CARBON DIOXIDE INTENSITY RATIOS:
A Method of Evaluating the Upstream Global Warming Impact of Long-Life Building Materials

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ABSTRACT

A carbon dioxide intensity ratio (CDIR) is defined here as the ratio between the net upstream CO_2 impact (emissions minus storage) of a material and the weight of the material. A material with a positive CDIR is a net CO_2 source and one with a negative CDIR is a net CO_2 sink.

The CDIRs indicate that metal, synthetic organic, and ceramic building materials are net sources of CO_2 emissions and that some natural organic or biomass materials are net CO_2 sinks. This is due to the capacity of biomass materials to absorb CO_2 and transform it to carbon in the mass of the material. The relative impacts of one material compared with another in terms of CO_2 released or absorbed is information that is relevant to assessing the upstream global warming impact of building materials and products.

1. INTRODUCTION

The countries that participated in the United Nations Framework Convention on Climate Change (UNFCCC) in Kyoto, Japan in December, 1997 jointly drafted an international agreement concerning global warming known as the Kyoto Protocol. Countries that approve the document agree to reduce six categories of greenhouse gas (GHG) emissions. The countries of the European Union agreed to an 8% reduction in total GHG emissions by 2012 compared with emissions of the reference year (1990 or 1995 depending on the GHG). The United States delegation agreed (in principle) to a similar goal: a 7% reduction of total GHG emissions compared to the appropriate reference year. Consequently, GHG reduction has recently become a highly visible political topic in many industrialized countries, including the U. S.

As in most industrialized countries, the most significant greenhouse gas emitted in the U.S. is carbon dioxide (CO_2), accounting for 80-85% by volume of the total global warming potential of all U. S. greenhouse gases. The industrial sector of the U.S. economy accounts for about one-third of national end-use CO_2 emissions. Aside from electric utilities, whose purpose it is to produce electric power for the rest of the economy, the top-ranked manufacturing industry of the industrial sector in terms of the total impact of upstream CO_2 emissions is the building industry, including new, maintenance, repair, and remodeling construction.

Industrial processes release CO_2 in two ways; by the combustion of fossil fuels and by the physical or chemical transformation of materials. A vast majority (98%) of CO_2 emissions resulting from the production of building materials is caused by fossil fuel combustion occurring during the upstream (i.e., pre-use) life cycle stages – raw material acquisition, transport, material or product manufacture, and distribution. Only a small fraction of the building industry's total (2%) results from upstream physical and chemical material transformation processes (e.g., the chemical reactions of cement production).

Some building materials (and wastes), both synthetic and natural, can function as sinks for CO_2. For example, biomass materials, such as wood, may contain as much as 53% carbon (by weight) in their material content. If significant amounts of carbon from atmospheric CO_2 can be stored semi-permanently in certain building materials, then perhaps some of these materials can be considered to be net CO_2 sinks. A net CO_2 sink is a material which contains an amount of carbon in its mass greater than the equivalent amount of CO_2 released during the upstream stages of the material's life cycle.

To date, most efforts to reduce GHG emissions during a building's useful life are focused on the energy consumption required to operate and maintain a building. Numerous energy efficiency measures that significantly reduce energy consumption during a building's use, operation, and maintenance (e.g., energy-efficient lighting) have been widely accepted and implemented by design professionals and the building industry. However, the use phase represents only one chapter in the building life-cycle story. The processing and manufacture of building materials cause enormous off-site impacts prior to the building's use. These impacts occur upstream during the source (raw material acquisition), transport, process (manufacturing), and distribution life cycle stages. Consider the building industry's share of total upstream CO_2 emissions for all sectors of the U.S. economy:

- It's the largest sector accounting for roughly 20% of total annual industrial emissions and 7% of the U.S. annual total.
- Upstream CO_2 emissions are roughly 5 times greater than direct emissions (for construction of the building) and 10-20 times greater than the annual operation (use) of the building.
- Within the building industry, the largest single material or product contributing to CO_2 emissions is portland cement-based ready-mix concrete (9%).

Looking at figures like these, it is evident that the practices of the building design and construction industry play a significant role in releasing GHGs, especially CO_2 emissions. With a potential crisis fast approaching and the likelihood of environmental impact methods being imposed through legislation and regulation, now is the time for the building industry professionals to become leaders rather than followers in developing new approaches to the design of the built environment. One objective of deriving a CDIR for the most commonly used building materials and products is to propose a building-industry response to the Kyoto Protocol by identifying and selecting renewable materials that are potentially net sinks of carbon. Namely, if the carbon from CO_2 "stored" in the building's materials is equal to or greater than the total carbon released as CO_2 during the upstream life cycle stages of the materials, then the useful life of the building may have "zero impact" on CO_2 contribution to global warming. The goal of alleviating the global greenhouse effect, however small, may be feasible.

2. MATERIAL FLOWS, HYDROCARBONS, AND CO_2 EMISSIONS

The use of hydrocarbons in life cycle of the production of materials is a major source and sink of CO_2. There are two types of hydrocarbons, fossil fuels and biomass . The conversion of fossil fuels to energy, usually by combustion, releases CO_2 into the atmosphere. Renewable biomass, such as a managed forest, absorbs atmospheric CO_2 and, as a consequence, its combustion results in no net CO_2 emissions. The exception is the use of non-renewable biomass, such as tropical hardwoods, which does result in net CO_2 emissions.

Fossil fuels and biomass can be used as energy sources and as feedstocks, the raw materials of production. When used as energy sources, they are converted directly into CO_2 emissions. When used as feedstocks, they are incorporated into materials or products. Depending on their life cycle characteristics, carbon-containing materials can be divided into short-life and long-life types. Short-life materials, such as detergents and fertilizers, are easily dissipated and subsequently quickly converted into CO_2. Long-life materials, such as plastics and wood, can potentially last for decades or centuries. As the consumption of materials increases, these materials are stored in the increasing product stock, as well as in waste disposal sites.

3. METHODOLOGY

In order to define which materials are CO_2 sources and which are CO_2 sinks, the life cycle of the material must be analyzed. The general methodology relies on an accurate portrayal of two industrial processes occurring during the upstream life cycle stages of each material: the embodied energy used (i.e. fossil fuel consumption) and the physical and/or chemical processes utilized to transform materials. The data can be provided in terms of a) national use and production database per time period (usually annual) for a particular industrial process or b) in terms of energy consumption figures from a specific manufacturer for a specific material for a specific period of time. In the former case, assuming that both the fuel source and production technology are consistent within a particular industrial sector, the following data is required:

- the energy supply fuel source and quantity per unit weight for raw material acquisition and transport to all processing facilities of a particular industrial sector;
- the quantity of material produced by that industrial sector (e.g., steel) per unit weight per year (gross), or the quantity of material actually reaching the national building sector end use stage per unit weight per year (gross – exports = net);

- the amount of carbon stored (if any) per unit of material;
- the energy supply fuel source(s) and the quantity of fuel consumed per year by that particular industrial sector;
- the carbon content of each type of fuel source; and
- the physical/chemical CO_2 emission processes and quantity of emissions per unit of material output.

Some difficulties are inherent in the national database method. When using national figures per annum, emissions resulting from the extraction and transport of imported raw materials may not be accounted for. In addition, there is a difference in embodied energy between materials produced from virgin resources (primary production) and recycled products. The emissions released by producing materials from recycled products are usually lower than for primary production because very often the energy requirements are much lower. It must be clarified whether energy consumption figures are for primary production only or if they include recycling processes.

In the case of a specific material from a specific manufacturer, the same data is needed, but it is probably site-specific. For example, the energy supply fuel source and quantity per unit weight for raw material transport is unique to each processing facility operated by a single manufacturer. Moreover, a particular building material may be processed or manufactured at more than one location, and one manufacturing facility may produce more than one material and not have energy consumption data separated by material. In the former case, it may be easier to collect data from one production facility rather than collect data from all facilities where the material is made. If the energy supply fuel source(s) and production technology is the same at all the facilities that produce the material, then the data from one facility may provide a sufficiently accurate portrayal of CO_2 emissions for the particular material being investigated (with the exception of transportation embodied energy). In the latter case, where more than one material is produced at the same facility, then the percentage (by weight) of the total facility output the particular material represents must be identified.

4. UPSTREAM CO2 INTENSITY RATIO

The carbon dioxide intensity ratio (CDIR) is defined here as the ratio between the net upstream CO_2 impact (emissions minus storage) of a material and the weight of the material. It can be described by the following equation:

$$CDIR = (CO2_e - CO2_s)/\text{material end use weight}$$

where $CO2_e$ = the weight of upstream CO_2 emissions
and
$CO2_s$ = the equivalent weight of CO_2 stored as carbon in the mass of the material

A material with a positive CDIR is a net CO_2 source and one with a negative CDIR is a net CO_2 sink.

The CDIRs for twenty-four common long-life building materials are shown in Figure 1 (at end of paper). Metals are net sources of CO_2. In the case of iron and steel, for every pound used in buildings, roughly two pounds of CO_2 are emitted upstream. Therefore, CO_2 emissions are 2 times greater than the end use weight of steel in buildings and the CDIR is 2. By weight, synthetic organic materials such as polystyrene have a similar impact. Ceramic materials, on the other hand, emit much less CO_2 per unit weight. For every pound of concrete used in buildings, for example, slightly less than 1/50 (0.02) pounds of CO_2 are emitted upstream. Therefore, CO_2 emissions are 1/50 the end use weight of concrete in building and the CDIR is 0.2. By weight, the upstream impact of portland cement is much greater, having a 1.2 CDIR.

Most natural organic building materials and products, such as sawn timber and plywood, are net sinks of CO_2. For example, for every pound of sawn timber, lumber, plywood, or particle board used in a building, the net storage of CO_2 is 1/4–1/2 pound for the life of the building or product. Therefore, these materials have a CDIR of –0.25 to –0.5. This is a very rough approximation, for the actual CO_2 emissions that can be allocated to timber and fiber production vary greatly from region to region and depend on the source (e.g., tropical), management practices, and type of wood (e.g., softwood or hardwood).

5. CONCLUSION

It appears that most metal, synthetic organic, and ceramic building materials are net sources of CO_2 emissions. Only natural organic or biomass building materials appear to be net CO_2 sinks. This seems obvious due to the capacity of biomass materials to absorb carbon dioxide and transform it to carbon in the mass of the material. However, the relative impacts in terms of CO_2 released or absorbed is information that is relevant to addressing the Kyoto Protocol agreement. Consider, for example, the design goal of a CO_2 emission "low-impact" or "balanced" building. The design process would include an analysis of the overall balance between CO_2 source and CO_2 sink materials. Specifications could state CO_2 balancing as a performance criteria for individual products or groups of products and building systems such as exterior closure or structural frame. For example, a reinforced concrete structure may be chosen over an all-steel structure because it achieves a better CO_2 balance, assuming that the volume of steel in the former is less than in the latter.

Two factors can improve the balance of CO_2 source materials; substitution of low CO_2 impact materials for high CO_2 impact materials and the selection of high recycled content materials. The first factor is demonstrated by the use of portland cement substitutes such as fly ash. Portland cement substitutes can significantly reduce the largest component of CO_2 emissions in the life cycle of concrete production. The manufacture of portland cement accounts for about 95% of all CO_2 emissions resulting from the production of concrete. The second factor is demonstrated by the manufacture of recycled content steel. The use of recycled steel can reduce CO_2 emissions if it can be manufactured into structural steel shapes at a lower energetic cost than steel made from virgin raw materials.

The Kyoto Protocol is a challenge to the U. S. building industry that should not be ignored. Every sector of the national economy must contribute to the goal of a 7% reduction of 1990 levels GHGs within the coming decade. Energy efficiency improvements in the production of building materials and the operation and maintenance of buildings will continue to play a significant role. Minimizing the upstream impacts of building materials must also be a part of the GHG reduction strategy. This will require an awareness on the part of building industry professionals of the CO_2 intensity of building materials and a commitment to specify materials that have minimal impact on global warming.

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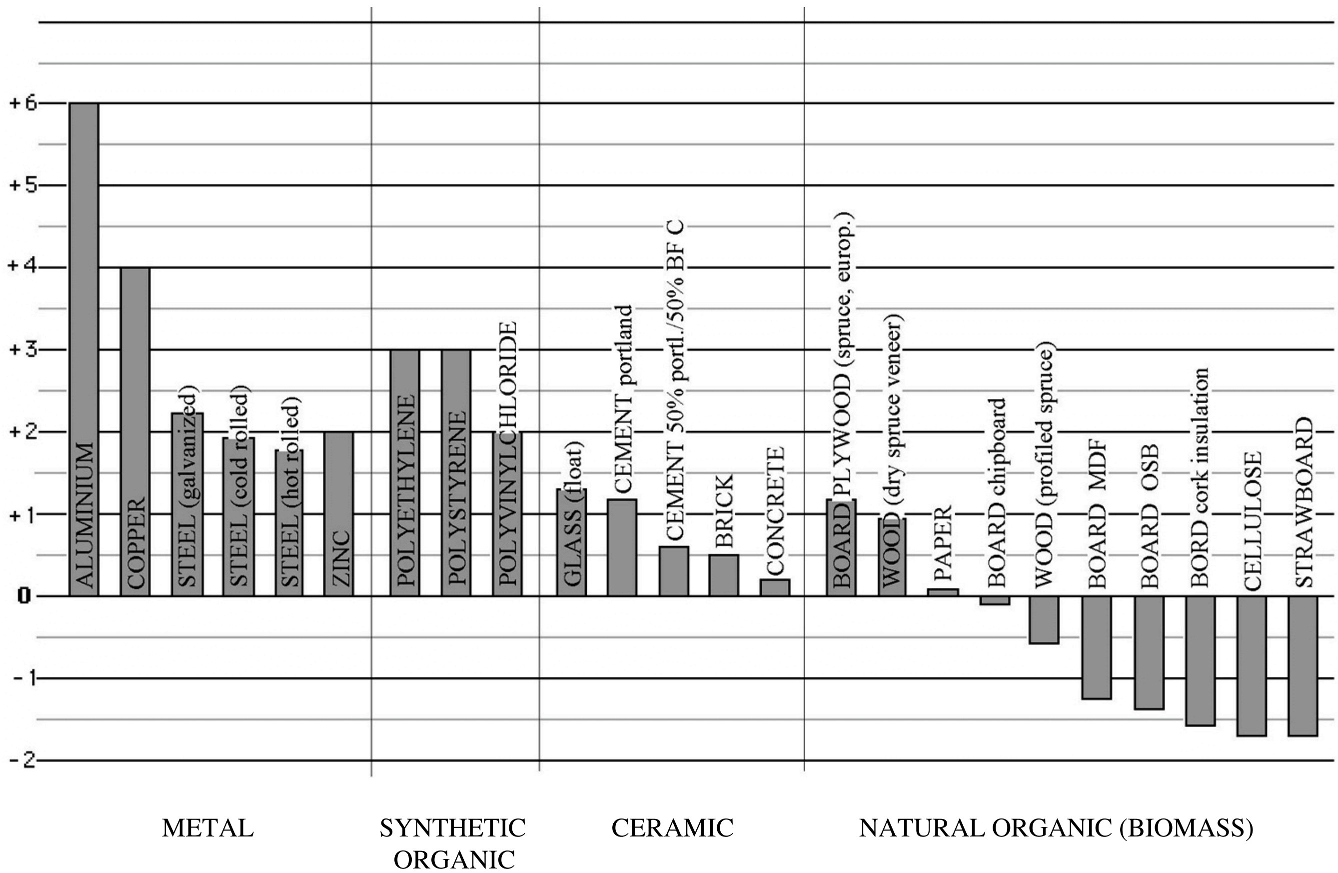

Fig. 1: Carbon Dioxide Intensity Ratios (CDIRs) by weight for twenty-four common building materials. A positive CDIR indicates a net upstream CO_2 source and a negative CDIR indicates a net upstream CO_2 sink. Metals, synthetic organic, and ceramic building materials are net upstream CO_2 sources. For example, aluminum manufacturing emits 6 pounds of CO_2 for every pound of material produced. Some natural organic or biomass materials are net upstream CO_2 sinks. In general, the denser the biomass material, the greater the carbon content and the greater the CO_2 accumulation. For example, medium density fiberboard (MDF) is a net CO_2 sink sequestering CO_2 (and converting it to carbon content) at a ratio of about 1.2 pounds of CO_2 for every pound of product produced.