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# THE EMBODIMENT OF EMBODIED ENERGY - A NEW ZEALAND PERSPECTIVE

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## Introduction

Following the oil crises of the 1970s, energy efficiency became of increasing concern to designers, operators and users of buildings. This concern was focused almost exclusively on the energy required to run the building - energy running costs are readily apparent to all the interested parties. A relatively few studies of embodied energy - the building's energy capital cost - were undertaken at that time; but the implications of these (see, for example, Kegel, 1975; Stein, 1977; Baird and Chan, 1983) were largely ignored by the mainstream of building providers. More recently, issues of sustainability and global environment concerns have prompted renewed interest in the energy embodied in our building stock.

The main aim of this paper is to demonstrate the effect of structural and material design decisions on the energy embodied in a simple five-storey commercial building. Following a brief outline of the nature of the embodied energy requirements of buildings, the embodied energy values of some common building materials are listed. The results of using these values to estimate the capital energy cost of the structure of the five-storey building, designed to four different specifications (reinforced concrete frame, reinforced concrete shear wall, structural steel frame and laminated timber frame) are presented together with a discussion of their likely ranges, taking into account the expected accuracy of the embodied energy values of individual building materials and the influence of the structural design assumptions made. Finally, some comments are made on the need to equate capital energy costs against running costs and refurbishment costs, and a plea is made for a more sustained research effort in this field.

## Embodied Energy Requirements of Building

The energy embodied in a building (termed its Gross Energy Requirement or GER) includes both direct and indirect energy requirements. The direct energy is the fossil fuel and electricity used at the building site and in transporting the materials to the site. The indirect energy is that used to manufacture materials, components, tools and machinery, plus the energy used to manufacture the

equipment used to extract these raw materials, and so on. Table 1 summarises the terminology, system boundaries, and expected proportions of GER at each of the four levels specified by IFIAS (International Federation of Institutes for Advanced Study, 1974, 1975).

**Table 1. Key Terms, Definitions and System Boundaries in Energy Analysis**

| IFIAS level | Percentage of GER | System Boundaries and Definitions | Terminology Used | |
|---|---|---|---|---|
| 1 | Less than 50% | The direct energy required to carry out a given process - also known as the Process Energy Requirement or PER | Direct Energy Requirement | Gross Energy Requirement or GER |
| 2 | Approx 40% | Energy involved in extracting materials. | Indirect Energy Requirement | |
| 3 | Rarely more than 10% | Energy needed to make capital equipment. | | |
| 4 | Very low | Energy to make the machines that make the capital equipment. | | |

In the case of the construction industry, in most industrialised countries it is largely factory based, with many processes carried out remote from the building site. Hence the direct energy requirement is relatively low - less than 20 per cent of the GER of the completed building in the UK, the USA and New Zealand (ie, at the lower end of the "less than 50% guidelines quoted above for IFIAS Level 1). The energy required for the manufacture of materials makes up the largest proportion, amounting to some 65% of the total construction industry energy requirements. Thus the energy embodied in building materials is by far the most important component of the gross energy requirement or capital energy cost of a building.

### GERs for Common Building Materials

Baird and Chan (1983) produced a detailed set of tables (approx 35) listing energy requirement values for all the main building materials, broken down by country, IFIAS level and source. This enabled both an inter-country (USA, UK and NZ) comparison of the GERs for 23 common materials and the development of a comprehensive listing of New Zealand GERs for nearly 80 building materials and related activities. For the purposes of the exercise described in this paper, the GER values for relevant materials were selected from the comprehensive listing, reviewed and updated where necessary (Treleaven, 1993), to produce Table 2.

**Table 2. GERs of materials used for the case study buildings**

| Construction category | Material | Units | GER MJ/Unit | Estimated error (±%) |
|---|---|---|---|---|
| Foundation Materials and Processes | Earthworks and Excavation | $m^3$ | 50 | 15 |
| | Pile Excavation | $m^3$ | 200 | 15 |
| | Hardfill | $m^3$ | 1043 | 15 |
| | Sand Blinding | $m^3$ | 1120 | 15 |
| | Damp Proof Membrane | $m^2$ | 60 | 15 |
| Concrete Materials and Reinforcing | Aggregates and Sand | $m^3$ | 1120 | 15 |
| | Cement | kg | 605 | 15 |
| | Insitu Concrete | $m^3$ | 3160 | 15 |
| | Precast Concrete | $m^3$ | 4100 | 15 |
| | Reinforcing Bar and Mesh | kg | 12 | 15 |
| Structural Steel and Related Items | Rolled Steel Sections | kg | 35 | 25 |
| | Fire Resistant Coatings | kg | 7 | 40 |
| | Linings | $m^3$ | 5000 | 15 |
| Timber and Related Items | Laminated Timber | $m^3$ | 4500 | 30 |
| | Framing Timber | $m^3$ | 1200 | 15 |
| | Ceiling Linings | $m^3$ | 5000 | 15 |
| | Fibreglass Insulation | $m^2$ | 110 | 15 |

## Comparative Studies of Whole-Building Embodied Energy

Until relatively recently, most comparative studies of the energy embodied in buildings with the same design, but utilising different materials, have been conducted on domestic buildings. Some of these (see for example Baird et al. 1984) have indicated that embodied energy savings of up to 60 percent are possible. More recently, comparative studies of larger building types have been attempted. Honey and Buchanan (1992) for example used Christchurch office buildings to compare the use of steel, concrete and timber construction; their results suggested GER values of 6.6, 5.6 and 3.7 $GJ/m^2$ of floor area respectively for offices in the 3-8 storey range. McArdle et al. (1993) conducted a study of four large Melbourne office blocks, obtaining GERs in the range 4.7-6.8 $GJ/m^2$ for the substructure, superstructure and finishes used (building services were omitted from their analysis).

Both of these more recent studies gained credibility as a result of their basis in existing buildings. They also highlighted the difficulties of making realistic comparisons in this way, such as the problems associated with locating similar

sized buildings and the corresponding relevant documentation of the various structural forms. Even if such information could be obtained it can be seen that dissimilarities due to peculiarities of individual sites and differences in layout and serviceability could make meaningful comparisons difficult. On the other hand, by modelling a hypothetical structure, it is possible for all relevant physical and design considerations to be equalized so that differences in performance could be attributed to the relevant factors with a greater degree of confidence; this was the approach taken here.

**Description of the case study buildings**

The focus of the research was a five-storey square plan commercial office building situated in Wellington, New Zealand. Five storeys is a convenient height to model buildings constructed from the selected materials, as the results obtained from the analysis could be reasonably applied to buildings in the three to eight-storey range without significant resizing of structural elements, as long as plan dimensions remain unchanged. The building form selected (see Fig 1) has a 25m square plan with a ground floor plus four complete levels of suspended floors and a smaller fifth level designated as plant room space above a central service core. A square footprint was chosen because it offered both simplicity in terms of engineering analysis and construction and scope for generalisation to other shapes of similar scale if required.

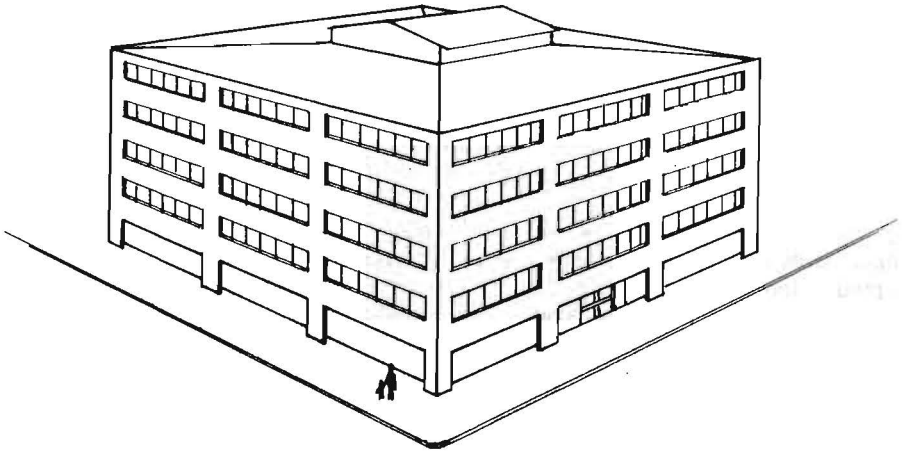

**Figure 1. Overall concept form of the five-storey case study building**

Four structural models were created to explore the relative merits of reinforced concrete frames, reinforced concrete shear walls, eccentrically braced steel frames and cross braced structural timber frames as the main structural systems of the buildings. Items common to all of the models such as the exterior cladding, suspended ceilings, mechanical services and lightweight framing to the central core were omitted from the energy analysis, but included in the calculations which determined the dimensions of the structural elements. Each design was carried out to provide buildings of similar performance and which differed only in the material of construction. Criteria to be satisfied in this respect include the ability to achieve identical subdivision of interior spaces, equal floor live load capacities, seismic performance in accordance with the 1984 NZ code of practice, equivalent acoustic properties between floors and equal resistance of the main elements of structure to fire.

In terms of their design and construction, the four buildings had many similarities and some important differences. Features common to all four included a piled foundation system, a concrete slab-on-grade ground floor, lightweight exterior cladding and a lightweight roof construction.

The structural framing systems for the concrete models and the steel frame model were designed and detailed for full ductility. The members of the timber frame model were designed for limit state conditions except the beam-column-brace joints which were designed to remain elastic under ultimate design loads. Steel beams and posts provided support for the roof for all the models except the timber frame building, for which support is provided by timber posts and beams.

The concrete models utilised the same precast flooring system for above ground storeys, consisting of prestressed concrete planks overlaid by an insitu concrete topping; the steel frame building also had a concrete floor system above ground level, but this consisted of an insitu concrete slab poured onto steel decking which acts as permanent formwork; these are representative of economical systems used by the New Zealand construction industry. The timber frame building was designed with a sawn timber floor system for all storeys above ground floor level. Both the steel frame and timber frame buildings required secondary beams to support the floor systems described above.

**Estimation of the GERs of the four building designs**

The quantities of materials required for each design were estimated, multiplied by the relevant embodied energy coefficient, and summed to give the total energy embodied in the building structure. These totals ranged from 4570 gigajoules (GJ) for the timber frame to 8360 GJ for the steel frame option, with the two concrete options at 6150 GJ (frame building) and 6000 GJ (shear wall building).

Figs 2 and 3 give the breakdown of these totals by building component and by building material respectively. It can be seen that each of the concrete options is quite similar in make up. The concrete shear wall option has a larger energy investment in foundations due to more extensive piling, but this is compensated

for by lighter perimeter beams and columns compared to the concrete frame building. In the case of the steel frame building, it should be noted that a large proportion of the embodied energy is made up of columns and beams; of the 4570 GJ embodied in framing members 1300 GJ or 28% is attributable to secondary floor beams. Secondary beams are not required for the concrete floors as these comprise prestressed units which are able to span further between supporting beams than is feasible with the composite concrete slab on steel deck. Secondary beams are also required for the timber structure but the embodied energy content of the laminated beams used is estimated to be only 350 GJ. The reasons for this are that, weight-for-weight, the timber beam has been assigned a much lower energy intensity than steel (7.5MJ/kg versus 35 MJ/kg) and that the timber floor being supported is much lighter than the concrete slab supported by the steel beams, therefore reducing the strength requirements for the beam.

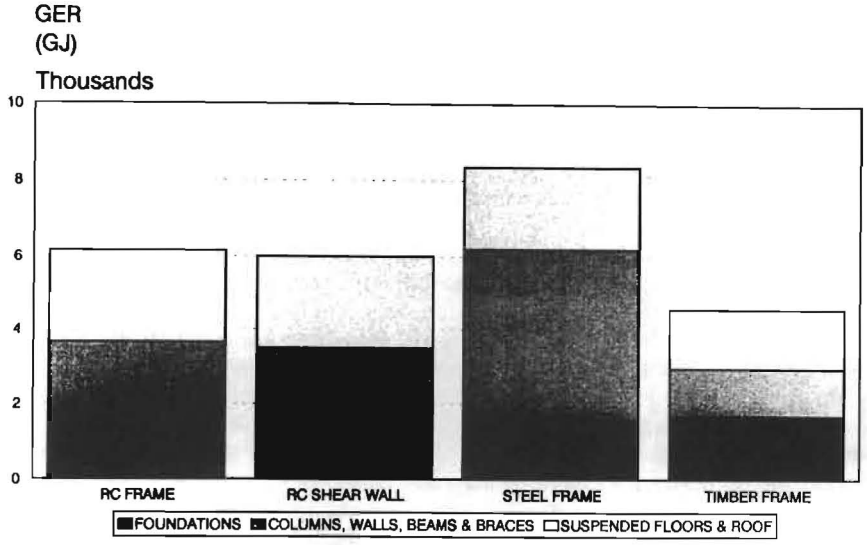


**Figure 2. GERs of the four building designs broken by building component**

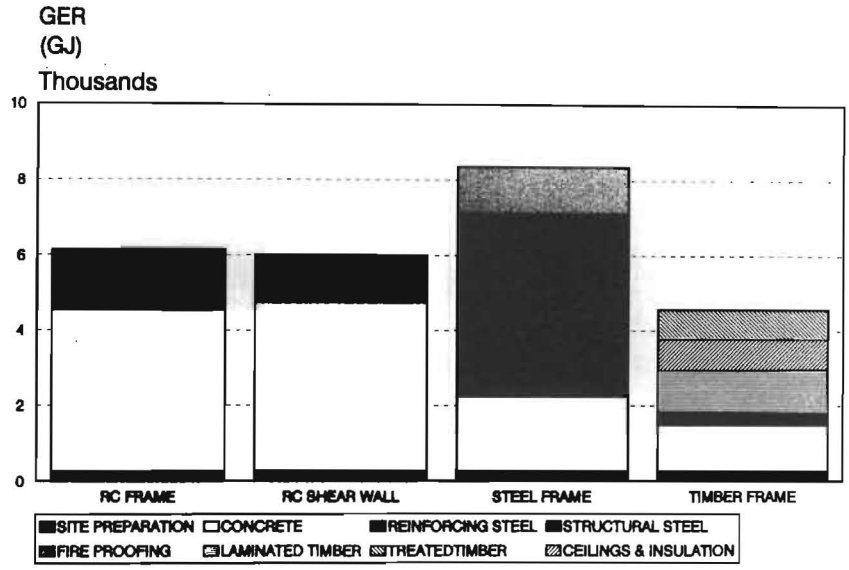


**Figure 3. GERs of the four building designs broken down by building material**

Given the approximate nature of the material GER values and the assumptions made in the structural design, it was felt appropriate to check their influence on the above estimates. Table 2 listed the estimated error in the GER values of the materials used in this study. Most of these are of the order of ± 15 per cent which is the margin of error associated with the input-output analysis method used in their development and updating for this study. A rather larger margin was allowed where updating was not feasible (± 25% for rolled steel sections) or no specific data was available (± 40% for fire resistant coatings) or accurate figures could not be sourced (± 30% for laminated timber due mainly to difficulties in isolating data on glues)

The structural design assumption with the greatest influence on the overall GER was found to be associated with the type of foundations needed. The results shown in Figs 2 and 3 are for buildings on relatively soft ground; buildings constructed on firmer soils would require substantially less piling. For this exercise, the effect of arbitrarily reducing piling content by half has been calculated for comparison with the initially estimated GERs. This influences the energy required for excavation, concrete and reinforcing; the remaining foundation elements, such as hardfill, ground beams and slab, being unchanged. On this basis, the reduction in calculated GER is approximately 750 GJ for each of the concrete options and 550 GJ for the steel and timber options. Variations due to differing seismic considerations were found to be insignificant in terms of the margin for error (100 GJ or less in all cases). Table 3 gives the anticipated ranges of GER values for the four building structures allowing for margins of error in the material GERs and the different foundations.

**Table 3. Ranges in the GERs of the four building structures**

| | Structural design option | | | |
|---|---|---|---|---|
| | RC Frame | RC Shear Wall | Steel Frame | Timber Frame |
| Estimated GER (GJ) | 6150 | 6000 | 8360 | 4570 |
| GER error margin (GJ) | ± 940 | ± 930 | ± 2040 | ± 870 |
| Foundation variation in GER (GJ) | -650 min<br>-750 max | -710 min<br>-830 max | -520 min<br>-600 max | -520 min<br>-600 max |
| GER Range for soft ground (GJ) | 5210-7100 | 5080-6930 | 6320-10400 | 3700-5450 |
| GER Range for firm ground (GJ) | 4460-6440 | 4240-6220 | 5720-9880 | 3100-4920 |

As can be seen, the selection of structural material can have a distinct impact on the embodied energy content of this particular type of building. The figures presented suggest that the ranking of structure types from least energy intensive to most energy intensive should be timber, followed by both of the concrete options and finally steel. The difference between mean values indicates that in terms of structural materials the steel frame building has 80% more embodied energy than the timber building and the concrete buildings have about 30-35% more than the timber building.

**Conclusions and commentary**

As has been made evident by the results of the study, the choice of construction material for the main structural elements of a building of this kind has a significant effect on its embodied energy content. The timber building has less embodied energy than the concrete buildings, which are in turn are less energy intensive than the steel frame building. In the extreme case, selection of a steel frame building over a timber frame building requires the commitment of nearly twice the embodied energy to procure the raw materials and manufacture the structural componentry.

However, while it is feasible to estimate the energy embodied in a large range of building materials and components and to use this information to make decisions about their selection, embodied energy must always be considered in the context of the total energy requirement over the lifetime of the building. In other words, the operating energy requirement must also be estimated and the influence of alternative material selections compared. In a preliminary study, Treleaven (1993) has estimated that if the energy running costs for heating, ventilating and

airconditioning were taken into account, the timber frame building discussed above would have a significantly higher total energy use, over a 50 year period, than the other three cases, as a result of its lower thermal mass.

Of course, apart from using low energy materials and achieving low energy consumption figures, designing low energy building to last for centuries rather than decades has the potential to save vast amounts of capital energy (Storey and Baird, 1994). Needless to say, the choice of materials and their detailing will need to be compatible with this concept to avoid the energy cost penalties of frequent replacement of components.

It should also be noted that despite the nomenclature, the energy capital cost of a building is unlikely to be able to be cashed in at the end of its useful life; unless it has been designed such that its components can be readily dismantled and its materials recycled - properties which are not a characteristic of the current building stock. Clearly, if this capital energy is to be recoverable, then building components must be designed for ease of disassembly.

As any perusal of the literature will show, only a relatively small amount of research has been carried out in this field, much of it a decade or more ago, and it is timely that there is renewed interest in the issues involved. It will be evident that before one can routinely evaluate the capital energy requirements and environmental impacts of different buildings and building components, the information available to designers requires substantial upgrading. While there is some energy data available for domestic construction in several countries, even that has resulted mainly from one-off research exercises which have not been updated to take account of changing processes. The energy data for commercial buildings is even more sparse.

What is needed is a database containing estimates of the range and distribution (ideally to IFIAS Level 4, but at least to Level 2) of the Gross Energy Requirements of building materials and components, manufactured and assembled in different ways, together with a comparative assessment of their overall environmental impact; plus consistent methodologies for the use of such a database to enable realistic comparisons to be made of the effects of using different materials.

In the past, such a concept would have been unrealistic, but the development of input-output analysis techniques, the availability of significant computer power, plus the traditional methods of the quantity surveyor, not to mention the motivation provided by the new wave of environmental consciousness, have made this an attainable goal. However, without the database described above, evaluation of the energy and environmental cost-benefit of alternative design options will not be possible. The time is long overdue for a more sustained research effort in this direction - another worthwhile challenge for the members of CIB Task Group 16?

**References**


Baird, G. and Chan, S.A., 1983 *Energy Cost of Houses and Light Construction Buildings and Remodelling of Existing Houses*, Report No 76, New Zealand Energy Research and Development Committee, University of Auckland, Auckland, 77pp.

Baird, G., Donn, M.R., Pool, F., Brander, W.D.S. and Chan, S.A., 1984: *Energy Performance of Buildings*, CRC Press, Florida, 202pp.

Honey, B.G. and Buchanan, A.H., 1992: *Environmental Impacts of the New Zealand Building Industry.* Research Report 92-2, Department of Civil Engineering, University of Canterbury, Christchurch, 161pp.

IFIAS, 1974: *Energy Analysis Workshop on Methodology and Convention*, International Federation of Institutes for Advanced Study, Workshop Report No. 6, Stockholm.

IFIAS, 1975: *Workshop on Energy Analysis and Economics*, International Federation of Institutes for Advanced Study, Workshop Report No. 9, Stockholm, 103pp.

Kegel, R.A., 1975: The Energy Intensity of Building Materials, *Heating, Piping, Air Conditioning*, June 1975, pp 37-41.

McArdle, S.A., Moylan, S.J., Pedler, S.D.M and Webb, G.J., 1993: *Embodied energy thesis - case study analysis of the embodied energy of office construction*, Faculty of Design and Technology, School of Architecture and Building, Deakin University, Geelong, 135pp + appendices.

Stein, R.G., 1977: *Architecture and Energy*, Anchor Press / Doubleday, New York, 322pp.

Storey, J.B and Baird, G., 1994: Sustainable Building Design in the City, *Transactions of the Institution of Professional Engineers New Zealand*, 20 (1/GEN), pp 7-14.

Treleaven, C.D., 1993: *The embodied energy content and thermal performance of commercial office type low rise buildings constructed from a range of building materials,* Diploma in Environmental Studies Research Report, Victoria University, Wellington, 110pp.