

Exergy, Life Cycle Assessment and Sustainability

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SUSTAINABLE DEVELOPMENT

**”Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”
Brundtland Report, “Our Common Future,”
United Nations World Commission on
Environment and Development, 1987**

A more recent – and broader – definition is the following (Gilbert, Stevenson, Girardet, Stren, 1996)

The concept of sustainability relates to the maintenance and enhancement of environmental, social and economic resources, in order to meet the needs of current and future generations. The three components of sustainability are:
Environmental sustainability – which requires that natural capital remains intact. This means that the source and sink functions of the environment should not be degraded. Therefore, the extraction of renewable resources should not exceed the rate at which they are renewed, and the absorptive capacity to the environment to assimilate wastes should not be exceeded. Furthermore, the extraction of non-renewable resources should be minimised and should not exceed agreed minimum strategic levels.

Social sustainability – which requires that the cohesion of society and its ability to work towards common goals be maintained. Individual needs, such as those for health and well-being, nutrition, shelter, education and cultural expression should be met.

Economic sustainability – which occurs when development, which moves towards social and environmental sustainability, is financially feasible.

So

KEY FACTORS FOR THIS WORK

Embodied energy – the energy used during its entire life cycle for manufacturing, transporting, using and disposing.

Environmental responsibility – as outlined in Agenda 21 is: *“the responsible and ethical management of products and processes from the point of view of health, safety and environmental aspects. Towards this end, business and industry should increase self-regulation, guided by appropriate codes, charters and initiatives integrated into all elements of business planning and decision-making, and fostering openness and dialogue with employees and the public*

Strategic Environmental Assessment (SEA) – is *“a structured, proactive process to strengthen the role of environmental issues in strategic decision making”* (Tonk and Verheem, 1998). SEA aims to integrate environmental (biophysical, social and economic) considerations into the earliest stages of policy, plan and programme development (Sadler, 1995). It is therefore a process of integrating the concept of sustainability into strategic decision-making.

Whole building – represents a method of designing, equipment and material selection, financing, construction and long-term operation that takes into account the complex nature of buildings and user requirements, and treats the overall building as an integrated system of interacting components

THE BUILDING INDUSTRY

Material consumption

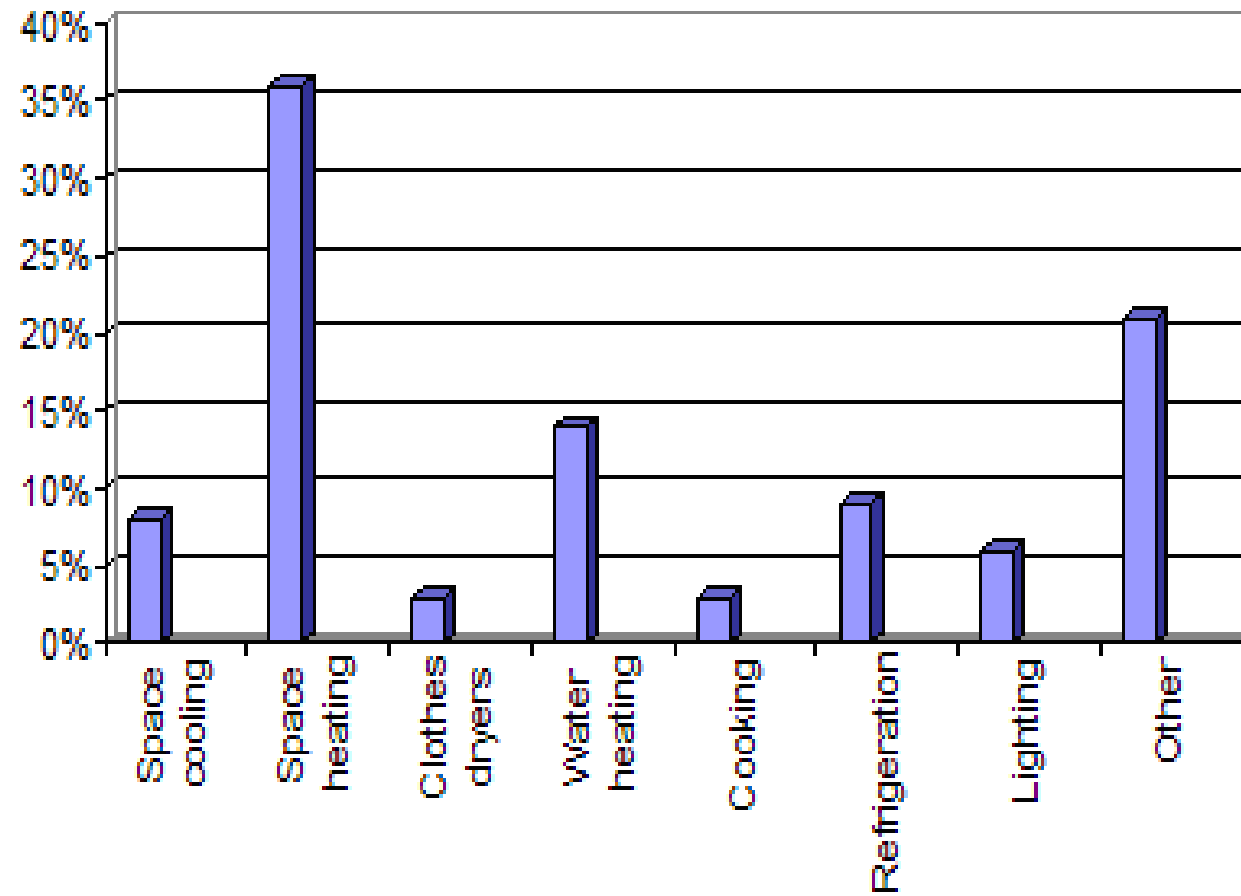
As much as 50 percent of all materials extracted from the earth's crust are transformed into construction materials and products. Issues to be considered go beyond the aesthetic requirement of materials. Consideration must be given to the impact of extraction, manufacturing, transporting, assembling, repairing, disassembling and recycling. The selection and use of material must generate the greatest benefit over the longest time.

Energy

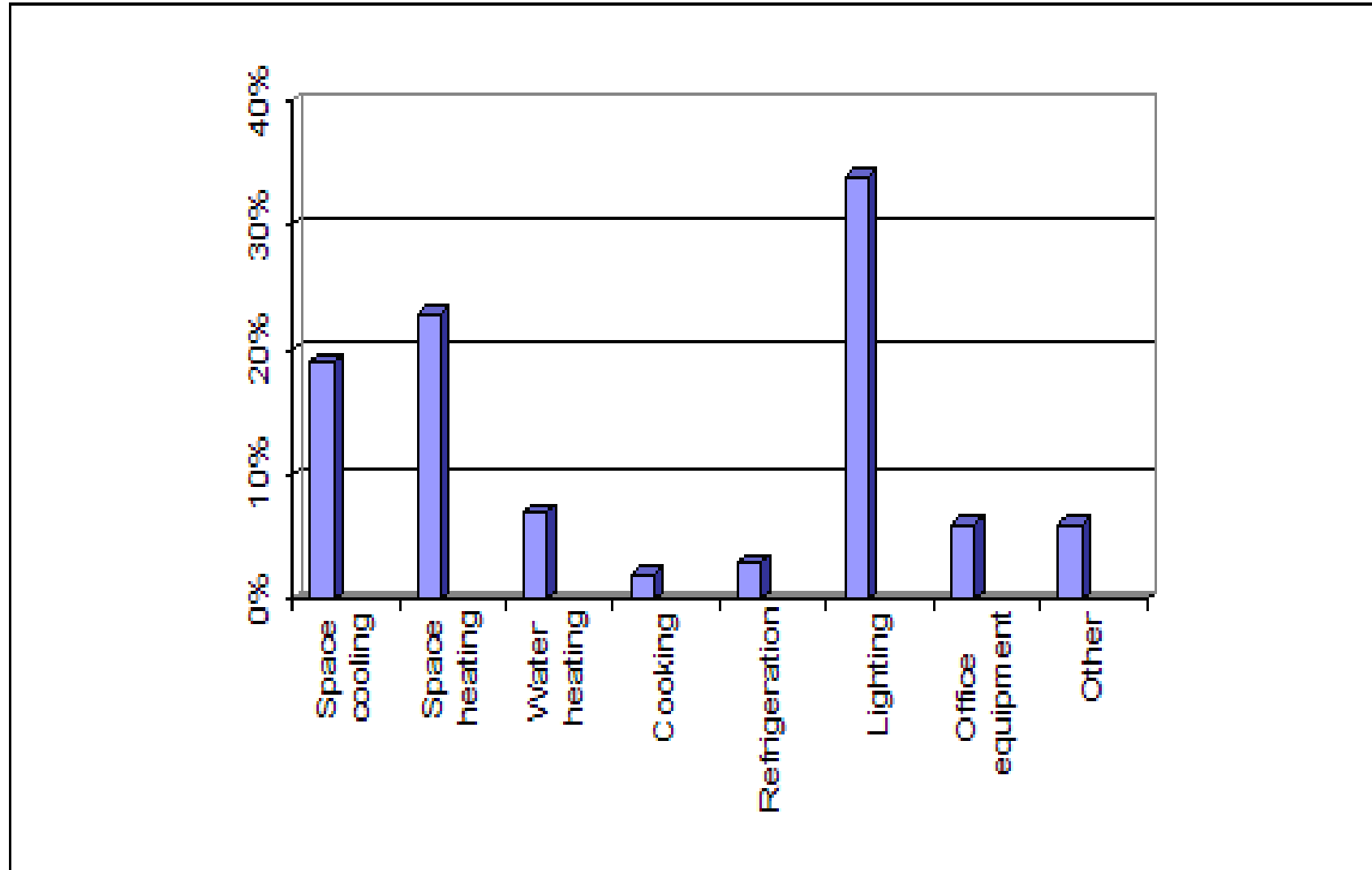
As can be seen from the previous Figure for the USA, buildings in use, including the embodied energy from manufacture, account for almost 40 percent of all energy end-use, a figure consistent with other developed economies.

An analysis of building sector consumption as shown in the following two Figures clearly illustrate the very real opportunities for reducing energy consumption and greenhouse gas emissions that exist through considered design. For example, the energy used for space heating and cooling, water heating and lighting accounts for 64 percent of the energy used.

Residential building energy end-use



Commercial and industrial building energy end-use



Waste generation

Apart from accounting for almost 50 percent of all materials extracted, these same materials constitute some 50 percent of all waste generated prior to recycling or reuse or final disposal. In the United Kingdom, some 70 million tonnes of construction and demolition materials and soil end up as waste. Some 13 million tonnes of that waste is made up of materials delivered to sites and discarded unused. Construction waste has emerged as a larger waste stream than demolition waste and constitutes the largest waste stream by weight in the EU. Disposing of these waste materials is presenting increased difficulties in many parts of the world. Increased emphasis needs to be placed on waste minimisation through the use of such strategies as waste-prevention planning and design, recovery-orientated construction, reparability (design for disassembly and repair in the factory) and recyclables (used products to be returned to their producer) and reuse.

Significant opportunity exists to recycle and reuse construction and demolition waste as aggregates in road construction for sub-base layers in concrete. Several countries are recycling up to 85 percent in this way. The European Parliament has approved a packaging directive that will oblige countries to recycle 55 percent of glass, paper, cardboard, metals and plastics by 31 December 2008. The consequence of this directive is that doorstep recycling will have to be done in every local authority, if not in every household in every country

TOOLS FOR SUSTAINABILITY ASSESSMENT

Two tools I want to distinguish and also try to relate in the search for material and processes that will fit within all the objectives set previously for sustainability.

These are:

EXERGY ANALYSIS

And

LIFE CYCLE ASSESSMENT

EXERGY

Exergy may be regarded as a measure of available energy.

In contrast to energy, exergy is consumed in all real world processes as entropy is produced .

The exergy destruction E is related to the sum of entropy production $\sum\Delta S$ by

$$\delta E = T_0 \sum \Delta S$$

where T_0 is the temperature of the surroundings

The use of **exergy** plays a very significant role in another tool, the Life Cycle Assessment (LCA).

An LCA may be divided into three major components: (i) goal definition and scoping, (ii) inventory analysis, and (iii) impact assessment. The latter can be further divided into three subcomponents:

- (a) classification (different inputs and outputs are assigned to different impact categories based on the expected types of impacts on the environment),
- (b) characterisation (relative contributions of each input and output to its assigned impact categories are assessed and the contributions are aggregated within the impact categories), and
- (c) valuation (relative importance of different environmental impacts from the system are weighted against each other)

Characterisation

The contribution C of an inflow or outflow is

$$C_{ij} = Q_{ij}M_i, (2)$$

where Q is the characterisation weighting factor (contribution per unit of inflow or outflow) and M the amount of inflow or outflow. The subscripts i denote different flows and j different impact categories (or subcategories).

The total contribution to the impact category (or subcategory) is then

$$C_j = \sum C_{ij} (3)$$

For abiotic deposits, there are several approaches for calculating Q .

It may be assumed to be equal to one, calculated from measures of deposits and current consumption , calculated from impacts associated with hypothetical future processes, or calculated from measures of exergy consumption or entropy production.

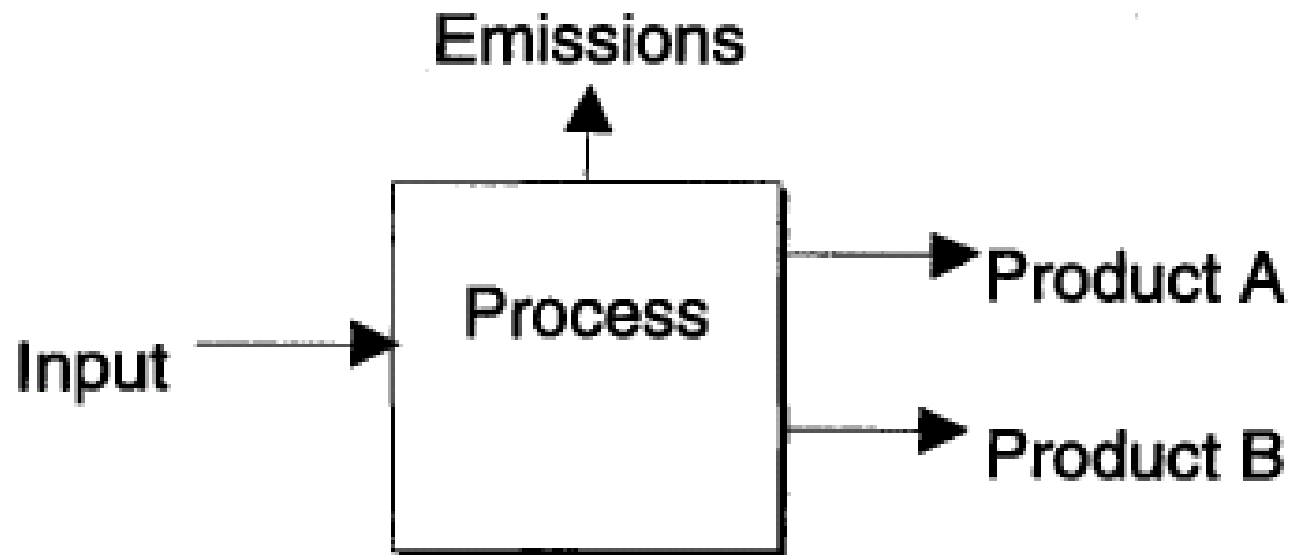
Exergy analysis has several uses in LCA, e.g., as a rough indicator for total environmental impact, or when performing an improvement assessment for identifying losses of useful energy.

Exergy may also be used as a measure of the depletion and use of energy and material resources.

Calculations of exergies of inflows to the system may either be performed in the inventory analysis or as a part of the characterisation.

In the second case , the characterisation weighting factors in Eq. (2) describe the exergy content per amount of inflow.

In the first case, the exergy may be used in the characterisation by adding the exergies of the inputs without any weighting.



However, when the exergies of natural resources have been calculated in societal analyses, or when calculating the cumulative exergy consumption, other system boundaries have been used than those for LCA.

In LCAs, the inputs should be the natural resources as found in the environment whereas in other applications, only parts of the natural resources have been included.

For example, only a specific metal compound in an ore may be included but not the content of the whole ore. Thus, for metal ores and some other resources, new calculations have to be made in order to find LCA-compatible data.

Table 1.

Equations used when calculating exergies of solid materials. Notation: n_i = number of moles of substance i ,
 e_{ch} = partial molar chemical exergy of substance i , R = gas constant,
 a_i = activity of substance i , e_c° = standard partial molar exergy,
 ΔG_i = standard Gibb's free energy of formation of substance i ,
 el = elements in substance i , K_r = equilibrium constant,
 r = reaction in which substance i is produced.

$$E_{ch} = \sum n_i e_{ch,i} + RT_o \sum n_i \ln a_i$$

$$E_{ch} = \sum n_i e_{ch,i}$$

$$e_{ch,i}^\circ = \Delta_f G_i^\circ + \sum_{el} n_{el} e_{ch,el}^\circ$$

$$\Delta_r G_r = \Delta_f G_i^\circ + \sum_{\text{other products}} \Delta_f G_{\text{products}}^\circ - \sum_{\text{reactants}} \Delta_f G_{\text{products}}^\circ$$

$$\Delta_r G_i^\circ = -RT \ln K_r$$

Table 2.
Chemical exergies of solid materials

Material	e_{ch} (MJ/kg ore)
Iron ore	0.42
Copper ore, type 1	0.63
Copper ore, type 2	7.9
Lead ore	0.56
Zinc ore	1.9
Nickel ore	8.8
Gold ore	8.3
Aluminium ore	1.1
Chromium ore	0.51
Platinum ore	0.58
Phosphorous ore	0.28
Lime	0.034
Rock	0.32
Sand	0.032

Table 3.

Typical values of the ratios of chemical exergies to the net V_i and gross V_f calorific values

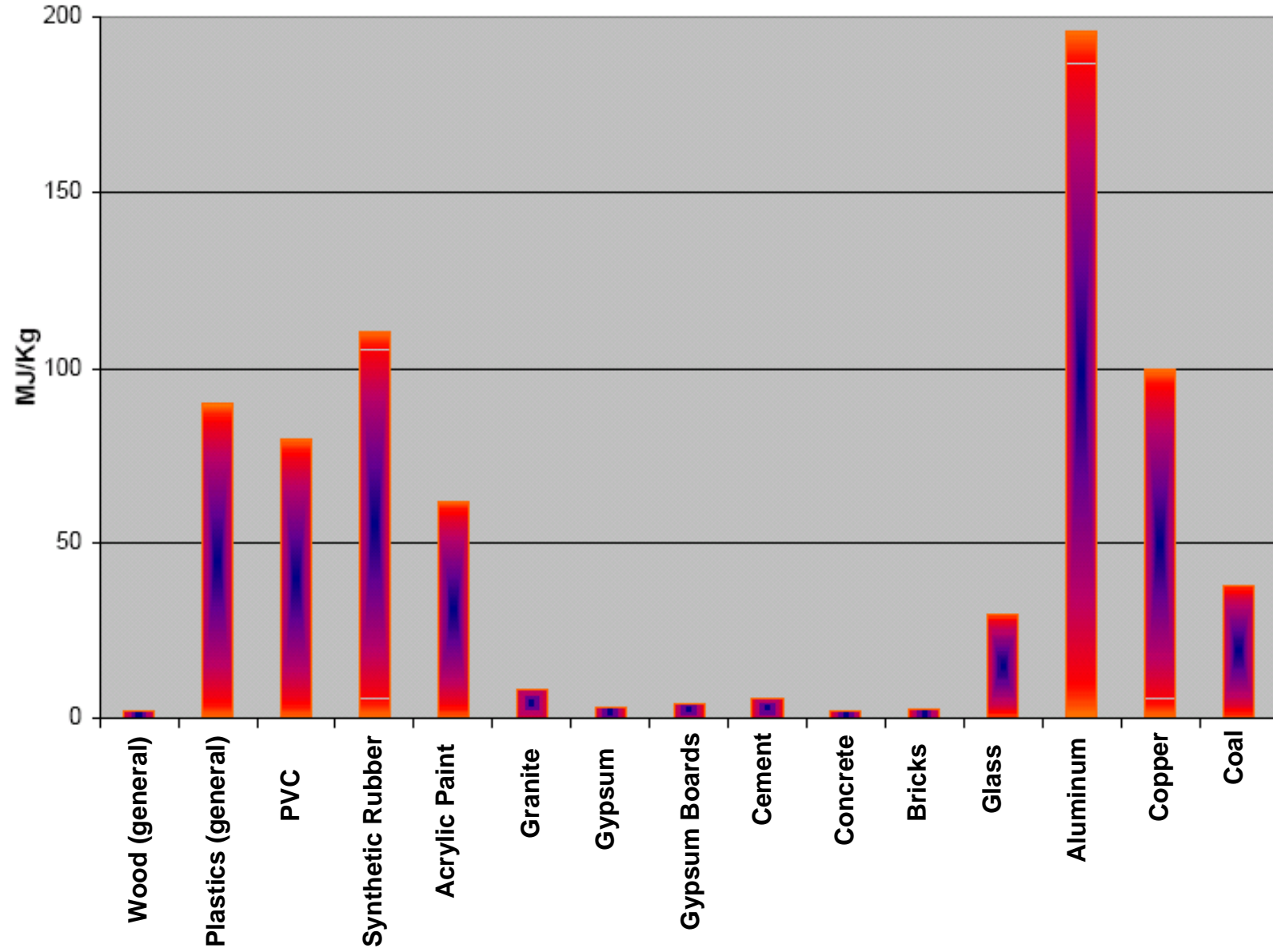
Fuel	e/V_i	e/V_F
Bituminous coal	1.09	1.03
Lignite	1.17	1.04
Fuel oil	1.07	0.99
Gasoline	1.07	0.99
Natural gas	1.04	0.94

The data presented in Table 2 provides characterisation weighting factors ($Q_{i,j}$) for abiotic deposits in Eq. (2), where M_i is the allocated inflow of the material to the technical system, while the data in Table 3 may be used to calculate the exergies of fuels.

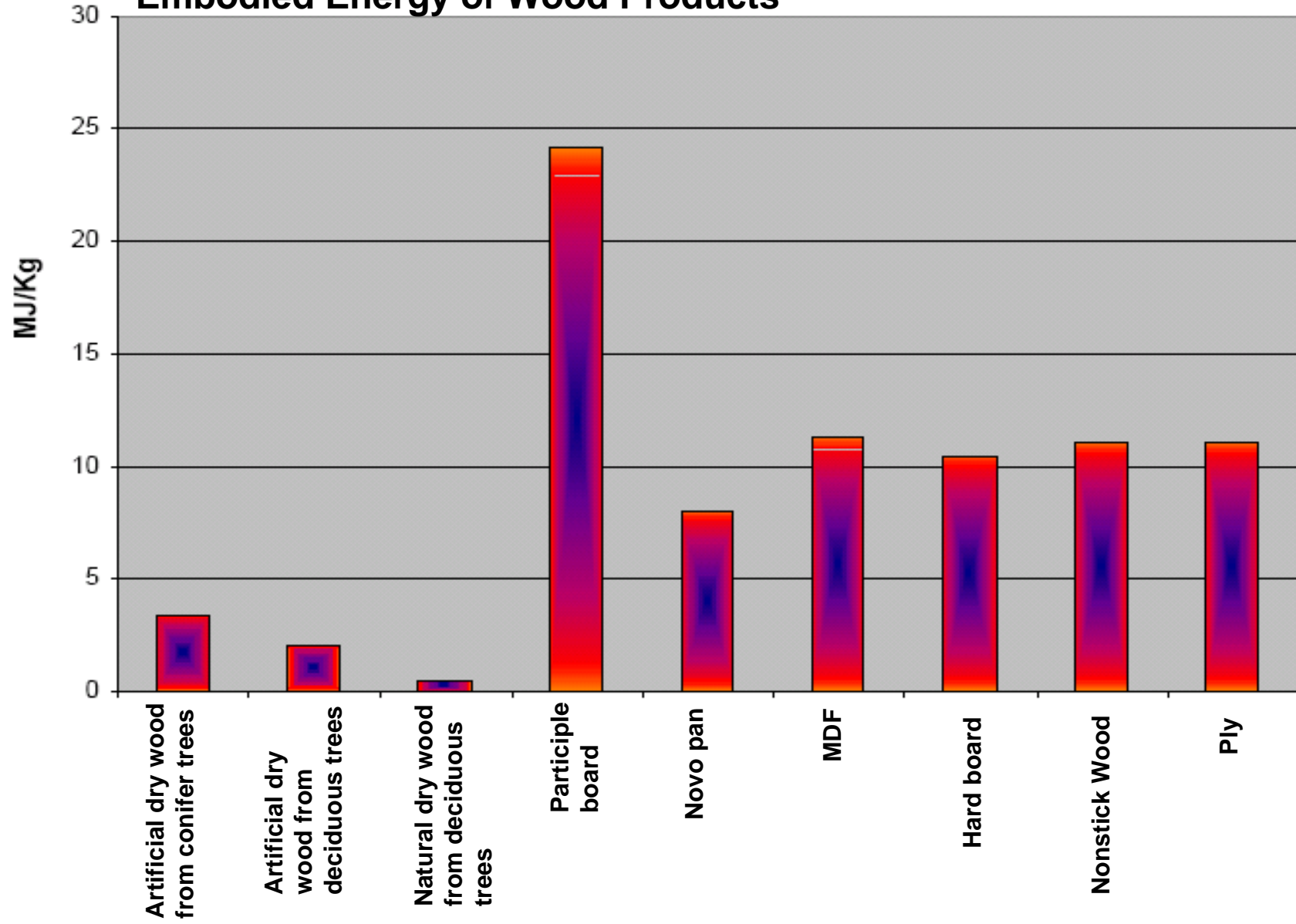
Exergy consumption may be used as a characterisation parameter also in the case of abiotic fund and flow resources, and possibly also for describing competition of biotic resources.

It should, however, be realised that exergy consumption does not describe all relevant aspects related to resource depletion and competition. For example, impacts on the biological diversity from the use of biotic fund resources are not described by exergy consumption. Further research including case studies for other resources, sensitivity analyses and testing in full LCAs, is however warranted.

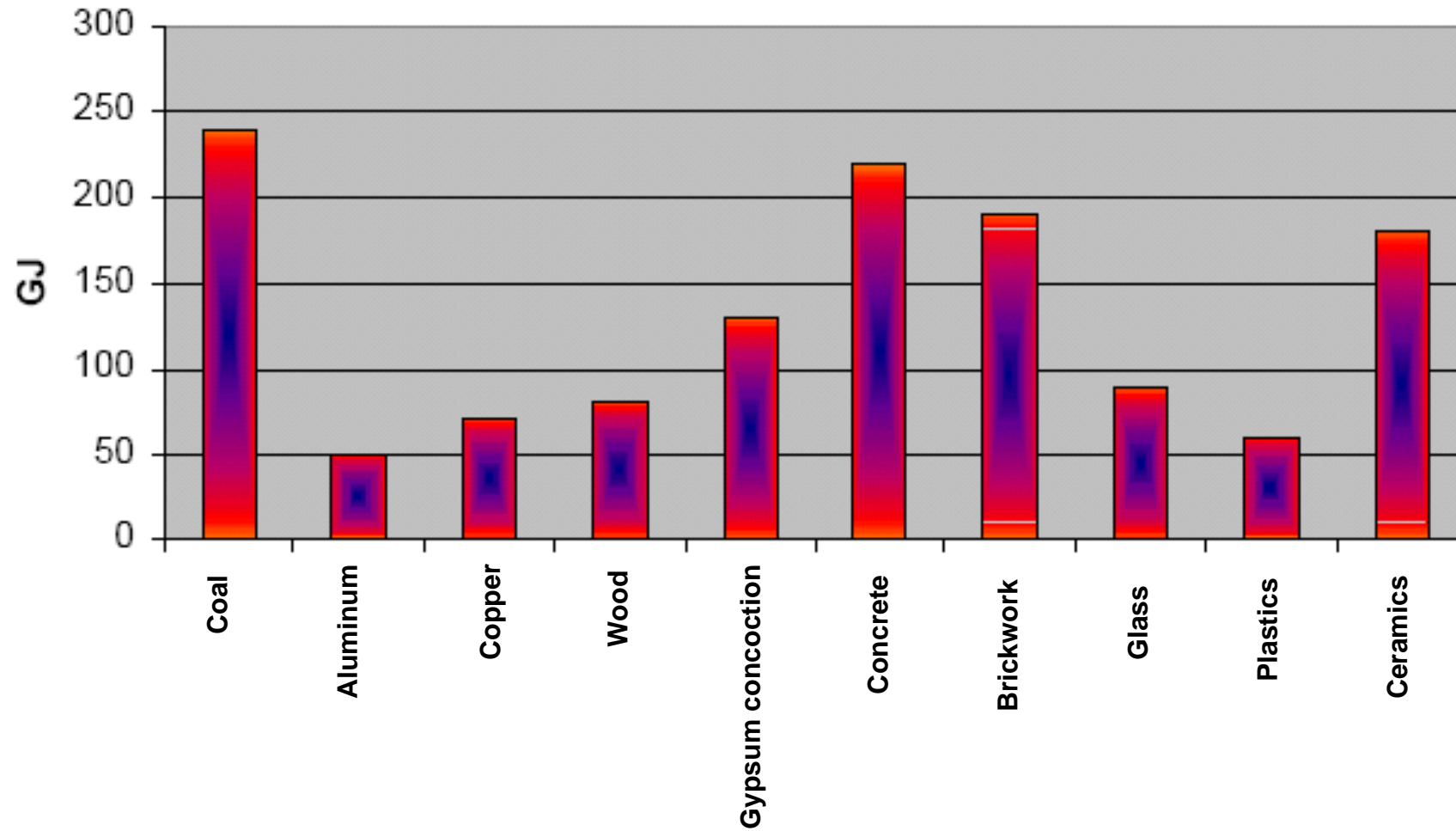
Embodied Energy of Common Materials



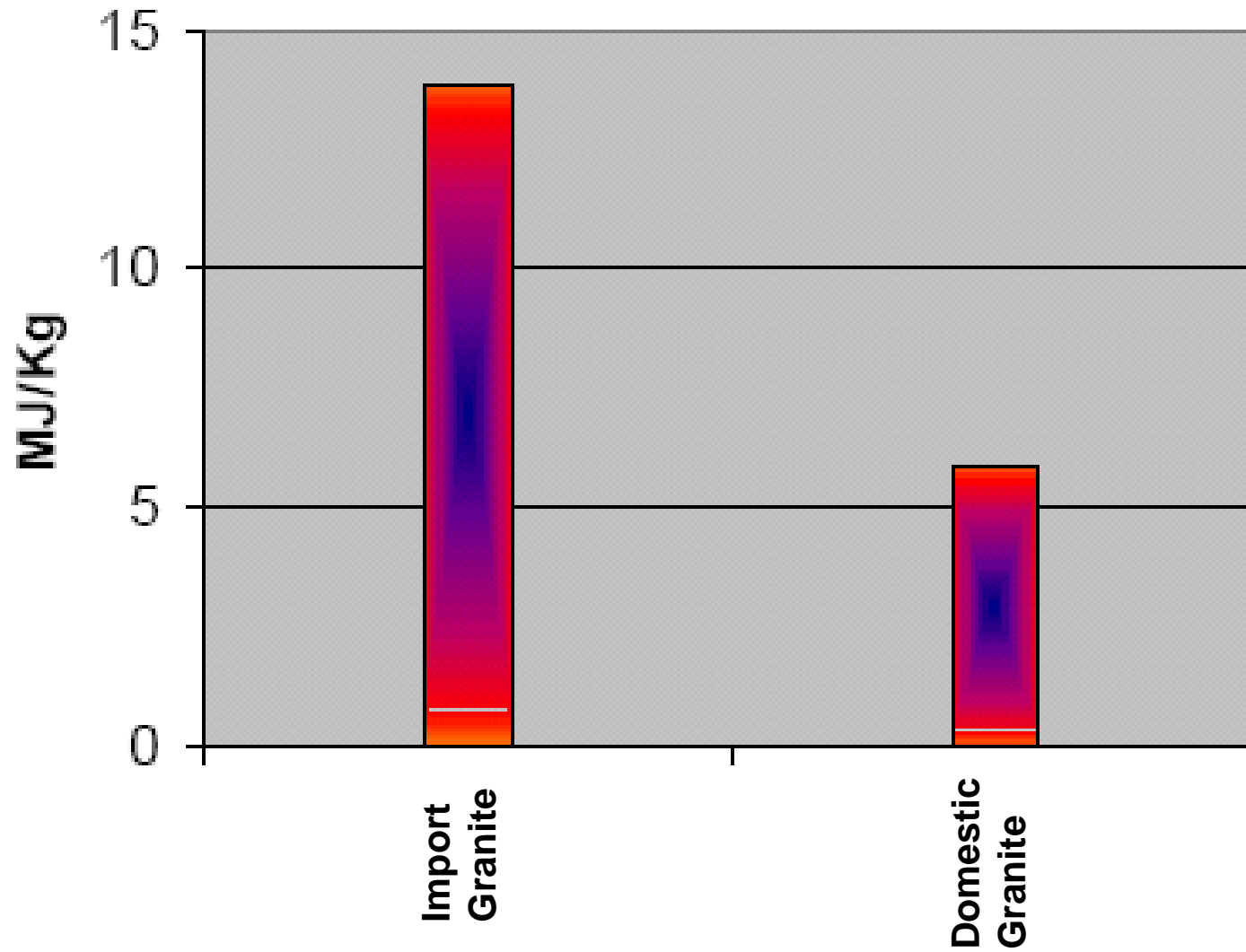
Embodied Energy of Wood Products



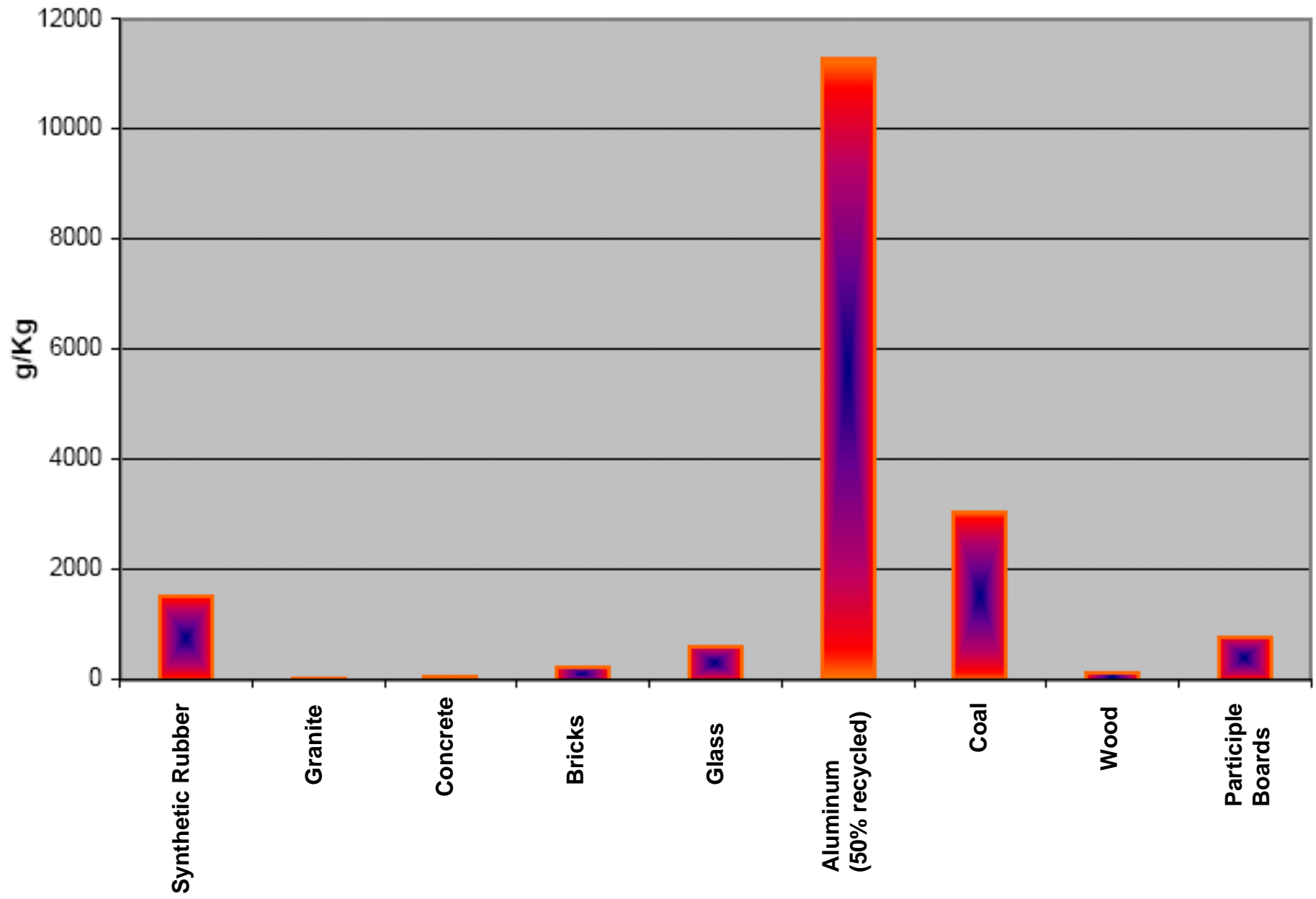
Embodied Energy in a Common Building



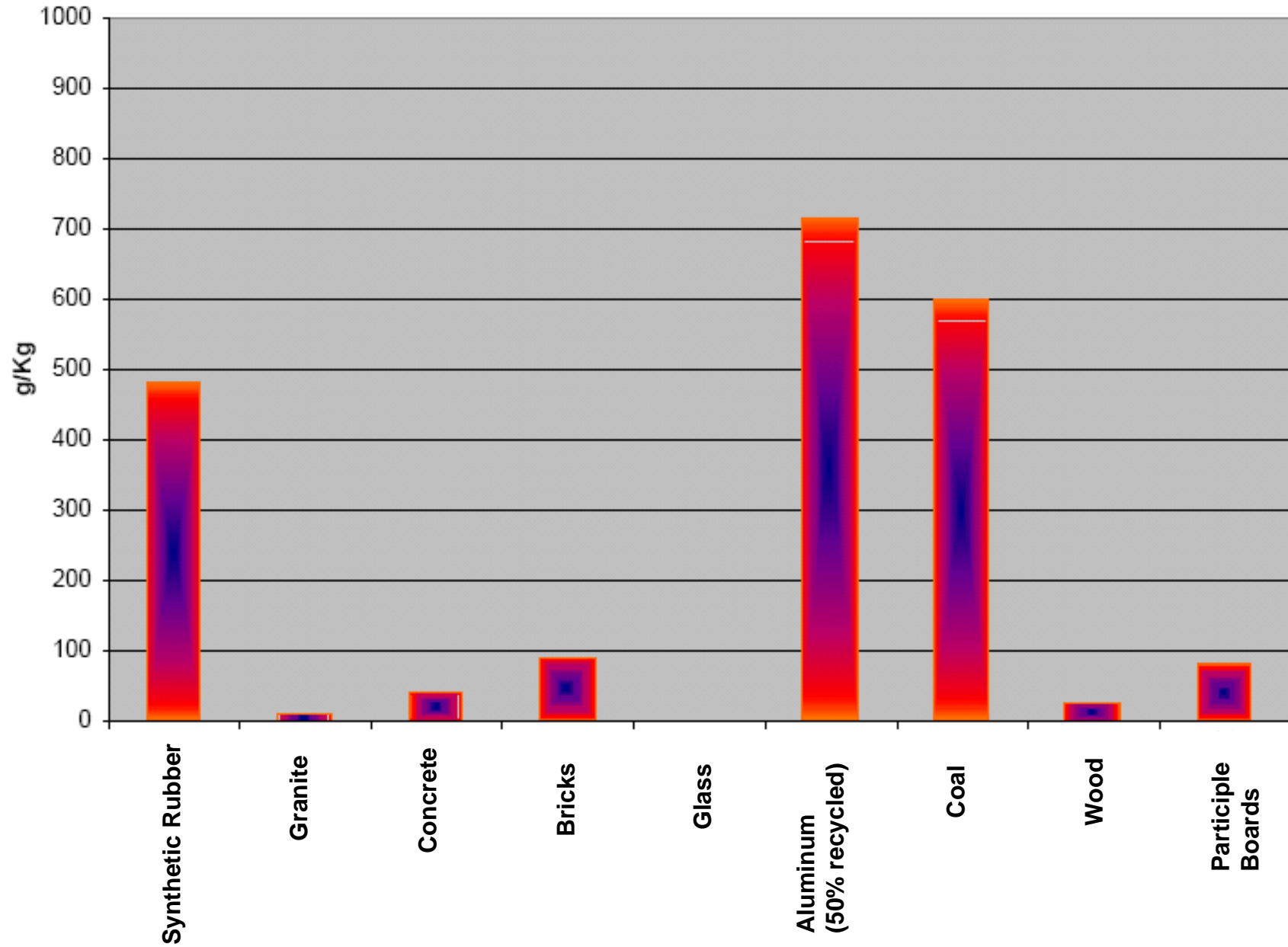
Embodied Energy from Transportation



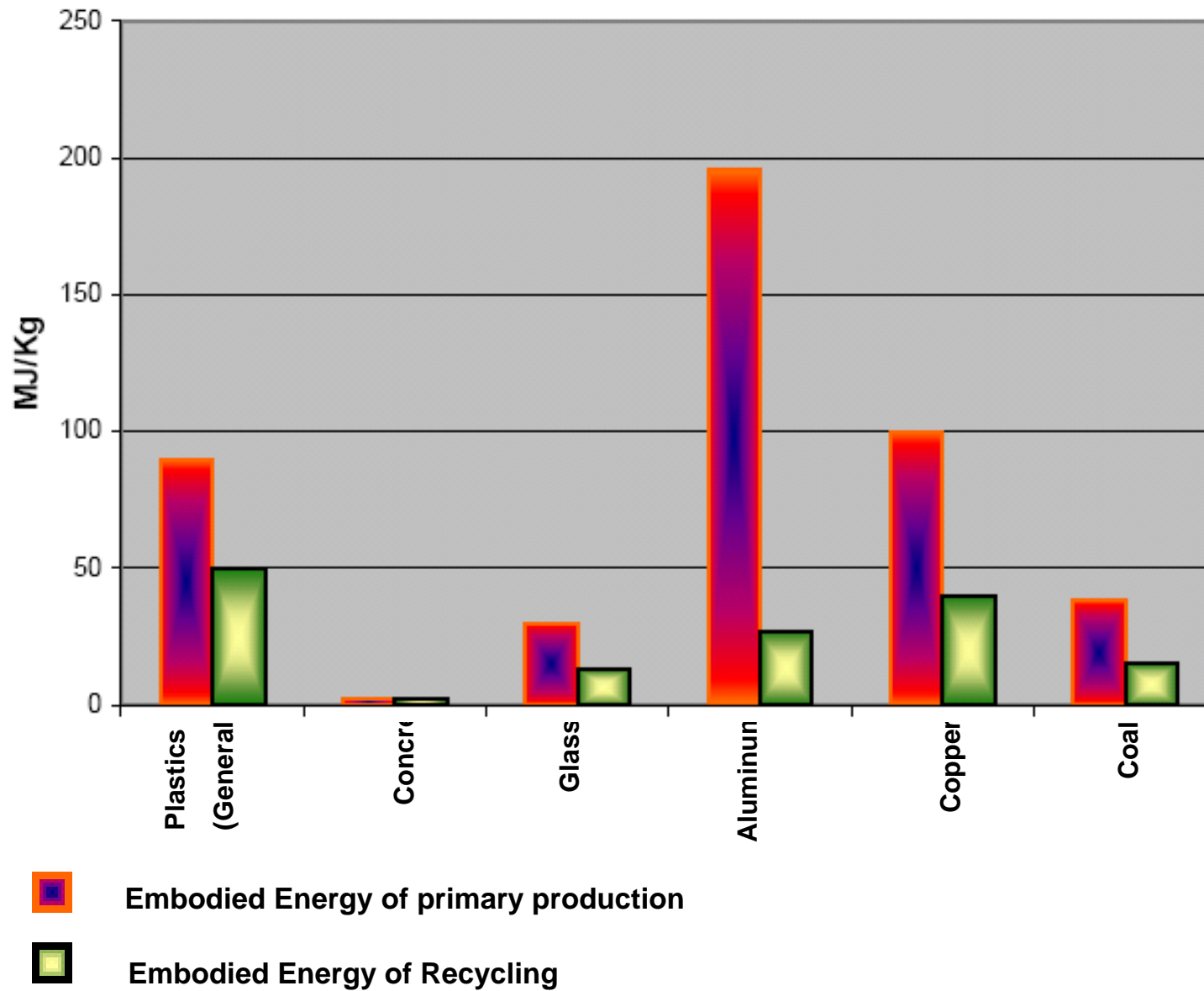
Air Emissions from the production of the materials



Row Material Usage during the production of Common Materials



Embodied Energy during the Recycle of Common Materials



Thank You!