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The energy embodied in building materials - updated New Zealand coefficients and their significance

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Following an outline of the three main methods of energy analysis the authors describe the application of a hybrid analysis method used during their recent update of the embodied energy coefficients of New Zealand building materials. Full tabulations are appended of the updated coefficients of over 100 building materials. While most of the coefficients were less than the values found in a 1983 study, over a quarter of them had risen by an average of 46% - some of the reasons for these apparent increases are attributed to the greater accuracy of the hybrid analysis method. When the effects of these changes on the total embodied energy of a 'standard' house shell were investigated, it was found to have reduced significantly - by over 50% in most cases - compared to 1983.

Keywords: embodied energy - building materials - energy analysis - standard house

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1. Introduction

As the pressures that humanity puts on the environment increase and become more apparent, there is a growing need for information on which to base sound solutions to the problem of protecting the future of the planet. Identifying and evaluating the damage caused by different human activities is a complicated problem, especially if one wants to be able to accurately compare one activity with another.

Whenever we perform some action we have some effect on the environment, as does the production and 'burning' of the energy we use to achieve that action. While not covering all considerations, energy analysis is one method which can be used, albeit crudely, to estimate the environmental impact of different activities. Broadly speaking, the more energy that is used, the greater the effect on the environment.

2. Energy analysis methods

Knowing how much energy is needed to produce building materials is a useful tool in assessing the environmental impact that buildings have. The three main methods of energy analysis are as follows:

2.1 Statistical analysis

This method utilises published statistics to determine energy use by particular industries. It is a useful and speedy method if statistics are kept that are consistent, thorough, pertinent and sufficiently detailed, but unfortunately these conditions have not been met in energy statistics in New Zealand in recent years. Hence, a solely statistical analysis approach is rarely possible.

2.2 Input-output analysis

Statistics NZ publishes the results of inter-industry studies approximately every five years. The resulting input-output tables are an economic tool used to examine dollar flows between sectors of a national economy. By examining the dollar flows to and from the energy-producing sectors of the economy, and comparing these with the known amount of energy produced by each energy sector, it is possible to trace the energy flows within the national economy, and to equate the dollar output of each sector with its energy usage. The great advantage of input-output analysis is that every dollar transaction, and hence every energy transaction, across the entire national economy is captured. The principal disadvantages are the aggregation of dissimilar products in individual sectors and the approximation of physical units by dollar values. While it is worthwhile using the input-output method to contribute to the final coefficients, this approach by itself is not suitable, given the limited extent of the most recent Statistics NZ survey, and the documented limitations of the method - see Bullard et al.[1]

2.3 Process analysis

This involves the systematic examination of the direct and indirect energy inputs to a process. The analysis usually begins with the final production process and works backwards as the energy of each contributing material or energy input needs to be ascertained. In spite of the considerable time required, process analysis is the most common method of energy analysis. This is because the data required can usually be obtained, albeit by dint of considerable delving and persistence. The time and effort required is the main disadvantage of the method. There are also likely to be particular pieces of data that cannot be obtained. However, process analysis produces results that are accurate and specific.

The process analysis undertaken for materials consists first of establishing the direct energy inputs to a process by a manufacturer and then examining the raw materials inputs to the process.[2, 3] In most cases this means obtaining an energy figure for each constituent material.

The almost infinite effort required to capture each small piece of energy flowing into the process, and the lack of data for many of these stages are the main disadvantages with process analysis. For this reason a process analysis was impracticable on its own.

Statistical analysis, input-output analysis, and process analysis all had some useful contribution to a realistic methodology for this project. None of these methods was suitable on its own; a combination of them was required.

2.3.1 Note on IFIAS levels

The IFIAS Workshops [2, 3] suggested the following four levels of energy analysis:

Level 1	Typically less than 50%	Direct energy involved in the process only
Level 2	Frequently around 40%	Energy involved in extracting materials
Level 3	Rarely greater than 10%	Energy needed to make capital equipment
Level 4	Usually very low	Energy to make the machines that make the capital equipment

These have been used throughout this study.

2.4 Hybrid energy analysis

Hybrid analysis attempts to incorporate the most useful features of the three analysis methods outlined above, especially input-output analysis and process analysis. A hybrid analysis begins with the readily available data for a process analysis. These are usually the direct energy inputs of the final production stage and possibly the materials acquisition stages immediately upstream of that final stage.

In our recent study,[4] a hybrid analysis method was used to produce updated embodied energy coefficients for materials used in the New Zealand building industry, and a detailed example of the method, as applied to the manufacture of recycled steel, was presented. A summary of the updated coefficients is given in Appendix 1, together with the year and source of the data, and the level to which the analysis was taken.

The starting point was a process analysis of the final stage of production. Direct energy and raw materials inputs were ascertained. A process analysis of each raw material was next undertaken where the significance of the raw material in the final figure justified the effort. At the point that the increasing effort in achieving detailed figures outweighed the small increase in accuracy provided, the process analysis was truncated. A figure from the input-output coefficients was then substituted to complete that part of the analysis.

By using a hybrid analysis, comprising primarily a process analysis supplemented with an input-output analysis, and with statistical data used where beneficial, it is believed that the end result was achieved more quickly and accurately than with any of the other analysis methods used alone.

The remainder of this paper is devoted to a comparison of the updated coefficients with the earlier set,[5] and estimates of their impact on the embodied energy content of a standard house design.

3. Changes in embodied energy coefficients, 1983 to 1996

Over a 13 year period, there would be an expectation that the energy coefficients of most materials would tend to reduce as a result of improvements in manufacturing energy efficiency.

For example, it is now common for sawmills to derive considerable energy from waste materials, giving an efficiency improvement to the sawmill industry in the order of 15% during the years between the studies.[6] There has also been a shift towards larger, more efficient sawmills, with smaller, older, less efficient mills closing. Over the same interval, over 50% of New Zealand's cement production has shifted from wet process manufacture to the more efficient dry process manufacture. In addition, new, more efficient plant was introduced to the steel industry in 1987.[7]

Owing to rises in the price of energy and economic conditions generally becoming more difficult for manufacturers, the tendency has been for gains in energy efficiency in all areas of manufacturing. There are also continuous incremental improvements as new machinery is introduced. This would suggest that an across the board improvement would be seen in the embodied energy coefficients of building materials but this was not found in all cases (see Appendix 2).

While nearly three-quarters of the materials did show a drop, by an average of 41%, the remainder showed a rise averaging 46%. This is broadly consistent with a general trend to increased energy efficiency. However, the large percentage increase in more than a quarter of the figures suggests that other factors are operating. One such factor is differences in the embodied energy analysis methods employed by the two studies. Examination of some specific materials will illustrate some of the issues.

3.1 Discussion of reasons for differences in coefficients

For illustration purposes, the discussion will cover cement and concrete, paint, sand and aggregate, steel, aluminium and other metals, as follows:

3.1.1 Cement and concrete

Baird and Chan[5] use information from a process analysis for their cement and pre-cast concrete figures.[8] Equivalent figures in Alcorn,[4] using a hybrid analysis method, show a moderate decrease, not inconsistent with the changes in the cement and concrete industry. For cement mortar and ready-mix concrete, however, Baird and Chan use an input-output analysis. Alcorn's hybrid analysis figures are 46.5% and 38.8% lower, respectively.

The input-output figures used by Baird and Chan were derived from a 1971/72 inter-industry study of the New Zealand economy.[9] This means that the data was twelve years old at the time of the Baird and Chan study. This is an inherent problem with input-output analysis.

The relevant industry category for cement and concrete in New Zealand, "Non-metallic minerals", also includes clay, glass, plaster, masonry and asbestos products, such as crockery, porcelain fixtures, pottery and earthenware, ceramic bricks and pipes, mirrors, masonry products, fence and telegraph posts, and tiles. This leads to serious problems of aggregation and price level variation.

The quarrying of limestone, clay, and marl - used in the manufacture of cement - is not included in the "Non-metallic minerals" industry category, but in the "Other mining and quarrying" category. This illustrates the problem of placing a material within an industry category: often it simply cannot be done accurately. The values of energy/$ attributed to a material are likely to be significantly different as a consequence of choosing one category over another.

These are problems typical of input-output analysis that make it unsurprising to find a large difference between the 'pure' input-output figures of this example and the more painstakingly obtained process-based hybrid analysis figures.

3.1.2 Paint

The figures for paint show large decreases (around 50% in some cases) from the earlier input-output figures of Baird and Chan to the recent hybrid figures. This is a case of substituting an overseas figure where no local one was available. Such an approach is better than having no figure at all, but significant differences are not unexpected, given the small size of New Zealand and hence the very specific conditions that apply.

3.1.3 Sand and aggregate

The Baird and Chan figures for sand and aggregate used input-output analysis. The figure for sand is very high when compared to the figure for aggregate. Both materials generally come from the same physical source, but sand can be expected to require slightly more processing to produce, either in crushing or simply in extra sieving, and consequently can be expected to have a very slightly higher energy intensity. In this case a MJ/$ figure for the "Mining and quarrying" category was used. Since sand and aggregate cost the same to produce and to buy, and are sold by volume, $1m^3$ of sand and $1m^3$ of aggregate will have equal embodied energy attributed to them. Since sand is some 60% heavier, however, the energy per kg will appear to be much lower for sand instead of slightly higher.

Other factors, such as rounding errors associated with such relatively small numbers are likely to be operating in this, as well as other examples, but are not traceable. This example illustrates the inherent problem of assuming physical amounts to be proportional to dollar amounts using input-output analysis.

3.1.4 Steel

Steel is one material which seems to be fairly consistent in energy requirements around the world, as it varies by 'only' about 20% around approximately the 30MJ/kg mark, according to different studies. Hence the drop of 8.6% for general steel between these two studies is unsurprising. The figures for steel sections and rod, however, illustrate problems of adapting data from overseas economies. Baird and Chan used input-output based figures from the United States[10] and applied them to New Zealand input-output data. This failed to take account of the technology relating to the New Zealand steel industry where wire rod and structural sections are produced from recycled steel only, whereas virgin steel is used for making coiled sheet, plate and tube steel only.

3.1 5 Aluminium

Baird and Chan's figures for aluminium are based on a process analysis.[11] Process analysis alone has its shortcomings, however, first among which is that of undercounting due to the effort required to follow all inputs sufficiently far upstream. It is impossible to know just what this analysis did and did not include, although an estimate was made for the transport of alumina to New Zealand, as compared to a comprehensive process analysis of the transport operation by Alcorn. There is no indication in Dawson[11] that the energy cost of energy production was included. For such an energy-intensive operation as aluminium production this is very significant.

3.1.6 Other metals

The figures for the other metals also show a rise over the interval. Brass, lead and copper, are all derived from the "Metal products NEC" category. Since these metals are not produced in New Zealand in their virgin form, the energy intensity being attributed to them comes from the remanufacturing into other products of the raw metals. This is clearly a much less energy-intensive operation than the smelting of raw materials. Hence the presentation of the embodied energy figures as for general metal is misleading without specific reference to and understanding of the data source. When they are compared to the later figures which include the energy of smelting overseas, it is not surprising to see rises in the comparative figures ranging from 25.8% to 53.8%.

The value in repeating the study of embodied energy coefficients of building materials after thirteen years has been not only to bring the figures up-to-date, but to elucidate some of the reasons for the wide variations often seen in embodied energy analyses. The comparison makes clear some of the pitfalls of using single method analysis and points to the value of a process-based hybrid analysis. It now remains to evaluate the influence of these changes on the energy embodied in a building.

4. Embodied energy of a 'standard' house shell, 1983 and 1996

When Baird and Chan published their work on the embodied energy of houses,[5] there existed a standard house design used as a yardstick by the New Zealand Institute of Valuers - the NZIV Modal House. This design dated back to the 1950s and was updated by the Building Industry Advisory Council as the BIAC Standard House. The Building Industry Advisory Council itself has now ceased to exist, but the BIAC house was still chosen for study to enable ready comparison with the Baird and Chan results.

The specifications for the BIAC Standard House include the following: floor area - $94m^2$; window area - $39m^2$; three bedrooms; open plan living/dining/kitchen; level site.

The model used is little more than a shell, comprising the walls, roof and floor only, but serves to facilitate comparisons between alternative materials, and has the advantage of being readily recognised by building professionals and lay people as a relevant vehicle to illustrate the implications of materials choices on the total embodied energy of a house. It was intended to demonstrate the effect of changes in material manufacturing technology and the effects of choosing a different embodied energy analysis strategy on the overall figures. The comparative results in GJ/m^2 of floor area are presented in Table 1.

As can be seen, the percentage changes over thirteen years are significant, ranging from 32 to 56 %. As discussed in the previous section, this reflects both changes in construction and materials manufacturing over the last thirteen years, and also significant changes in the embodied energy figures applied in the two studies.

TABLE 1: Embodied energy comparison of a standard house shell - Baird and Chan (1983) versus Alcorn (1996)

WALL	***ROOF***	***FLOOR***	***Baird & Chan*** ***(GJ/m^2)***	***Alcorn*** ***(GJ/m^2)***	***CHANGE*** ***%***
Weatherboard	Concrete tile	Particle board	1.5	0.7	-53
		Concrete slab	1.9	0.9	-53
	Corrugated galvanised	Particle board	1.9	0.9	-53
		Concrete slab	2.3	1.1	-52
Concrete masonry	Concrete tile	Particle board	1.9	1.3	-32
		Concrete slab	2.3	1.4	-39
	Corrugated galvanised	Particle board	2.3	1.4	-39
		Concrete slab	2.7	1.6	-41
Brick veneer	Concrete tile	Particle board	2.4	1.1	-54
		Concrete slab	2.7	1.2	-56
	Corrugated galvanised	Particle board	2.8	1.3	-54
		Concrete slab	3.2	1.4	-56

The combination of weatherboard walls, concrete tile roof and particle board floor still remains the lowest energy option of those investigated. While the combinations including the concrete masonry wall have come down significantly, those including the brick veneer wall have been reduced still further so that overall they now rank just behind the weatherboard options.

5. Acknowledgements

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7. Appendix 1: Embodied energy coefficient, year, and source of data.

(L1) and (L2) signify coefficients taken to IFIAS Levels 1 and 2 respectively (see paragraph 2.3.1 above); all other coefficients have been taken to IFIAS Levels 3 or 4.

MATERIAL	MJ/kg	YEAR	SOURCE OF BASIC DATA
Aggregate, general	0.10	1993	Industry data
virgin rock	0.04	1994	Manufacturer
river	0.02	1994	Manufacturer
Aluminium, virgin	191	1994	Companies in New Zealand and Australia. Published data for carbon anodes. Process analysis of Trans-Tasman shipping operation
extruded	201	1995	
extruded, anodised	227	1995	
extruded, factory painted	218	1995	
foil	204	1995	
sheet	199	1995	
Aluminium, recycled	8.1	1995	Manufacturer
extruded	17.3	1995	"
extruded, anodised	42.9	1995	"
extruded, factory painted	34.3	1995	"
foil	20.1	1995	"
sheet	14.8	1995	"
Asphalt (paving)	3.4	1995	Manufacturer
Bitumen	44.1	1995	Manufacturer
Brass	62.0	1994	Manufacturer
Carpet	72.4	1991	Sheltair Scientific Ltd, 1991
felt underlay	18.6	1992	AIA, 1994
nylon	148	1992	"
polyester	53.7	1992	"
polyethylterephthalate (PET)	107	1992	"
polypropylene	95.4	1992	"
wool	106	1994	Industry data
Cement	7.8	1994	Industry data
cement mortar	2.0	1994	Lawson, 1994
fibre cement board	9.5	1994	Manufacturer
soil-cement	0.42	1995	Industry data (L2)
Ceramic			
brick	2.5	1994	Manufacturer
brick, glazed	7.2		"
pipe	6.3	1994	Franklin Associates, 1991
tile	2.5	1994	Manufacturer

Concrete			
block	0.94	1994	Manufacturer (L2)
brick	0.97	1994	Manufacturer (L2)
GRC	7.6	1994	Manufacturer
paver	1.2	1994	Manufacturer
pre-cast	2.0	1994	Lawson, 1994 (L2)
roofing tile	0.81	1991	Sheltair Scientific Ltd, 1991
ready mix 17.5 MPa	1.0	1994	Manufacturer
30 MPa	1.3	1994	"
40 MPa	1.6	1994	"
Copper	70.6	1994	Manufacturer
Earth, raw			
adobe block, straw stabilised	0.47	1994	Manufacturer
adobe, bitumen stabilised	0.29	1991	AIA, 1994
adobe, cement stabilised	0.42	1995	Industry data (L2)
rammed soil cement	0.80	1994	Lawson, 1994 (L2)
pressed block	0.42	1995	Industry data (L2)
Fabric			
cotton	143	1991	AIA,1994
polyester	53.7	1991	"
Glass			
float	15.9	1994	Manufacturer (L2)
toughened	26.2	1994	" (L2)
laminated	16.3	1994	" (L2)
tinted	14.9	1994	" (L2)
Insulation			
cellulose	3.3	1995	Manufacturer
fibreglass	30.3	1991	AIA, 1994
polyester	53.7	1991	"
polystyrene	117	1991	Sheltair Scientific Ltd, 1991
wool (recycled)	14.6	1995	Manufacturer
Lead	35.1	1995	Manufacturer
Linoleum	116	1991	AIA, 1994
Paint	90.4	1994	Manufacturer
solvent based	98.1	1994	"
water based	88.5	1994	"
Paper	36.4	1988	AIA, 1994
building	25.5	1995	Manufacturer (L2)
kraft	12.6	1994	Industry data (L2)
recycled	23.4	1991	AIA, 1994
wall	36.4	1988	"
Plaster, gypsum	4.5	1991	Sheltair Scientific Ltd, 1991
Plaster board	6.1	1995	Manufacturer
Plastics			
ABS	111	1991	Franklin Associates Ltd, 1991
HDPE(high density polyethelene)	103	1994	Manufacturer
LDPE(low density polyethelene)	103	1994	"
polyester	53.7	1991	AIA, 1994
polypropylene	64.0	1994	"
polystyrene, expanded	117	1994	“
polyurethane	74.0	1991	Manufacturer
PVC	70.0	1992	Manufacturer; industry data; (L2)

Rubber			
natural latex	67.5	1991	AIA, 1994
synthetic	110	1994	Lawson, 1994 (L2)
Sand	0.10	1993	Industry data
Sealants and adhesives			
phenol formaldehyde	87.0	1994	Lawson, 1994 (L2)
urea formaldehyde	78.2	1990	AIA, 1994
Steel, recycled	10.1	1995	Manufacturer
reinforcing, sections	8.9	1995	"
wire rod	12.5	1995	"
Steel, virgin, general	32.0	1994	Lawson, 1994 (L2)
galvanised	34.8	1994	Lawson, 1994 (L2)
imported, structural	35.0	1994	Manufacturer (L2)
Stone, dimension			
local	0.79	1993	Industry data
imported	6.8	1994	Importer (L1)
Straw, baled	0.24	1978	Long, Taylor and Berry, 1978 (L1)
Timber, softwood		1992	AIA, 1994 (All timbers to L1 u.o.s.)
air dried, roughsawn	0.3	1995	Industry data
kiln dried, roughsawn	1.6	1995	"
air dried, dressed	1.16	1995	"
kiln dried, dressed	2.5	1994	Lawson, 1994
mouldings, etc	3.1	1995	Industry data
hardboard	24.2	1994	"
MDF	11.9	1994	Manufacturer (L4)
glulam	4.6	1992	"
particle board	8.0	1994	Lawson, 1994
plywood	10.4	1994	"
shingles	9.0	1991	Sheltair Scientific Ltd, 1991
Timber, hardwood			
air dried, roughsawn	0.50	1994	Lawson, 1994
kiln dried, roughsawn	2.0	1994	"
Vinyl			
flooring	79.1	1991	Sheltair Scientific Ltd, 1991(L2)
Zinc	51.0	1994	Lawson, 1994 (L2)
galvanising (per kg steel)	2.8	1994	Manufacturer (L2)

8. Appendix 2: Comparison of embodied energy coefficients, 1983 to 1996

MATERIAL	UNITS	Baird & Chan (1983)	Alcorn (1996)	CHANGE %
Aggregate, general	MJ/kg	0.3	0.1	-66.7
Aluminium, virgin	MJ/kg	129.5	191	47.5
extruded	MJ/kg	145	201	38.6
foil	MJ/kg	154	204	32.5
sheet	MJ/kg	145	199	37.2
Brass	MJ/kg	49.3	62	25.8
Cement	MJ/kg	8.98	7.8	-13.1
cement mortar	MJ/m³	5980	3200	-46.5
Concrete-pre-cast	MJ/m³	4780	4700	-1.7
-ready mix, 17.5 MPa	MJ/m³	3840	2350	-38.8
Copper	MJ/kg	45.9	70.6	53.8
Glass	MJ/kg	31.5	15.9	-49.5
Insulation-fibreglass	MJ/kg	150	30.3	-79.8
Lead	MJ/kg	25.2	35.1	39.3
Paint	MJ/m²	15	6.5	-56.7
solvent based	MJ/m²	12	6.1	-49.2
water based	MJ/m²	7.5	7.4	-1.3
Paper-building	MJ/m²	7.46	4.97	-33.4
Paper-wall	MJ/m²	14.92	12.74	-14.6
Plaster Board	MJ/m³	5000	5890	17.8
Plastics-low density polyethylene	MJ/kg	112	103	-8.0
Plastics-polypropylene	MJ/kg	175	64	-63.4
Plastics-polystyrene, expanded	MJ/kg	100	117	17.0
Plastics-PVC	MJ/kg	96	70	-27.1
Rubber-synthetic	MJ/kg	148	110	-25.7
Sand	MJ/kg	0.04	0.1	150.0
Steel-recycled-reinforcing, sections	MJ/kg	59	8.9	-84.9
Steel-recycled-wire rod	MJ/kg	35	12.5	-64.3
Steel-virgin,general	MJ/kg	35	32	-8.6
galvanised	MJ/kg	37	34.8	-5.9
Timber, air dried, roughsawn	MJ/m³	848	165	-80.5
air dried, dressed	MJ/m³	4692	638	-86.4
hardboard	MJ/m³	20626	13310	-35.5
glulam	MJ/m³	4500	2530	-43.8
particle board	MJ/m³	12892	5694	-55.8
plywood	MJ/m³	9439	5720	-39.4