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The Carbon and Energy Intensity of Manufacturing

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1. INTRODUCTION

As concerns about global warming grow, increased attention will be focused on those economic activities which disproportionately consume energy and emit carbon to the atmosphere. In this paper we review the carbon and energy intensity of manufacturing activities. Current estimates are that human activities contribute about 7GtC/yr to the atmosphere[1]. The developed world with only 15% of the population contributes disproportionately to this figure, using on the order of 50% of world energy, and emitting on the order of 50% of the carbon. Of this 3.5 GtC/yr, direct use in the manufacturing sector generally accounts for between 25 to 45% [Greening 1998]. Including indirect energy use, as well as the growing contribution from the developing world, we can estimate that worldwide, manufacturing contributes at least 2 GtC/year. This does not include energy and emissions during the use phase of the manufactured products except for those related to the manufacturing sector. For example, in the United States the primary energy end use activities are usually represented as 1) residential and commercial (40%), 2) industrial (30%), and 3) transportation (30%) [LLNL 2002]. Direct manufacturing energy use corresponds to 80% of industrial use, resulting in approximately 24% of primary energy[2] use in the U.S. [DOE 1999a]. However, when commercial use and transportation that are related to manufacturing are also added, manufacturing use of energy in the U.S. grows to 50% of the total. In terms of the two major economic sectors in the United States (manufacturing and services), an input/output analysis that includes both direct and indirect energy use shows that manufacturing is 2 to 3 times more carbon and energy intensive than services, i.e. 1150 g CO_2 E/$ Vs 580 g CO_2 E/$, and 21.4 MJ/$ Vs 6.8 MJ/$. [Hendrickson et al 2006]. Similar results can be obtained in other developed countries. Within the manufacturing sector, energy intensity (energy per unit of economic activity) can vary by two orders of magnitude, with the highest intensities for those sectors producing fuels (petroleum and coal) and primary materials such as paper products, cement, chemicals and metals [DOE 1999b]. As a result, it can frequently be the case that the largest energy and carbon load for fabricated products is associated with the materials used in the product and not necessarily with the manufacturing processes per se [Gutowski 2007].

Additional insight can be gained by disaggregating our current anthropogenic carbon emissions in terms of four components: population, GDP per population, energy per GDP and carbon per energy. We will refer to these four components respectively as 1) population, 2) affluence, 3) energy intensity and 4) carbon intensity. This is shown as a mathematical identity in equation 1.1.

Writing this equation in differential form and looking at recent historical trends enables us to identify how these components contribute to our current increase of 1.5% a year in global carbon emissions. This is shown below, using approximations estimated from the data of Pacala and Socolow 2004.

$$\text{Carbon} = \text{Population} \times \frac{\text{GDP}}{\text{Pop}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\mathit{Carbon}}{\mathit{Energy}} \qquad (1.1)$$

$$\frac{?\text{Carbon}}{\text{Carbon}} = \ +1\% \qquad +2\% \quad -1.25\% \quad -0.25\% \ = \ +1.5\%$$

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[1] 7GtC = 7 x 10^9 metric tons of carbon

[2] "primary" energy goes back to sources such as coal, oil and nuclear, hence electricity is considered a "carrier" that relies on primary energy.

These results reveal that while we are improving in terms of both of the “technology” terms i.e. energy intensity and carbon intensity, these are offset by the “growth” terms i.e. population and affluence. The goal to improve technology to the point where it can offset growth is not quite as simple as it may seem because of potential feedback effects [Herring 1998].

2. STRATEGIES FOR MANUFACTURING FIRMS TO REDUCE THEIR CARBON FOOTPRINT

There are a variety of strategies both technical and practical by which manufacturing firms can reduce their carbon footprint. In the remainder of this paper we will outline four strategies and go into more detail concerning the energy and carbon intensity for specific manufacturing systems and processes.

2.1 Manufacturing versus Services

Our previous statistics show that the services sector of the U.S. economy has approximately ½ the carbon intensity of the manufacturing sector in terms of carbon per economic output i.e. (160gC/$ Vs 310gC/$). Therefore it appears that one approach to decarbonizing a company is to sell more services than manufactured items. This topic has many variations. For a manufacturing firm, this could mean selling the product imbedded into a service. In other words, instead of selling automobiles, one would sell transportation, or instead of selling copying machines, one would sell copying services. Such an approach was used by Xerox who retained ownership of their copying machines and set up a system for reusing and remanufacturing equipment components, thereby reducing material and energy requirements for manufacturing. This strategy can also provide periodic opportunities to improve the energy efficiency of the equipment during the use phase. Other company examples are Caterpillar, who remanufactures used equipment, and Interface Carpets who sells floor covering services. Note that the ultimate benefits of this approach would require a case by case analysis that would include not only the company’s behavior, but also potential changes in the behavior of customers and competitors.

2.2 Decarbonize Fuels

A second strategy for reducing the carbon footprint of a manufacturing firm is to focus on the carbon intensity of the fuels used. Carbon emissions from carbon based fuels can be calculated directly from stoichiometric balances. Table 2.1 gives the carbon emissions per MJ of fuel used for four common fuels and for electricity from the U.S. Grid.

Table 2.1. Carbon Intensity of Common Fuels and for the U.S. Electric Grid

Energy Source	**Carbon Intensity gC/MJ**
Coal (carbon)	30
Oil (0.856 g C/g Oil)	20
U.S. electrical grid	18
Gasoline (octane)	18.5
Natural Gas (methane)	15

Notice that coal is twice as carbon intensive as natural gas. The U.S. grid which uses a mix of fuels including 50% coal, 20% natural gas, 20% nuclear and 7% hydro results in approximately 18 grams of carbon per MJ of primary fuel used. Change in the energy fuel source often implies a large capital investment or changing a supplier. Changes in location also affect the carbon intensity of energy used. For example, while the U.S., U.K. and Germany all have fairly high carbon intensities, France which relies on 78% nuclear and 14% hydro emits only a few grams carbon per MJ of energy used, while Norway which relies on 99% hydro may emit even less[3].

2.3 Invest in Carbon Offsets

In carbon trading schemes, it is often possible to offset one's carbon footprint by investing in carbon sequestration projects such as planting trees or managing land use. An alternative is to invest in projects which directly displace carbon emissions, such as helping to finance solar collectors to replace diesel powered boilers. This is a popular strategy in certain segments of society, for example travel companies often provide this service for their environmentally conscious travelers. There are a variety of web sites one can consult to learn about these investment options as well as methods for certifying that the carbon emissions are actually offset. These include carbonoffsets.org, the "Climate Biz" web site and carbonneutral.com. Manufacturers however, are in a different position. They often have the opportunity to invest in technology in their own factories. Examples would be wind power, solar/thermal, photovoltaics, improved insulation on furnaces, new energy efficient technology, etc.

2.4 Increase Energy Efficiency

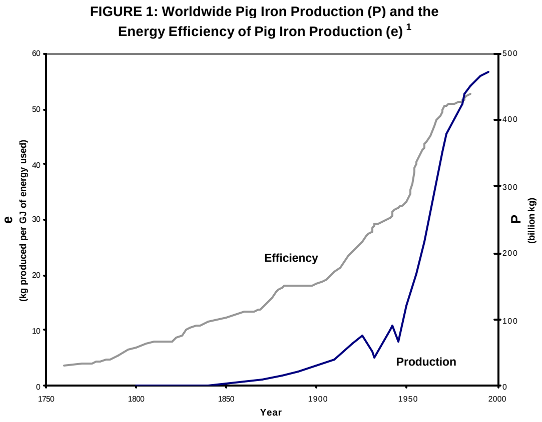

Figure 2.1. Worldwide Pig Iron Production (P) and the Energy Efficiency of Pig Iron Production (e)[1]

Increasing energy efficiency can come in two forms, 1) good housekeeping, and 2) technical solutions. Good housekeeping includes items such as turning off the lights, insulating the furnace, and fixing leaks in the compressed air lines. Providing new technology to improve the efficiency of the manufacturing process or system is what engineers do, and have been doing for a long time. In fact, on average manufacturing appears to improve it's energy efficiency by at least one to two percent per year. This happens even during times of declining energy prices. Figure 2.1 shows the historical record for world-wide pig iron production in terms of kg of pig iron produced per GJ of energy used and yearly production in terms of 10^9 kg = 1 Tg produced per year. The efficiency improvements shown here average just over 1% per year for the 184 years covered [Dahmus 2007].

The theoretical limit for producing iron from ore is around 149kg/GJ so there is still room for significant improvements, however as this limit is approached progress will slow. The second law efficiency of other metal producing sectors in the United States are listed below in Table 2.2 in terms of the exergy of the pure metal divided by the exergy of the inputs per kg of metal out. [Masini & Ayres 2000].

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[3] Note that nuclear and hydro are not carbon free. Fuel processing, land use changes and the decomposition of flooded vegetation all affect the carbon cycle.

Table 2.2. Exergy and Efficiency for Four Metal Sectors in the U.S.

Metal	$\underline{B}^{o}$**(MJ/kg)**	B_{in}**(MJ/kg)**	$\underline{B}^{o}$ / B_{in}	**Ore grade (percent)**
Steel	6.7(Fe)	34.2	20%	Ore 53% + scrap 93%
Aluminum	32.9	346.5	10%	26% Alu (bauxite)
Copper	2.1	203.7	1%	0.6%
Zinc	5.2	252	2%	9%

The low efficiencies for copper (1%) and zinc (2%) can be explained in part due to the low metal concentrations in the ores. The low efficiency for aluminum (10%) can be explained in part due to the low efficiency (on the order of 30%) for the production of electricity.

The efficiencies of conventional manufacturing processes are in the single digits. For example the Second Law efficiencies of metal machining, metal casting and polymer injection molding usually range from 3 – 7%. Strategies to improve these processes include, for example, changing hydraulic controls to electric. This has had a significant impact on the controls in machine tools, and is currently a very effective way to reduce the energy required for injection molding, particularly for small tonnage machines. In casting, the energy efficiency of the melting process depends upon the technology and its age, as well as the boundaries of the analysis. For example, at the foundry, electric induction melting looks efficient, but when the losses at the utility are included, the cupola usually looks better.

We have collected data on a large number of manufacturing processes and have plotted their electrical energy requirements per kilogram of material processed as a function of the process rate in Figure 2.2 [Gutowski 2006]. The figure shows that the energy intensity and hence the carbon intensity of manufacturing processes varies by about seven orders of magnitude. The most efficient processes per unit of material processed are conventional processes such as casting, machining and injection molding. In the middle are the “advanced” machining processes such as wire EDM, grinding, abrasive water jet and finish machining. At the high end are primarily the vapor phase processes associated with microelectronics fabrication. Going from lower right to upper left also represents a chronological progression in process development. Hence the newer processes have had less time to improve their efficiencies with time. Similarly the high intensity processes process considerably smaller quantities of materials and are used on higher value added products making them economically viable. Never the less, when carbon is taxed, these processes will need to significantly improve.

Before leaving this topic, it is necessary to point out that efficiency gains at the process level do not necessarily result in absolute reductions at the factory or enterprise level. This is because efficiency and growth are coupled phenomena. Generally speaking, efficiency should be accompanied by changes in prices and/or policies to result in real reductions [Herring 1998, Dahmus 2007].

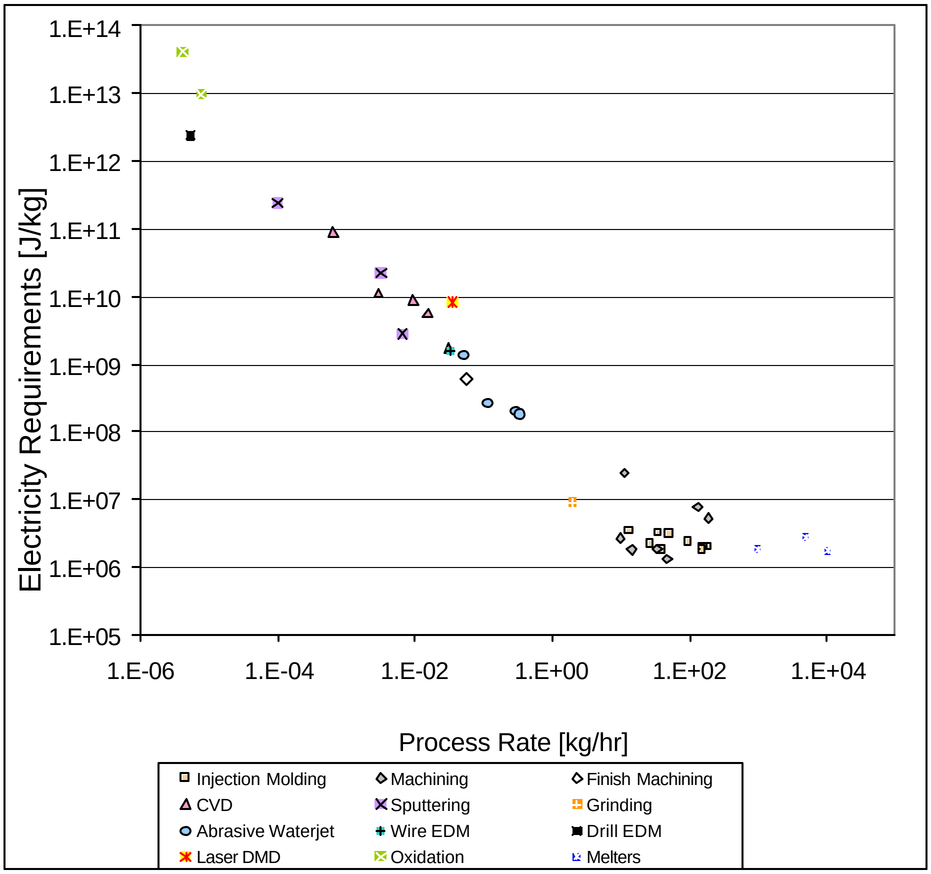

Figure 2.2. The Electrical Energy per Unit of Material Processed Vs Process Rate for 12 Manufacturing Processes. [Gutowski, 2006]

3. MEASURING THE ENERGY/CARBON ASSOCIATED WITH A PRODUCT

A summary of the energy or carbon associated with a product can be presented by stage in its life cycle. For example, Sullivan et al 1998 presented an energy summary for a late 1990's era (1532 kg) U.S. family sedan assuming the vehicle traveled 120,000 miles at 23 mpg over a 10 year life. The results are; Materials Production 95 GJ (10%), Manufacturing 40GJ (4%), Use phase 820 GJ (85%), Maintenance, Repair and End of Life 19 GJ (1%). For this product the Use phase dominates and the primary carbon responsibility of the manufacturer would be to design a car with higher fuel efficiency. The next highest category would be Materials and Manufacturing which together constitute 14% of the total. A second example is a late 1990's era desktop computer (24 kg) with a three year life. In this case, the maximum energy stage over the life of the computer shifts to Materials and Manufacturing, which together use about 6.4 GJ (80%) of the total. The second highest category for the computer would be the Use phase with 1.5 GJ (20%) [Williams 2004]. This shift occurs because semiconductor processing is very energy intensive and computers have relatively short lives in the Use phase.

These examples demonstrate how the carbon load associated with a product may shift to different phases of its life cycle depending upon characteristics of the product and how it is used. Drawing large system boundaries for carbon analysis is necessary to track down all of the different contributions. However, it leads to problems when allocating responsibility for these different contributions. A product manufacturer may claim that the carbon associated with materials manufacturing should reside with the materials manufacturer. Similarly a manufacturer may claim that customers do not show a preference for high fuel efficient vehicles. Problems of this sort would be most likely solved by policy and regulation. For example, carbon taxes would increase the cost of materials and fuel, which will influence the behavior of the customers and the manufacturers. Overall, because of its broad influence over materials selection and product and process design, manufacturing will play a central role in any scheme to reduce global carbon emissions. As this plays out, some companies will find new and profitable opportunities, while some will struggle to address this issue. In either case, a good first step in meeting this challenge would be to understand your carbon footprint.

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