Assessment of embodied energy analysis methods for the Australian construction industry

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ABSTRACT: Environmental assessment of buildings typically focuses on operational energy consumption in an attempt to minimise building energy consumption. Whilst the operation of Australian buildings accounts for around 20% of total energy consumption nationally, the energy embodied in these buildings represents up to 20 times their annual operational energy. Many previous studies, now shown to be incomplete in system boundary or unreliable, have provided much lower values for the embodied energy of buildings and their products. Many of these studies have used traditional embodied energy analysis methods, such as process analysis and input-output (I-O) analysis. More recently, hybrid embodied energy analysis methods have been developed, combining these two traditional methods. These hybrid methods need to be compared and validated, as these too have been considered to have several limitations.

This paper aims to evaluate a recently developed hybrid method for the embodied energy analysis of the Australian construction industry, relative to traditional methods. Recent improvements to this hybrid method include the use of more recent I-O data and the inclusion of capital energy data. These significant systemic changes mean that a previous assessment of the methods needs to be reviewed. It was found that the incompleteness associated with process analysis has increased from 49% to 87%. These findings suggest that current best-practice methods of embodied energy analysis are sufficiently accurate for most typical applications. This finding is strengthened by recent improvements to the I-O model.

Conference theme: Architecture and the environment
Keywords: buildings, embodied energy analysis, input-output analysis, hybrid analysis

INTRODUCTION

Whilst the operational energy consumption of buildings accounts for the highest proportion of the total energy consumed in the physical life cycle of a building, there is a considerable amount of energy that is consumed in the other stages of a building's life. These stages include the extraction of raw materials; processing of raw materials; manufacture of building materials and products; construction of the building; maintenance; refurbishment; demolition; and disposal. These stages incorporate the embodied energy of the building. Many previous studies have shown that the embodied energy portion of a building's life cycle energy consumption can account for a significant portion of the total life cycle energy consumption of a building. There is therefore a need to assess the life cycle energy consumption of buildings and building products in order to determine the areas in which the majority of this energy is being consumed and where and how a reduction is possible.

Traditional methods of quantifying embodied energy, namely process analysis and I-O analysis, have been shown to have significant limitations, despite the different benefits each method offers. The most important stage of an embodied energy analysis is the quantification of the inputs to the product or system. Traditionally, a boundary has been drawn around the quantification of inputs to the product being assessed, mainly due to difficulties in obtaining necessary data and the understanding of this data. Many inputs are therefore neglected in the quantification of inputs to a product, and thus the system boundary is incomplete. These inputs are often incorrectly assumed to be negligible.

Due to the inherent problems with process analysis and I-O analysis, hybrid methods of embodied energy analysis have been developed in an attempt to minimise the limitations and errors of these traditional methods. Hybrid methods combine both process data and I-O data in a variety of formats. Few attempts have been made to validate particularly recently developed hybrid embodied energy analysis methods, relative to traditional methods. Therefore the aim of this paper is to evaluate a recently developed hybrid method for the embodied energy analysis of the Australian construction industry, relative to traditional methods, considering recent improvements to this method.

1. BACKGROUND

The embodied energy of an entire building, or an item, or a basic material in a building, comprises direct and indirect energy. Indirect energy is used to create the inputs of goods and services to the main process, whereas direct energy is that used directly for the main process, whether it is the construction of the building, product assembly, or material manufacture (Figure 1).

![Figure 1: Embodied energy analysis system boundary](image-url)
1.1 Embodied energy analysis methods

The accuracy and level of comprehensiveness associated with an embodied energy analysis is dependent on which of the main analysis methods is chosen: process analysis, I-O analysis or hybrid analysis (Trelaro 1997). The two base methods of embodied energy analysis are susceptible to different types of errors and have different benefits. The most widely used of these methods, process analysis, can be significantly incomplete. Results of studies by Bullard, Penner and Pilati (1978), Miller and Blair (1985), Peet and Baines (1986) and Lenzen and Dey (2000) have proved that even extensive process-based inventories do not achieve sufficient system completeness. This is primarily due to the complexity of the upstream requirements for goods and services (Lave et al. 1995). The magnitude of the incompleteness varies with the type of product or process and depth of study but can be 50% or more (Trelaro 1997, Lenzen 2001a). These errors can be exacerbated as more and more process analysis data is collected, due to the flawed paradigm of the local systems. The incompleteness associated with process analysis can be improved with the use of I-O data. The second base method of embodied energy analysis is I-O analysis. This method uses national average I-O data for each sector of the economy and is considered by many researchers to be more comprehensive than process analysis (eg. inter alia, Trelaro 1997, Lenzen 2001a, Lave et al. 1995). This method has a systemically complete system boundary, which can therefore potentially solve the major drawback of the process analysis method. However, I-O analysis is generally used 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 (Suh 2000, Carnegie Mellon University 2002). For this reason, the I-O model should initially be seen as a scoping tool and secondly as an estimation method for missing data from the process analysis method. While I-O analysis is systemically complete, some I-O systems are inappropriately constructed, and may leave out significant aspects of the economy (for example, capital investment, Lenzen 2001a). Some of the other main limitations of I-O analysis are detailed by Miller and Blair (1985) and Lenzen (2001a) and include: homogeneity assumption, proportionality assumption, sector classification and aggregation.

Hybrid techniques attempt to combine the benefits of both base methods, while minimizing their respective limitations. Process-based hybrid analysis (after Bullard, Penner and Pilati 1978) is almost exclusively based on incomplete process analysis data, suffering similar limitations to those outlined above for the two base embodied energy analysis methods (Trelaro 1997). The I-O systemic completeness is only applied to the components of the model upstream from the process analysis data. Downstream and horizontal incompleteness can still occur, to significant levels. To some extent, these errors can therefore be compounded, despite the practitioner’s or researcher’s best efforts to minimise them.

I-O-based hybrid analysis combines process data and I-O data in a different way to process-based hybrid analysis, in order to exclude downstream and horizontal incompleteness. The direct inputs to a specific product or process being studied are calculated using process analysis. 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 (Trelaro 1997). The I-O model is disaggregated to allow the inputs for which process analysis data is available to be subtracted, leaving a remainder that can be applied to the study to fill all the remaining gaps (as demonstrated in Trelaro, Love and Holt 2001).

The energy inputs required through the manufacture of machinery and other capital equipment has always been ignored in embodied energy analysis studies. This is due to the difficulty in determining the time that the equipment was used in production for amortising these inputs (Alcorn 1997) and in calculating the inputs embodied in products through the purchase and use of capital equipment. These inputs are as much a part of a product’s life cycle as is any other direct or indirect input. Lenzen (2001b) and Gorree et al. (2002) have estimated that capital inputs may account for between 10 and 17% of the total inputs of an embodied energy analysis of any product. Unlike previous embodied energy analysis methods, the inclusion of capital input data in the I-O model used in this study provides a more comprehensive assessment of the energy embodied in particular products.

1.2 Previous embodied energy studies of buildings and building related products

In the past, embodied energy studies have been performed on a number of building types, including commercial, residential and recreational, and building related products, including, but not limited to, washing machines and other household appliances, hot water systems and photovoltaic systems. 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.

An individual residential building embodies approximately 2000 gigajoules (GJ) (Trelaro, Love and Holt 2001). Previous studies, now shown to be incomplete in system boundary, have shown significantly lower values (for example, Hill 1978, Bekker 1982, Baird and Chan 1983, Lawson 1996, Adalberth 1997, Pullen 2000, Fay, Trelaro and Iyer-Raniga 2000). The values from these studies are at most around half of that figure given by Trelaro, Love and Holt (2001). This trend does not necessarily suggest that the energy intensity of material manufacture is increasing, nor is it a factor of increasing house area. The fundamental cause of the difference in values is often the use of different embodied energy analysis methods. Therefore, this suggests that a comparison of methods is required.

The I-O-based hybrid analysis method proposed by Trelaro (1997) has been recently included in the life cycle and embodied energy studies (Crawford and Trelaro 2004, Crawford, Trelaro, and Bazilian 2002), which have demonstrated the possible significance of the choice of embodied energy analysis methods. An evaluation of this I-O-based hybrid analysis method has previously been performed (Crawford and Trelaro 2003). This I-O-based hybrid analysis method is currently preferred, but has yet to be evaluated against other embodied energy analysis methods since recent improvements to the method have occurred.

1.3 Evaluation techniques

Previously, researchers have used a number of techniques to evaluate the various methods of embodied energy analysis. These have included error analysis (various types, including truncation error analysis), gap
analysis and a comparative analysis (Treloar 1997, Lenzen 2001a). Error analysis is used to assess the error associated with the use of I-O data (Lenzen 2001a). Truncation error analysis is used to assess the extent of incompleteness associated with the use of process analysis data in a process-based hybrid analysis context (Bullard, Penner and Pilati 1978). The different forms of error analysis are used to evaluate the initial data inputs, however often these are so complex that the sum of the effects of the errors in a national I-O model can be quite different when applied to an individual product. This process can then introduce further errors, which are often ignored.

More recently, other methods have been developed to overcome this limitation in error analysis by focussing on the outputs of the embodied energy analysis methods. Gap analysis is used to assess the difference between process analysis results and hybrid analysis results, as an evaluation of the completeness of each method (Treloar 1997). A comparative analysis is used to compare the I-O values for the process analysis components that are used in an I-O-based hybrid analysis as a measure of the reliability associated with the I-O data (Treloar 1997). These last two methods are best used together to evaluate and compare embodied energy analysis methods.

This leads to a number of questions to be answered in the remainder of this paper:
1. Is the I-O-based hybrid analysis method the most comprehensive of the embodied energy analysis methods currently available?
2. Are capital energy inputs a significant contributor to the total embodied energy of buildings and related products?

2. METHOD

The need to test the I-O-based hybrid embodied energy analysis method comes about by the compounding errors evident in the process-based hybrid analysis method. In order to evaluate the I-O-based hybrid analysis method, to provide a more accurate representation its associated completeness and reliability, the results from this embodied energy analysis method were compared to the results from traditional and other hybrid embodied energy analysis methods. Each of these methods was applied to a range of building types and products. The steps involved in each of the embodied energy analysis methods are detailed below. Each method is described separately, even though the hybrid methods involve the use of the methods described before each of them. In other words, for an I-O-based hybrid analysis, these method descriptions can also be seen as the four main steps to this analysis (Figure 2).

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

2.1 Process analysis

The process analysis involved collecting process specific data for the inputs into the product being studied. The quantities of material inputs were determined based on the architectural plans, specifications, bill of quantities, the manufacturers of the various products or through assumptions where information was unavailable or unknown. The direct inputs of energy into the main product and those material inputs (direct energy into upstream material inputs are considered as indirect energy into the main product) were quantified. A material energy intensity database (Grant 2002) was used to determine the energy embodied in these material inputs. After multiplying these intensities by the material quantities, the resultant energy inputs were then summed to give the embodied energy using process analysis.

2.2 Input-output analysis

The first step of the I-O analysis was to determine the direct and total energy intensities of the appropriate sector for the product being studied. National I-O tables, produced by the Australian Bureau of Statistics (ABS) were combined with national energy data from the Australian Bureau of Agricultural and Resource Economics (ABARE) to develop an energy-based I-O model of the economy. The I-O tables were divided into the sectors of the Australian economy (for example: ‘residential construction’, ‘household appliances’, ‘road transport’). Each one of these economic sectors has a respective direct energy intensity and total energy intensity, both quantified in GJ/$1000 of product, representing the amount of energy used directly and in total to produce $1000 worth of products from that specific sector. It was therefore necessary to determine which sector the product being studied belongs to in order to determine the total energy intensities to be applied to that product. The retail price of the product was obtained from the supplier of the product, or if this was unavailable, for example for buildings, an estimate was made based on literature and/or necessary assumptions.

Traditionally, the consideration of capital inputs, such as the machinery used for the manufacture of building materials, has been ignored. Recent improvements to the I-O model include the consideration of these capital inputs, thus providing a more comprehensive and complex system boundary than ever before.

2.3 Process-based hybrid analysis

The quantities of basic materials obtained through the process analysis were used as the basis for the process-based hybrid analysis. For this, a number of hybrid material energy intensity figures, combining both process and I-O data, were derived, as detailed in Crawford (2004). A hybrid energy intensity figure was calculated for all of the most common basic materials, such as concrete, steel, timber and glass. These figures are expressed in GJ/unit (usually t, kg, m²) of material and represent a simplified method of incorporating process analysis data into the analysis, giving the quantity of energy embodied in, for example, a kilogram of that material.

Once the hybrid material energy intensities had been calculated, they were multiplied by the quantities of basic materials of the product. These individual material embodied energy figures were then summed to obtain the embodied energy for the product, using process-based hybrid analysis. The direct energy component of the product was calculated by I-O analysis where a process value was unavailable. The direct energy intensity figure (GJ/$1000) from the I-O model used in the initial I-O analysis was multiplied by the price of the product, divided by 1000, to give the quantity of direct energy input to the product (GJ/product).
2.4 Input-output-based hybrid analysis

The incompleteness associated with the previous three embodied energy analysis methods is overcome by using a hybrid method based on I-O tables, increasing the completeness of even a process-based hybrid analysis. This method is based on the data gathered in the process analysis, and uses the figure from the process-based hybrid analysis to increase the completeness of the embodied energy analysis even further. The first step was to extract the inputs from the relevant sector of the economy from which the product belongs, by using an algorithm developed by Treloar (1997) and the energy-based model based on 1996-97 I-O data. Then from the inputs extracted, the inputs that were counted in the process analysis inventory were identified. The total energy intensities of each of the inputs represented in the process analysis inventory were subtracted from the total energy intensity of the sector. If a process analysis value was available then the relevant input from the input extraction was subtracted from the total energy intensity of the sector to avoid double counting. The remainder of the unmodified inputs (the total energy intensity of the sector minus those inputs subtracted, in GJ/$1000) were then multiplied by the price of the product ($) and divided by 1000 to give the additional embodied energy for the product, in GJ. The process-based hybrid analysis embodied energy value was then added to this figure, minus the direct energy component (as this is included in the remainder of unmodified inputs) to give the total embodied energy, using I-O-based hybrid analysis.

2.5 Evaluation method

This section describes the evaluation methods used to provide a detailed assessment of the use of the I-O-based hybrid analysis method, as applied to a range of products, components and materials. The evaluation methods that were used for the evaluation of the I-O-based hybrid analysis and other embodied energy analysis methods in this study include:

- gap analysis; and
- comparative analysis.

Gap analysis was used to assess the difference between the process analysis results and the I-O-based hybrid analysis results for each of the case studies. This was done by subtracting the equivalent process analysis result from the I-O-based hybrid analysis result. The purpose of this was to show the increase in the embodied energy result obtained through the use of I-O data, through the application of the more complete I-O-based hybrid analysis method.

This gap was expressed as the percentage of completeness of the process analysis result when compared to the results from the I-O-based hybrid analysis method (Equation 1).

\[
GAP = \left( \frac{IOHA - PA}{IOHA} \right) \times 100
\]

(1)

Where \( PA \) is the embodied energy of the main product through process analysis; and

\( IOHA \) = the embodied energy of the main product through I-O-based hybrid analysis.

A comparative analysis was used to evaluate the process analysis and I-O analysis values for the whole buildings and products, individual components and materials, as a measure of reliability. The I-O analysis values were those extracted from the I-O model which are, through the process of the I-O-based hybrid analysis, substituted with process analysis data. The process analysis values were therefore those substituted in place of the I-O values. The comparison between I-O and process analysis values was then evaluated through correlation.

2.6 Case studies

In order to evaluate the use of the I-O-based hybrid analysis method, the evaluation techniques were applied to a range of different products, components and materials. The case studies selected to evaluate the I-O-based hybrid analysis method include two commercial office buildings, a residential building, a sports centre (all located in Melbourne, Australia) and a number of building related products including a solar hot water system, building integrated photovoltaic system and a washing machine. These seven case studies have been summarised in Table 1 below.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Commercial building</td>
<td>8/15 storey, 47 000 m², concrete frame and precast concrete structure</td>
<td></td>
</tr>
<tr>
<td>2 Commercial building</td>
<td>3 storey, 11 588 m², steel frame and precast concrete structure</td>
<td></td>
</tr>
<tr>
<td>3 Residential building</td>
<td>1 storey, 109 m², brick veneer</td>
<td></td>
</tr>
<tr>
<td>4 Sports centre</td>
<td>2 storey, 8 947 m², steel frame and precast concrete structure</td>
<td></td>
</tr>
<tr>
<td>5 Solar hot water system</td>
<td>Electric boosted, collector area 3.96 m² (2 x 1.98 m²), 300L tank, $2 986</td>
<td></td>
</tr>
<tr>
<td>6 Building integrated PVs</td>
<td>75W c-Si modules, 1.26 m² (2 x 0.63 m²), $ 1560</td>
<td></td>
</tr>
<tr>
<td>7 Washing machine</td>
<td>Typical 5kg model, $1 050</td>
<td></td>
</tr>
</tbody>
</table>

Once the I-O-based hybrid analysis and other embodied energy analysis methods had been applied to each case study and the results of the embodied energy analysis determined, the evaluation methods were applied. The results obtained from these evaluations were then used to determine any advantages to using the I-O-based hybrid analysis method over the other embodied energy analysis methods.

3. RESULTS AND DISCUSSION

The results of the assessment of the energy embodied in each of the case studies, using each of the embodied energy analysis methods, are shown below (Table 2). These results show both the modified (process analysis) and unmodified (I-O analysis) proportions for the I-O-based hybrid analysis values.

<table>
<thead>
<tr>
<th>Case study</th>
<th>PA (GJ/m²)</th>
<th>I-OA (GJ/m²)</th>
<th>PHA (GJ/m²)</th>
<th>I-O-based hybrid analysis (GJ/m²)</th>
<th>Total (GJ/m²)</th>
<th>% PA value</th>
<th>% I-O value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.1</td>
<td>16.0</td>
<td>19.4</td>
<td>29.4</td>
<td>34</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>12.5</td>
<td>17.8</td>
<td>25.8</td>
<td>31</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.9</td>
<td>6.4</td>
<td>14.4</td>
<td>17.0</td>
<td>41</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8.1</td>
<td>11.0</td>
<td>16.0</td>
<td>21.8</td>
<td>37</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>16.1 GJ</td>
<td>64.1 GJ</td>
<td>30.2 GJ</td>
<td>69.4 GJ</td>
<td>23</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>7.9 GJ</td>
<td>25.7 GJ</td>
<td>8.0 GJ</td>
<td>36.6 GJ</td>
<td>28</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2.4 GJ</td>
<td>22.5 GJ</td>
<td>6.2 GJ</td>
<td>28.1 GJ</td>
<td>13</td>
<td>87</td>
<td></td>
</tr>
</tbody>
</table>

For all of the case studies, besides the residential building (3), the process analysis results were lower than the respective I-O analysis results. This may be due to only a small amount of process data being available for these case studies or the price for the individual products being higher than the I-O sector average. This reflects the views of Lenzen and Dey (2000) who found that
process analysis results are consistently lower than results calculated using I-O analysis. The process-based hybrid analysis results show the effect of one method of combining process data and I-O data. All of the building case study process-based hybrid analysis results are moderately higher than the respective I-O analysis results. This may be due to the possible underestimation of the price of the buildings used in the calculation of the I-O analysis results. This may mean that I-O analysis provides a significant underestimation of the embodied energy of the buildings studied. Therefore, the results of the gap evaluation are also likely to be conservative. In contrast, the process-based hybrid analysis results for the building product case studies are significantly lower than the respective I-O analysis results (Table 2). This may be due to the complexity of these products or that only a small amount of process data was available.

The results from the application of the I-O-based hybrid analysis to each of the case studies show a significant increase above those results from the process-based hybrid analysis (Table 2). This was to be expected due to the use of I-O data to fill the gaps associated with the process-based hybrid analysis method. Most notable is the I-O-based hybrid analysis results are more than double the equivalent process-based hybrid analysis results for the building product case studies (Table 2). The main reason for this may be due to the complexity associated with the building products, or that only a small amount of process data was available. This possible lack of available process data is reflected in the percentage of the total I-O-based hybrid analysis results for each case study made up of I-O data.

In comparison to results from the previous evaluation of the I-O-based hybrid analysis method (Crawford and Treloar 2003), the increased complexity of the I-O model and the inclusion of capital input data has resulted in a significant increase in the total energy embodied in all of the case studies. These increases range from 30% for the sports centre case study and up to 176% for the washing machine case study. Also, the I-O component, or gap, has increased from the 41% and 48% of buildings and building products respectively, of the previous evaluation.

3.1 Gap analysis

Table 2 shows the results of the gap analysis for each of the case studies. This gap is expressed as the percentage of completeness of the process analysis result (a) when compared to the I-O-based hybrid analysis result (b) (refer to Table 2). The gap between the process analysis results and I-O-based hybrid analysis results of the building and building product case studies ranges from 59% (residential building), and can be up to 87% (washing machine) (up from 49% in previous assessments, showing the increased complexity of the improved model), with an average gap across all case studies of 70%. This evaluation has shown that traditional process analysis suffers from significant incompleteness, and that I-O-based hybrid analysis, through its increased complexity, provides a more comprehensive evaluation of energy inputs to buildings and building products. The incompleteness associated with process analysis has been identified by Lenzen (2001a) to be in the range of 50%. The results obtained from this study support Lenzen, and show that this gap is even greater for certain buildings and building products, much greater than those previously reported (Lave et al. 1995, Lenzen 2001a, Lenzen and Treloar 2003).

The gap between the process-based hybrid analysis and I-O-based hybrid analysis results ranges from 15-34% for the building case studies and 53-72% for the building product case studies. The reason for the considerable gap in process-based hybrid analysis results is again due to the incompleteness associated with the process data. The significance of this gap shows that even process-based hybrid analysis does not always provide a comprehensive assessment of the inputs of particular products. A breakdown of the gap between process analysis and I-O-based hybrid analysis results of the material inputs to each product was performed to provide a more detailed and less aggregated evaluation than on a whole product basis. However, on this more detailed level, the gap between traditional process analysis and I-O-based hybrid analysis results remains significant.

3.2 Comparative analysis

The results of the comparative analysis for each of the case studies are shown in Figure 4. The initial I-O values for each case study, including those for the individual material inputs, are compared to the modified process analysis values of embodied energy to determine the validity of the I-O values, against the typically more reliable process analysis values. A logarithmic scale is used to avoid smaller values being lost for the sake of visual comparison. The intent here is to indicate that the national average I-O data is not always a perfect model for the process analysis data.

![Figure 4: Comparison of I-O values and process analysis values for all case studies, by product and material.](image)

With the majority of points being above the bottom-left to top-right diagonal (59% of products and materials), the initial I-O analysis values are shown to be fairly conservative. Based on these results, the use of I-O data to fill gaps in the hybrid model is also likely to be conservative. While this comparison shows a strong correlation for a very small number of materials and products (~17%), there is a weak correlation for the overwhelming majority of the comparisons (average correlation of 0.67), well below what is considered to be a strong correlation (0.9). This may be due to problems with either form of data, however, I-O data is still likely to provide a reasonable model for filling the gaps in process-based methods.

3.3 Capital inputs

Whilst the I-O-based hybrid analysis method evaluated in this study has been used for a number of years now, the
inclusion of capital inputs (to any method for that matter) is only a new development. Previous studies (Crawford and Treloar 2003, Crawford 2004) using an I-O model based on data exclusive of capital equipment inputs showed lower results than those calculated in this current study, for the same case studies. Table 3 shows the I-O-based hybrid analysis results of these previous studies and based on these results, the percentage that capital inputs contribute to the more recent results.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Previous I-OA results (GJ/unit)</th>
<th>Current I-OA results (GJ/unit)</th>
<th>% Capital in current results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.2</td>
<td>29.4</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>23.6</td>
<td>25.8</td>
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<td>25</td>
<td>28.6</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>18.3</td>
<td>21</td>
</tr>
</tbody>
</table>

This study has shown that capital inputs may account for up to 22% of a products embodied energy, with an average across the buildings and building products looked at in this study, of 15%. This value is reflected by the views of Lenzen (2001b) and Gorree et al. (2002), who believe that capital inputs account for between 10 and 17% of total energy inputs of any particular product. As capital inputs are rarely accounted for in an embodied energy analysis, the exclusion of these inputs is one reason for the incompleteness associated with past embodied energy studies. The inclusion of capital equipment inputs in the I-O model has shown to increase the gap between I-O-based hybrid analysis and process analysis results even further.

**CONCLUSION**

In this paper, the main embodied energy analysis methods were applied to a range of building types and products in order to evaluate a recently developed input-output-based hybrid embodied energy analysis method. It was found that current levels of available process data are insufficient. This is evident with gaps of up to 87 and 72% shown for process analysis and process-based hybrid analysis methods respectively. The use of I-O data to fill the gaps associated with traditional process analysis was evaluated. The comparison between equivalent process and I-O values showed that I-O data does not provide a very reliable representation of the equivalent process values, for material inputs or whole products. Therefore, the use of I-O data to account for inadequate or missing process data is not very reliable. However, as there is currently no other method for filling the gaps in traditional process analysis, and as I-O data is considered to be more comprehensive than process data, with the errors possibly somewhat lower, using I-O data to fill the gaps in traditional process analysis appears to be better than not using any data at all. This appears to be of even greater importance for more complex products, such as building related products. Whilst previous embodied energy studies have neglected to account for capital energy inputs, even those based on comprehensive hybrid approaches, this study has shown the significance of these capital inputs. Excluding these capital inputs from any embodied energy analysis can result in underestimates in embodied energy results of up to 22%. The inclusion of capital inputs has emphasised the incompleteness associated with traditional embodied energy analysis methods.

This study showed that I-O-based hybrid analysis is currently the preferred method for the embodied energy analysis of Australian buildings and building related products due to its superior level of system boundary completeness when compared to traditional methods. The inclusion of capital inputs has increased the suitability of current embodied energy analysis methods. Further research includes improving the quantity of process data available in order to increase the reliability of data inventories. Subsequent re-validation of the input-output-based hybrid analysis method and the evaluation methods used may be necessary in the light of expected constant future improvements in data availability.

**REFERENCES**


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