AN ASSESSMENT OF THE ENERGY AND WATER EMBODIED IN COMMERCIAL BUILDING CONSTRUCTION

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SUMMARY

Growing global concern regarding the rapid rate at which humans are consuming the earth's precious natural resources is leading to greater emphasis on more effective means of providing for our current and future needs. Energy and fresh water are the most crucial of these basic human needs. The energy and water required in the operation of buildings is fairly well known. Much less is known about the energy and water embodied in construction materials and products. It has been suggested that embodied energy typically represents 20 times the annual operational energy of current Australian buildings. Studies have suggested that the water embodied in buildings may be just as significant as that of energy. As for embodied energy, these studies have been based on traditional analysis methods, such as process and input-output analysis. These methods have been shown to suffer from errors relating to the availability of data and its reliability. Hybrid methods have been developed in an attempt to provide a more reliable assessment of the embodied energy and water associated with the construction of buildings. This paper evaluates the energy and water resources embodied in a commercial office building using a hybrid analysis method based on input-output data. It was found that the use of this hybrid analysis method increases the reliability and completeness of an embodied energy and water analysis of a typical commercial building by 45% and 64% respectively, over traditional analysis methods. The embodied energy and water associated with building construction is significant and thus represents an area where considerable energy and water savings are possible over the building life-cycle. These findings suggest that current best-practice methods of embodied energy and water analysis are sufficiently accurate for most typical applications, but this is heavily dependent upon data quality and availability.

Keywords: commercial buildings, embodied energy analysis, embodied water analysis, hybrid analysis

1. INTRODUCTION

With the construction and operation of buildings accounting for an increasing proportion of the energy and water consumed in Australia there is now widespread acceptance that building designers must ensure that new additions to the building stock minimise their life-cycle energy and water consumption. Environmental assessment of buildings typically focuses on the consumption of operational energy and water requirements in an attempt to minimise building energy and water consumption. Whilst the operation of Australian buildings accounts for around 20% of total energy consumption nationally, the energy consumed through the other stages of a building's life may be just as significant across the industry. The embodied energy and water include the extraction and processing of raw materials, manufacture of building materials and products, and construction of the building.

Previous studies have assessed the energy embodied in building construction, but these have usually been based on incomplete data or methods. Many of these studies have used traditional analysis methods, such as process analysis and input-output (I-O) analysis. More recently, hybrid analysis methods have been developed, combining these two traditional methods, in an attempt to provide a more comprehensive assessment of the embodied resources associated with the construction of buildings. The water embodied in building construction has rarely been considered. The same methods used to assess the energy embodied in buildings can be applied to the issue of embodied water analysis. **The aim of this research is therefore to assess the embodied energy and water associated with commercial building construction**.

2. BACKGROUND

The total life-cycle energy requirements of buildings include their operational energy and embodied energy [1-2]. Operational energy has been the subject of much research into energy conservation and efficiency, and includes that used for heating, cooling, ventilation, lighting, vertical transport and other power. The operational requirements of buildings have also received most attention in relation to water consumption. Embodied energy has been largely ignored in studies on building energy conservation and efficiency, whilst the embodied water associated with buildings has rarely ever been considered. Embodied energy and water incorporates the energy and water which is used through the combined processes of extracting raw materials from the ground, processing, manufacturing and construction [3]. The embodied energy and water of an entire building, or an item, or a basic material, comprises direct and indirect energy and water. Indirect energy and water is used to create the inputs of goods and services to the main process, whereas direct energy and water is that used directly for the main process, whether it be the construction of the building, product assembly, or material manufacture [4] (Fig. 1.).

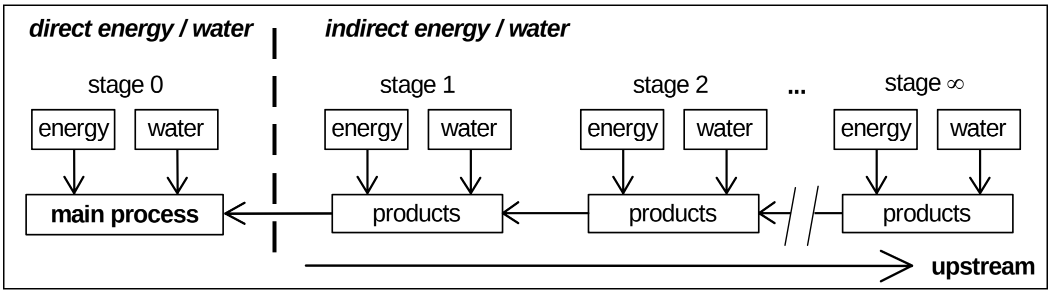

Figure 1. Embodied energy and water analysis system boundary (after [4])

Treloar [5] and Fay, Treloar and Iyer-Raniga [3] have shown that the embodied energy portion of a building’s life-cycle energy consumption can account for a significant portion of its total life-cycle energy consumption. Initial studies have suggested that building embodied water is also significant [6-7]. However, the studies performed to date have not included any specific data from individual materials manufacturing processes, being based solely on I-O analysis. While I-O analysis is considered to be comprehensive, it is subject to errors and therefore the studies performed using this method are considered inferior to those using more complex analysis methods, particularly those that have been performed relating to the issue of embodied energy.

Whilst improvements in efficiency are being made in terms of operational energy and water consumption, more emphasis now needs to be placed on the increasingly significant embodied energy and water component. Reliable methods for assessing environmental impacts, especially energy and water consumption, within the construction sector are needed to assist in identifying the most significant areas of consumption.

There are a number of methods that can and have been used for the embodied energy analysis of a building or product. These methods are able to be applied to embodied water analysis. The accuracy and extent of an embodied energy or water analysis is thus dependent on which of the main analysis methods is chosen: process analysis, I-O analysis or hybrid analysis [4].

The process analysis method is seen to have major limitations, most significantly, system incompleteness. The most important stage of this method is the quantification of the inputs to the product or system. Traditionally, a boundary has been created around the quantification of inputs to the product(s) being assessed, mainly due to difficulties in obtaining necessary data and the understanding of these data. Many inputs are therefore neglected in the quantification of inputs to a product, and thus the system is incomplete. This is primarily due to the complexity of the upstream requirements for goods and services [8]. The magnitude of the incompleteness varies with the type of product or process and depth of study but can be 50% or more [4], [9]. These errors can be exacerbated as more and more process analysis data is collected, due to the flawed paradigm. Results of studies by Bullard, Penner and Pilati [10], Miller and Blair [11], Peet and Baines [12], Lenzen [13], Treloar, Love and Holt [14] and Lenzen and Treloar [15] have proved that even extensive process-based inventories do not achieve sufficient system completeness.

National average statistics that model the financial flows between sectors of the economy, referred to as I-O data, can be used to fill the gaps that are caused by system incompleteness [4]. Each of these economic sectors is characterised by a total energy and water intensity in units of GJ or kL/$1000 of product. These intensities represent the amount of energy or water used to produce $1000 worth of products represented by that specific sector. An I-O analysis is simply a multiplication of the respective intensity by the cost of any particular product, divided by 1000.

The use of I-O data in an I-O analysis is generally treated as a black box, with no understanding of the composition values being assumed in the model for each process. Also, because they are based on many inherent assumptions appropriate for national modelling, even a perfect I-O model may not lead to valid results for a particular product [16-17]. While I-O analysis is systemically complete, some I-O systems are inappropriately constructed, and may leave out significant aspects of the economy, as demonstrated by Lenzen [9] and Lenzen and Treloar [18] for capital investment. Some of the other main limitations of I-O analysis are detailed by Miller and Blair [11] and Lenzen [9] and include homogeneity and proportionality assumptions, sector classification and aggregation.

Due to the inherent problems with process analysis and I-O analysis, hybrid methods of analysis have been developed in an attempt to minimise the limitations and errors of these traditional methods [19]. Hybrid methods combine process data and I-O data in a variety of formats [4], [10], [19]. Whilst providing a more comprehensive system boundary, with the use of I-O data, hybrid methods based on process data, namely process-based hybrid analysis [10], suffer from the same inherent limitations of process analysis [4]. The I-O systemic completeness is only applied to the components of the model upstream from the process analysis data. However, hybrid methods based on I-O data are considered systemically complete in that they are based on a much more comprehensive system boundary.

I-O-based hybrid analysis combines process data and I-O data in a different way to process-based hybrid analysis, in order to avoid downstream and horizontal truncation. The direct inputs to a specific product or process being studied are calculated using process analysis. While process data is not usually easy to obtain, its use maximises the reliability of the analysis at this stage. Further upstream indirect processes are accounted for by either further applications of process analysis or I-O analysis when the process analysis data is unavailable or is considered too time consuming to collect relative to the significance of the process in question [4]. The I-O model is disaggregated into paths, with each path representing the flow of energy or water from one economic sector to the next, for each and every activity. This allows the paths for which process analysis data is available to be subtracted from the I-O model, leaving a remainder that can be applied to the study in an holistic manner to fill all the remaining gaps (as demonstrated in [14]).

Those studies that have assessed the energy embodied in building construction have usually been based on incomplete data or methods (e.g. [1-3], [20-22]). These studies have used the range of methods outlined above, and thus, depending on which method has been used, end up with varying and, in some cases, conflicting results.

3. METHOD

The need for a hybrid analysis method for assessing the energy and water embodied in commercial buildings comes about by the compounding errors evident in traditional process and I-O analysis methods. More recently, the use of process-based hybrid analysis has been shown to also suffer from many of the limitations associated with these traditional methods of analysis. A hybrid analysis method based on I-O data is expected to provide a more reliable and comprehensive analysis than any of these previously used methods. To highlight the importance of using an I-O-based hybrid analysis, the results from this analysis method were compared to the results from traditional and process-based hybrid analysis methods. These methods were applied to the range of building materials contained within the chosen case study building. The steps involved in the I-O-based hybrid analysis method are detailed below. For this, the steps for process analysis, I-O analysis and process-based hybrid analysis are also required (Fig. 2).

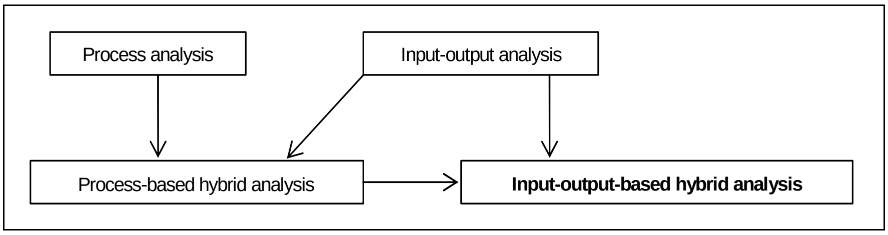

Figure 2. Outline of method for I-O-based hybrid analysis

3.1 Input-output-based hybrid analysis

An I-O-based hybrid analysis uses the data gathered in a traditional process analysis, and the figure from a process-based hybrid analysis and increases the completeness of the analysis even further, with the use of I-O data. For this study, process data was derived based on the quantities of material inputs into the case study building and a material intensity database [23].

A number of hybrid material intensity figures, combining both process and I-O data, were derived. A hybrid energy and water intensity figure was calculated for all of the most common basic materials. These figures are expressed in GJ or kL/unit (usually t, kg, m^2, m^3) of material and represent a simplified method of incorporating process data into the analysis, giving the amount of energy and water embodied in, for example, a kilogram of that material. For each basic material, the hybrid material intensity (I_M) was calculated using equation (1).

$$I_M = PI_M + \left(TI_n - TI_M\right) \times \frac{\$_M}{1000} \tag{1}$$

Where:

PI_M = the process material intensity;

TI_n = the total intensity of I-O sector *n*, representing the basic material;

TI_M = the total intensity of the I-O path representing the basic material;

$\$_M$ = the total price of the basic material.

Once the hybrid material energy and water intensities had been calculated, they were multiplied by the delivered quantities of basic materials of the case study building. These individual material embodied energy and water figures were then summed to obtain the respective process-based hybrid analysis values for the building.

National I-O tables, produced by the Australian Bureau of Statistics [24] were combined with national energy data from the Australian Bureau of Agricultural and Resource Economics [25] and national water data from the Australian Bureau of Statistics [26] to develop an energy-based and water-based I-O model of the economy. A number of these models have been developed for Australia (e.g. [4], [27]). The I-O tables are divided into 106 sectors of the Australian economy, e.g. ‘residential construction’, ‘road transport’, ‘other construction’. For each one of these economic sectors, a direct and total energy and water intensity was calculated in units of GJ or kL/\$1000 of product, representing the amount of energy or water used directly and in total to produce \$1000 worth of products from that specific sector. The I-O theory underlying these calculations is extensively documented elsewhere ([4], [11], [19], [28-30]) and shall therefore not be repeated here. In a hybrid I-O analysis of any product, the product’s component breakdown is linked to the economic sectors in order to determine the energy and water intensities that should be applied from the I-O model.

The I-O model was disaggregated to allow the inputs for which process analysis data is available to be subtracted, leaving a remainder that was applied to the study in a holistic manner to fill all the remaining gaps, as demonstrated by Treloar, Love and Holt [14]. From the inputs subtracted from the relevant sectors of the economy from which the product belongs (‘other construction’ sector), the inputs that were counted in the process analysis inventory were identified. The total energy and water intensity of each of the inputs represented in the process analysis inventory was subtracted from the total energy and water intensity of the sector. Whenever a process analysis value was available then the relevant input from the input extraction was subtracted from the total energy and water intensity of the sector to avoid double counting.

The remainder of the unmodified inputs (the total energy or water intensity of the sector minus those inputs subtracted (GJ or kL/\$1000)) were then multiplied by the price of the case study building (\$) and divided by 1000 to give the additional energy and water inputs (GJ and kL) for the product. The process-based hybrid analysis value was then added to this figure, minus the direct energy and water components (as these are included in the remainder of unmodified inputs) to give the I-O-based hybrid analysis total.

3.2 Commercial building case study

A three-storey commercial office building was analysed to demonstrate the embodied energy and water associated with commercial building construction. The building chosen for this analysis was designed to be environmentally sustainable and is located in Melbourne, Australia. It has a gross floor area of 11 600m^2 and includes two levels of office space, a glazed atrium, an auditorium, canteen and enclosed car parking. The constructional elements of this building consist of a reinforced concrete slab substructure, steel structure, external walls of pre-cast concrete and aluminium cladding panels, toughened glass solar double glazed windows, toughened glass curtain walls, internal walls of single skin brickwork and Hebel blocks, and floor finishes including insitu terrazzo and marble.

The system boundary considered for the collection of process data for this case study included those items which were part of the bill of quantities used for the analysis [31]. The main building elements which formed part of this bill included the building substructure, columns, floors, staircases, roof, walls, windows, doors, screens and finishes. Items such as fitments, sanitary fixtures, appliances, plumbing, electrical and external items were not included, due to the difficulty associated with obtaining this data. The exclusion of these items should have little impact on the results of the analysis as these items are generally considered to be small in relation to the total embodied energy and water of this type of building [5]. The high level of detail used in the quantification of those items which have been included within this system boundary is considered sufficient for a comprehensive assessment of the energy and water embodied in this commercial building.

The total and direct energy and water intensities of the ‘other construction’ sector, which include commercial buildings, were used in the embodied energy and water calculation of the commercial office building.

4. RESULTS AND DISCUSSION

The results of the analysis of the energy and water embodied in the commercial building are presented in this section. These results are presented for the range of embodied energy and embodied water analysis methods currently available, including the I-O-based hybrid analysis method.

4.1 Embodied energy

The embodied energy analysis results of the commercial building case study, using each of the embodied energy analysis methods, are shown below (Table 1). These results show both the process and I-O data proportions for the I-O-based hybrid analysis values of the energy embodied in the commercial building.

PA (GJ/m^2)	I-OA (GJ/m^2)	PHA (GJ/m^2)	I-O-based hybrid analysis (I-OHA)		
			Total (GJ/m^2)	% PA value	% I-O value
8.0	12.5	17.8	25.8	31	69

Table 1. Embodied energy of commercial building case study for each analysis method

A large range of embodied energy figures is evident for the commercial building studied, depending on the method of analysis used (Table 1). These results range from 8.0 GJ/m^2 using process analysis, to 25.8 GJ/m^2 using I-O-based hybrid analysis. Table 1 shows that the process analysis embodied energy value (8.0 GJ/ m^2) of the commercial building case study is considerably lower than the value calculated through the I-O analysis (12.5 GJ/m^2). This difference in values can be attributed to the truncation typically associated with process analysis, representing the gap between the respective methods.

The process-based hybrid embodied energy figure shows the effect of one method of combining process data and I-O data. The process-based hybrid analysis value (17.8 GJ/m^2) is significantly higher than the respective I-O analysis value. This is due to the sum of the process analysis data used to substitute into the I-O model being higher than the sum of the I-O values for which it replaced. As expected, the process-based hybrid analysis value is also higher than the process analysis value due to the inclusion of I-O data.

The I-O-based hybrid analysis value shows an even greater increase in the total embodied energy value for the commercial building case study over the process-based hybrid analysis value (45% increase) (Table 1). This increase reflects the improved system completeness associated with an I-O-based hybrid analysis, through the inclusion of I-O data to fill the gaps associated with the process-based hybrid analysis. The percentage of the total I-O-based hybrid embodied energy value made up of I-O data is 69%. This figure represents the gap in traditional process analysis.

The I-O-based hybrid embodied energy analysis value can be broken down to show the total embodied energy for each material group (Fig. 3) and for each building element (Fig. 4) of the commercial building case study. These material group and elemental figures also show the process and I-O data components, of the total embodied energy of the specific material groups and elements.

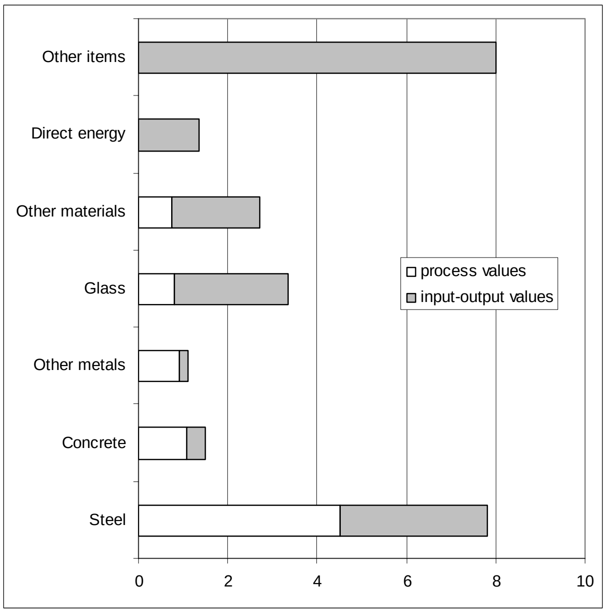

Figure 3. Commercial building embodied energy, by material group (GJ/m^2 GFA)

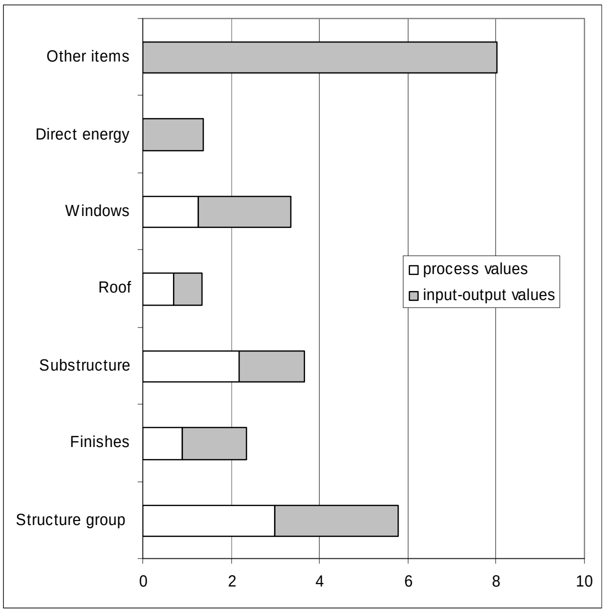

Figure 4. Commercial building embodied energy, by building element (GJ/m^2 GFA)

Figure 3 shows that the embodied energy of the commercial building is dominated by the 'steel' materials group (30%) and 'other items' group (31%). The 'other items' group includes all of the indirect inputs to the building not accounted for by a process-based hybrid analysis, typically including the energy consumed in providing financial and administrative services and the energy used in the transformation of basic materials (e.g. steel) into complex items (e.g. motors). The significance of the 'other items' group shows the gaps that currently exist with process-based hybrid analysis methods. Other than the 'other metals', 'steel' and 'concrete' material groups, process data typically accounts for less than 45% of the total energy embodied in each material group. Whilst individually these material groups represent a small proportion of the total energy embodied in the building case study, combined they represent almost a quarter of the total embodied energy of the building. The gaps left by process data alone lead to compounding errors at the whole building level.

The 'structure' group (22%) and 'other items' group (31%) dominate the embodied energy in terms of building elements (Fig. 4). For each of the element groups, other than 'direct energy' and 'other items' groups which are accounted for in total by I-O data, process data accounts for less than 60% of the energy embodied in each element. Whilst a process-based hybrid analysis can be used to account for the gaps associated with the individual building elements, the 'other items' group can only be accounted for with the use of the I-O-based hybrid analysis. This shows that the gap associated with a process-based hybrid analysis figure, in this case, is as high as 31%.

On the whole building level it is shown that the embodied energy added through the use of I-O data is quite significant at 69% (Table 1). Up to 45% of this I-O data is attributable to the 'other items' component. The remainder of the I-O data is associated with the system boundary truncation of those inputs calculated using process analysis, traditionally considered as the gap [10].

4.2 Embodied water

The embodied water analysis results of the commercial building case study, using each of the analysis methods, are shown below (Table 2). These results show both the process and I-O data proportions for the I-O-based hybrid analysis values of the water embodied in the commercial building.

PA (kL/m^2)	I-OA (kL/m^2)	PHA (kL/m^2)	I-O-based hybrid analysis (I-OHA)		
			Total (kL/m^2)	% PA value	% I-O value
6.3	27.6	32.9	54.1	12	88

Table 2. Embodied water of commercial building case study for each analysis method

As is the case for the results of the embodied energy analysis, a large range of embodied water figures is evident for the building case study (Table 2). These results range from 6.3 kL/m^2 using process analysis, to 54.1 kL/m^2 using I-O-based hybrid analysis. Table 2 shows that the process analysis embodied water value (6.3 kL/m^2) of the building case study is considerably lower than the value calculated through the I-O analysis (27.6 kL/m^2). As for embodied energy, this difference in values can be attributed to the truncation typically associated with process analysis, representing the gap between the respective methods.

The I-O-based hybrid analysis value shows a significant increase above the process-based hybrid analysis value (64% increase) (Table 2). This is due to a corresponding increase in the proportion of ‘other items’, not accounted for with a process-based hybrid analysis. The percentage of the total I-O-based hybrid embodied water value made up of I-O data is 88%. This figure represents the gap in traditional process analysis and indicates that, compared to the I-O data component of the embodied energy value - 69% (Table 1), even less process water data exists than process energy data.

As was done for the embodied energy value, the I-O-based hybrid embodied water value can be broken down to show the total water embodied in each material group (Fig. 5) and in each building element (Fig. 6) of the building case study. These material group and elemental figures also show the process and I-O data components, of the total embodied water of the specific material groups and elements.

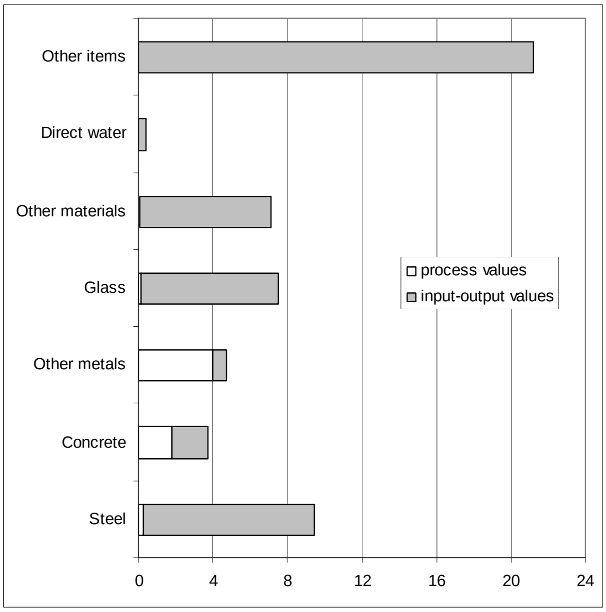

Figure 5. Commercial building embodied water, by material group (kL/m^2 GFA)

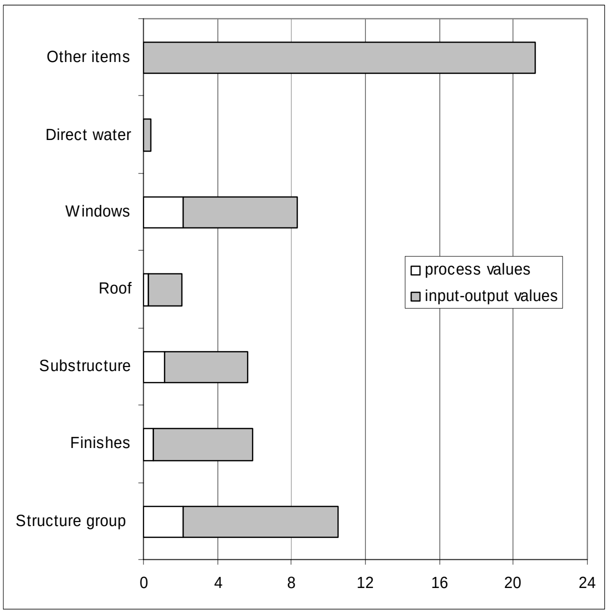

Figure 6. Commercial building embodied water, by building element (kL/m^2 GFA)

The water embodied in the case study building is dominated by the ‘steel’ materials group (17%) and ‘other items’ group (39%) (Fig. 5). As for the embodied energy material group breakdown, the ‘other items’ group contributes the most to the water embodied in the case study building, however, by an even greater proportion. In this case, the ‘other items’ group includes all of the indirect inputs to the building not accounted for by the process-based hybrid analysis, typically including the water consumed in providing financial and administrative services and the water used in the transformation of basic materials (e.g. steel) into complex items (e.g. motors). This again shows the gaps associated with the process-based hybrid analysis method and the significance of using the I-O-based hybrid analysis method.

Whilst the ‘other metals’ group contains a high proportion of process data, in this case the water embodied in the aluminium within the building (85%), the proportion of process water data for all other material groups is relatively insignificant.

The ‘other items’ group (39%) dominates the elemental breakdown of the water embodied in the case study building, followed by the ‘structure’ group (19%) and ‘windows’ group (15%) (Fig. 6). The direct water associated with the case study building is shown to be insignificant, accounting for less than 1% of the total water embodied in the building. The quantification of indirect water requirements is therefore of most importance.

On the element group level, other than ‘direct water’ and ‘other items’ groups which are accounted for in total by I-O data, process data accounts for less than 27% of the water embodied in each element. As for the embodied energy analysis, a process-based hybrid analysis can be used to account for the gaps associated with the individual building elements. Again, the ‘other items’ group can only be accounted for with the use of the I-O-based hybrid analysis and thus a gap as high as 39% is associated with the process-based hybrid analysis figure of the water embodied in the case study building.

On the whole building level it is shown that the embodied water added through the use of I-O data (88%) (Table 2) is even more significant than the I-O data proportion of the energy embodied within the case study building (69%) (Table 1). Up to 44% of this I-O data is attributable to the ‘other items’ component. The remainder of the I-O data is associated with the system boundary truncation of those inputs calculated using process analysis.

A comparison between the embodied energy and water values for the case study building shows that the direct water requirements represent a much smaller proportion of the total water embodied in the building (0.7%) than the direct energy requirements represent of the total energy embodied in the building (5.3%). This finding suggests that the indirect water requirements are of even greater importance than the indirect energy requirements of the building, highlighting the need for further in depth analysis of the indirect water requirements of commercial building construction. However, the proportion of the embodied water system boundary defined by process data (12%) is much lower than the proportion of the embodied energy system boundary defined by process data (31%). Clearly, more process water data is required for urgent improvements in the reliability of embodied water analyses.

Whilst I-O analysis is considered to be systemically complete, the I-O analysis results for both the embodied energy and water of the case study building show the process-based hybrid analysis values being higher, despite the truncation associated with this method. This is due to the sum of the process analysis data that was used to substitute into the I-O model, being higher than the sum of the I-O values for which it replaced. This also reflects some of the errors associated with I-O data in that it does not always reflect the more specific process data.

In terms of the material group breakdown of the embodied energy and water requirements of the case study building, the ‘other items’ group accounts for the greatest proportion in both cases (31 and 39%, respectively), followed by, in both cases, the ‘steel’ materials group. The ‘other items’ group covers those inputs not accounted for in a typical process-based hybrid analysis and thus shows the need for using an I-O-based hybrid analysis method for assessing the embodied energy and water associated with buildings.

5. CONCLUSION

This paper has evaluated the embodied energy and water associated with a commercial office building using a hybrid analysis method based on I-O data. It was found that the use of this hybrid analysis method increases the embodied energy and water of this commercial building by 45% and 64% respectively when compared to using a process-based hybrid analysis. Whilst the use of a process-based hybrid analysis has been shown to improve the completeness of a process analysis, a hybrid approach based on I-O analysis, as used in this study, has shown to provide an even more comprehensive assessment of the embodied energy and water associated with commercial building construction. The energy and water embodied in the case study building was found to be 25.8GJ/m^2 and 54.1kL/m^2 respectively. This study has also highlighted the truncation associated with an embodied energy and water analysis based on process analysis. These findings suggest that current best-practice methods of analysis are sufficiently accurate for assessing the embodied energy and water associated with commercial buildings, but this is heavily dependant upon data quality and availability.

A comparison between embodied energy and water results shows that a considerably lower proportion of the embodied water system boundary is defined by process data, in comparison to the proportion of the embodied energy system boundary defined by process data. This makes it clear that much more process water data is urgently required.

Whilst this study has considered only one building, it may be possible to extrapolate these findings to other building types and other products, such as furniture, appliances, renewable energy systems and other technologies. Significant increases in embodied energy and water values are likely through the use of the I-O-based hybrid analysis method across all products of the economy, due to the increased complexity associated with this method of analysis when compared to traditional analysis methods.

This study has shown that the energy and water embodied in commercial buildings is much more substantial than previously thought. With recent improvement in terms of building operational efficiency, the importance of considering methods of reducing the embodied energy and water associated with buildings is of increasing concern.

This analysis is intended as a comparison only of the energy and water embodied in building construction as a greater breadth of case studies is required to enable specific conclusions to be applied to the construction industry in a holistic manner. Further research involves using the I-O-based hybrid analysis method to assess the water embodied in other buildings and building types as well as other products, and an evaluation of the data reliability for embodied water analysis.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1 Bekker, P.C.F. (1982) A Life-Cycle Approach in Building, *Building and Environment,* **17**(1), 55-61.

2 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, Auckland, November.

3 Fay, R., Treloar, G. and Iyer-Raniga, U. (2000) Life-Cycle Energy Analysis of Buildings: A Case Study, *Building Research and Information,* **28**(1), 31-41.

4 Treloar, G.J. (1997) Extracting Embodied Energy Paths from Input-Output Tables: Towards an Input-Output-Based Hybrid Energy Analysis Method, *Economic Systems Research,* **9**(4), 375-391.

5 Treloar, G.J. (1996) *The Environmental Impact of Construction - A Case Study,* ANZAScA Monographs 001, Australia and New Zealand Architectural Science Association, Sydney, November, 95p.

6 Lenzen, M. and Foran, B. (2001) An Input-Output Analysis of Australian Water Usage, *Water Policy,* **3**(4), 321-340.

7 Treloar, G.J., McCormack, M., Palmowski, L. and Fay, R. (2004) *Embodied Water of Construction,* Practice Note GEN 58, Building Design Professionals Environment Design Guide, Red Hill, May, 9p.

8 Lave, L.B., Cobas-Flores, E., Hendrickson, C.T. and McMichael, F. (1995) Life-Cycle Assessment: Using Input-Output Analysis to Estimate Economy-Wide Discharges, *Environmental Science and Technology,* **29**(9), 420A-426A.

9 Lenzen, M. (2001a) Errors in Conventional and Input-Output-Based Life-Cycle Inventories, *Journal of Industrial Ecology,* **4**(4), 127-148.

10 Bullard, C.W., Penner, P.S. and Pilati, D.A. (1978) Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis, *Resources and Energy,* **1**, 267-313.

11 Miller, R.E. and Blair, P.D. (1985) *Input-Output Analysis - Foundations and Extensions,* Prentice Hall, New Jersey.

12 Peet, N.J. and Baines, J.T. (1986) *Energy Analysis: a Review of Theory and Applications,* Report No.126, New Zealand Energy Research and Development Committee, Auckland, 56p.

13 Lenzen, M. (1999) Greenhouse Gas Analysis of Solar-Thermal Electricity Generation, *Solar Energy,* **65**(6), 353-368.

14 Treloar, G.J., Love, P.E.D. and Holt, G. (2001) *Using National Input-output Data for Embodied Energy Analysis of Individual Residential Buildings*, Construction, Management and Economics, **19**, 49-61.

15 Lenzen, M. and Treloar, G.J. (2003) Differential Convergence of Life-Cycle Inventories Toward Upstream Production Layers: Implications for Life-Cycle Assessment, *Journal of Industrial Ecology*, **6**(3-4), 137-160.

16 Suh, S. (2000) *Missing Inventory Estimation Tool (MIET): http://www.leidenuniv.nl/cml/_ssp/software/*, last accessed 5th November.

17 Carnegie Mellon University (2002) *Economic Input-Output Life Cycle Assessment: http://www.eiolca.net/*, last accessed 5th November.

18 Lenzen, M. and Treloar, G.J. (2004) Endogenising Capital – A Comparison of Two Methods, *Journal of Applied Input-Output Analysis*, in press.

19 Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. and Norris, G. (2004) System Boundary Selection in Life-Cycle Inventories, *Environmental Science and Technology*, **38**(3), 657-664.

20 Tucker, S.N., Salomonsson, G.D., Treloar, G.J., MacSporran, C. and Flood, J. (1994) Environmental Impact of Energy Embodied in Construction, *Proceedings: RITE workshop*, Kyoto, October 31 - November 1, 5p.

21 Lawson, W.R. (1996) *Building Materials, Energy and the Environment: Towards Ecologically Sustainable Development*, The Royal Australian Institute of Architects, Red Hill, 135p.

22 Pullen, S. (2000) Energy Used in the Construction and Operation of Houses, *Architectural Science Review*, **43**(2), 87-94.

23 Grant, T. (2002) *Australian Material Inventory Database of Life Cycle Assessment Values for Materials*, RMIT, Melbourne.

24 Australian Bureau of Statistics (2001) *Australian National Accounts, Input-Output Tables, 1996-97*, ABS Cat. No. 5209.0, Australian Bureau of Statistics, Canberra, Australia.

25 Australian Bureau of Agricultural and Resource Economics (2000) *Australian Energy Consumption and Production*, Table C1AUST, Historical data update, Electronic file (unpublished), Australian Bureau of Agricultural and Resource Economics.

26 Australian Bureau of Statistics (2000) *Water Account for Australia, 1993-94 to 1996-97*, ABS Cat. No. 4610.0, Australian Bureau of Statistics, Canberra, Australia.

27 Lenzen, M. and Lundie, S. (2002) *Input-Output Model of the Australian Economy based on Published 1996-97 Australian Input-Output Data*.

28 Leontief, W. (1966) *Input-Output Economics*, Oxford University Press, New York, USA.

29 Proops, J.L.R. (1977) Input-Output Analysis and Energy Intensities: A Comparison of Methodologies, *Applied Mathematical Modelling*, **1**(March), 181-186.

30 Lenzen, M. (2001b) A Generalised Input-Output Multiplier Calculus for Australia, *Economic Systems Research*, **13**(1), 65-92.

31 Jones, D.G. (2002) *Toyota Corporate Headquarters: Bill of Quantities*, D.G. Jones and Partners PTY LTD, Melbourne, 60p.