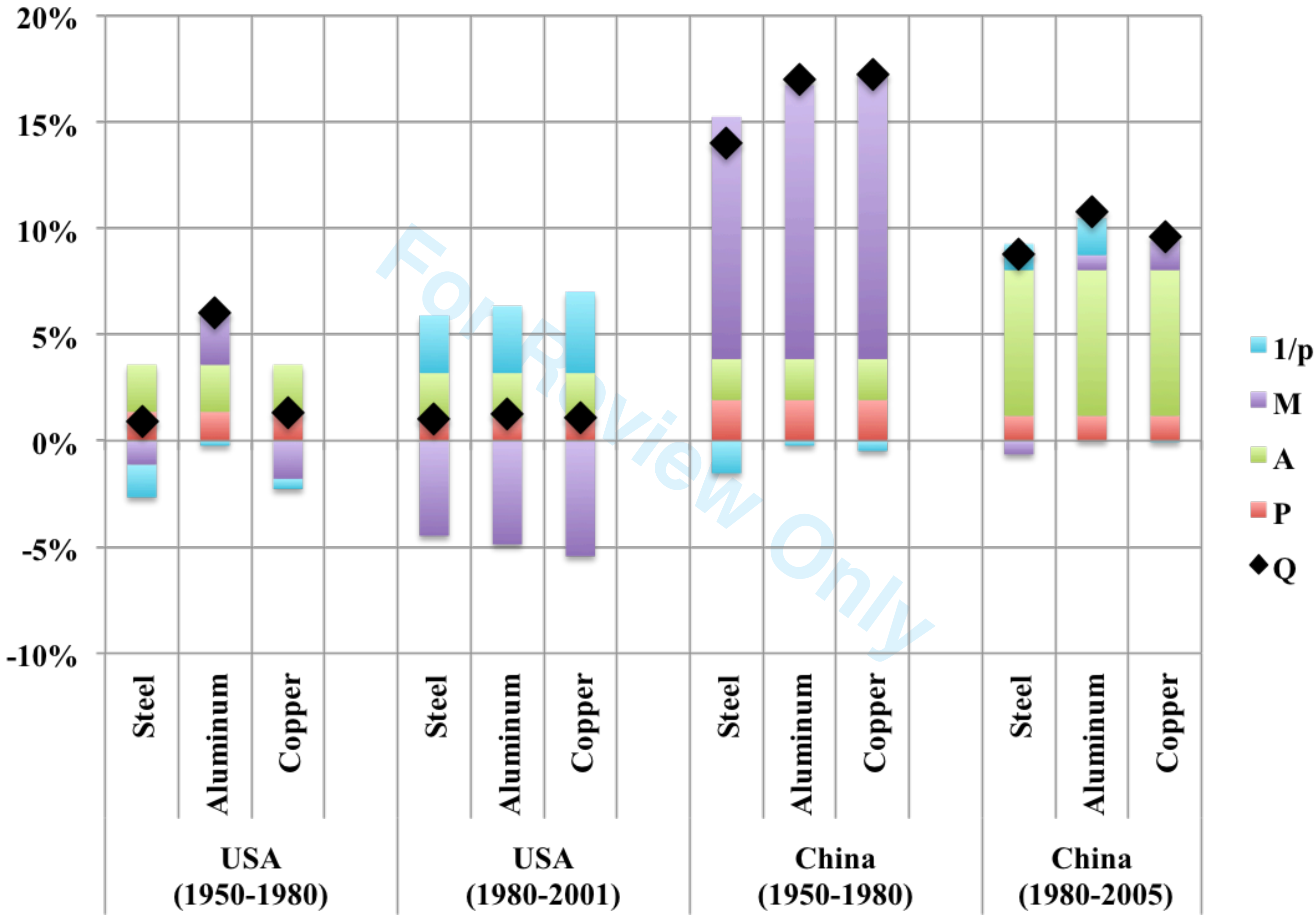

19 000
18 000
17 000
16 000
15 000
14 000
13 000
SEC (kWh/t primary Al)
1980
1985
1990
1995
2000
2005
North America
Europe
World average
Latin America
Asia
Oceania
Africa
East Asia
IEA



y = 16.832x^1.2646
R² = 0.95088
Pt
Au
Pd
Wafer grade Si
Ag
Ni
Ti
Plastics
Zn
Mg
Pb
Al
Glass
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
Price of Material (USD/kg)
Energy Intensity (MJ/kg)


Embodied Energy (MJ/kg)
1,000,000
100,000
10,000
1,000
100
10
1
0.1
Pt
Au
Pd
Ag
Si
Mg
Ti
Ni
Al
S. Steel
Zn
Plastics
Alumina
Rubber
Cu
Steel
Pb
Glass
Paper
Wood
Brick
Concrete
y = 247.84x^-0.595
R² = 0.85794
0.0001
0.001
0.01
0.1
1
10
100
1,000
10,000
100,000
World Production/Consumption (Million tonnes)

Region (Time)	Material	Q	P	A	M	1/p
USA (1950-1980)	*Steel*	0.9%	1.4%	2.2%	-1.1%	-1.5%
	Aluminum	6.0%	1.4%	2.2%	2.6%	-0.2%
	Copper	1.3%	1.4%	2.2%	-1.8%	-0.5%
USA (1980-2001)	*Steel*	1.0%	1.1%	2.1%	-4.5%	2.7%
	Aluminum	1.3%	1.1%	2.1%	-4.9%	3.2%
	Copper	1.1%	1.1%	2.1%	-5.4%	3.8%
China (1950-1980)	*Steel*	8.2%	1.8%	2.3%	5.5%	-1.5%
	Aluminum	8.5%	1.8%	2.3%	4.5%	-0.2%
	Copper	10.4%	1.8%	2.3%	6.5%	-0.5%
China (1980-2005)	*Steel*	8.3%	1.2%	8.6%	-2.6%	1.2%
	Aluminum	9.7%	1.2%	8.6%	-1.8%	1.7%
	Copper	8.6%	1.2%	8.6%	-1.1%	0.0%


20%
15%
10%
5%
0%
-5%
-10%
Steel
Aluminum
Copper
Steel
Aluminum
Copper
Steel
Aluminum
Copper
Steel
Aluminum
Copper
USA (1950-1980)
USA (1980-2001)
China (1950-1980)
China (1980-2005)
1/p
M
A
P
Q