

The Inherent Building Energy-Cost Relationship: An analysis of thirty Melbourne case studies

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ABSTRACT

This study investigates the energy and cost performance of thirty recent buildings in Melbourne, Australia. Commonly, building design decisions are based on issues pertaining to construction cost, and consideration of energy performance is made only within the context of the initial project budget. Even where energy is elevated to more importance, operating energy is seen as the focus and embodied energy is nearly always ignored. For the first time, a large sample of buildings has been assembled and analysed to improve the understanding of both energy and cost performance over their full life cycle. The aim of this paper is to determine the relationship between energy and cost using regression analysis for a range of building functional types. The conclusion is that energy and cost are strongly correlated, independent of building area, and equations are presented for future modelling of energy using cost as the independent variable.

Keywords: energy-cost relationship, correlation, optimisation, energy prediction, Melbourne.

INTRODUCTION

Energy has become a significant issue worldwide. Greenhouse gas emissions (GGE) and the perceived threat of climate change (caused by phenomena such as global warming and ozone depletion) is identified by Beggs (2002; p.10) as driving, "more than any other issue", change in energy consumption attitudes. Since the energy crisis of the mid-1970s attention has been directed towards strategies that lower operating energy demand (Robertson, 1991), yet it has been only recently that the impact of energy embodied in building materials themselves has come under scrutiny. Despite this trend, the routine analysis of embodied energy remains absent (Treloar et al., 2002).

Proper energy analysis during the design process can no longer be simply overlooked. ASEC (2001; p.100) indicate that "total energy use has doubled [in Australia] over the last 25 years [...] at a faster rate than GDP". The rationale behind this paper firmly lies with the perceived lack of integration of energy analysis into current practice. Capital cost still remains the primary criterion for building procurement decisions (Brown and Yanuck, 1985; Langston, 1991; Bull, 1992), while other criteria are given less significance either due to a narrow myopic focus (Ashworth, 1988) or because a suitable multi-criteria technique has not been satisfactorily identified (van Pelt et al., 1990).

Energy analysis is costly, time-consuming and, when undertaken during the design phase, usually based on a large number of assumptions (Verbeek and Wibberley, 1996). Even so, it is likely to produce conflicting advice to that generated from capital cost estimates (Arnold, 1993). This occurs because energy analysis takes a long-term view, one that introduces multiple stakeholders and wider social concerns, rather than merely reflecting immediacy and profit-centred objectives. It has been argued over many

years (e.g. Stone, 1960; Kirk and Dell'Isola, 1995; Flanagan and Norman, 1983; Langston and Lauge-Kristensen, 2002) that costs should also be accounted over a longer time span. Known as life cycle costs (LCCs) or whole life-costing (WLC), these comprise both initial (capital) and recurrent (operating) components that can be aggregated to give a more realistic picture of the total expenditure commitment (Fuller, 1982).

The problem essentially is how two criteria, one measured in financial terms and the other in pure energy terms, can ever be reconciled to provide clear building design guidance. In fact, any comparison of particular material choices will usually indicate that cost and energy ratios vary widely (Irurah and Holm, 1999). Yet at the level of an entire building this differential is expected to be less – a view that is supported to some extent by the manner in which embodied energy intensities are often determined (i.e. from national input-output financial tables) and operating energy interpreted (i.e. incurred cost).

Embodied energy is defined as the energy used in building construction, including all the upstream processes such as raw material mining, manufacture, packaging and transportation to site. Operating energy is defined as the energy used in maintaining a comfortable indoor environment, including heating, ventilation and air conditioning, as well as lighting, power for equipment and other recurrent energy requirements. Both are measured in primary energy terms.

Capital cost is defined as the expenditure used in building construction, including labour, materials, plant and overheads, but often excluding contingencies, professional fees, land acquisition costs and goods and services tax, which are all treated as purchase costs. Operating cost is defined as the expenditure required to clean, repair, maintain, replace and otherwise manage proper usage of the building over its life, including the cost of energy provision. All costs need to be expressed in real terms (constant dollars).

If there is an inherent relationship between energy and cost that can be exploited to enable better design solutions to be identified, then it should be possible to quantify energy directly from a life-cost investigation. The outcomes will naturally be dependent on the chosen time horizon for the study but will simplify the process of embodied energy calculation (in particular) that to date has proved elusive to common practice. Nevertheless, it should be remembered that the biggest cost to an organisation is usually the salaries of its employees, and that this matter has no real connection with energy demand. Salaries can be shown to represent more than 80% of life-costs (Evans et al. 1998; Langston 2005). For the purposes of this study, staff salaries and related occupancy costs are ignored.

The purpose of this paper is to discover the extent of any relationship between energy and cost, using regression analysis, for a range of building types in Melbourne, Australia. From this information, a better understanding of facilities performance can

be obtained, leading to further insight into the relationship between energy and cost. The structure of this paper is to review previous research findings, to outline the method adopted in this research, to analyse the results, and to make observations and draw conclusions for practice.

BACKGROUND

Previously published research about the relationship between energy and cost is largely confined to a few studies (Costanza, 1980; Costanza, 1984; Lavine and Butler, 1982; Oka et al., 1993; Ding, 2004). These are explored in more detail below.

Costanza (1980) adapt input-output analysis to calculate the total (direct plus indirect) energy required to produce goods and services in the U.S. economy. He states that usually the energy required to produce labour and government services and the solar energy input to the economy is overlooked. The omission can be traced to the assumption that traditional primary energy factors of economic production (land, labour and capital) are independent. He makes the strong case that these input factors are not independent and that energy is required for their production. Embodied energy intensities can be calculated in this case by using input-output data.

The results of such an analysis show that there is a strong correlation between embodied energy and dollar values for a 92-sector U.S. economy if the energy required to produce labour and government services is included. Costanza (1980; p.1224) concludes his research with the observation that *“the most important implication is that the physical dimensions of economic activity are not separable from limitations of energy supply”*. He continues by arguing that the universally-appealing notion of unlimited economic growth with reduced energy consumption must be firmly put to rest beside the equally appealing but impossible idea of perpetual motion. It is easy to get a “free lunch” by looking only at small parts of the system in isolation, but when the entire system is analysed it becomes clear that the cost of “your lunch” is just being transferred to another part of the system.

Costanza (1984) reaffirms his earlier work. Input-output models of the economy, modified to include households and government as endogenous sectors, are used to calculate each sector’s direct plus indirect (embodied) energy consumption based on estimates of the distribution of direct energy inputs to the sectors. Dollar value of sector output is highly correlated with this energy indicator. Therefore an economy can be said to operate on an energy theory of value since it can be scientifically proven to be proportional to an appropriate energy indicator.

Lavine and Butler (1982; p.2) determine from their research that the dollar value of economic output is accurately predicted by embodied energy figures. They quote other studies by Brown and Lugo, Kemp et al. and Hall et al. (not separately cited), as well as Costanza, undertaken in the 1980s. In all cases strong correlations between the embodied energy value of inputs to an economy and the monetary value of the economy’s output are shown. They conclude:

“Since the global system operates at approximately steady state, the net work output of the global system must equal the sunlight energy input. [...] This ‘work output’ interpretation of embodied energy suggests the hypothesis that embodied energy values can predict economic values. The reasoning is that economic value is achieved in direct proportion to economic work, and economic work is in direct proportion to the work output achieved with the use of

resource inputs to the economy. Because embodied energy is a measure of such work output, embodied energy also may be a measure of economic value.”

Lavine and Butler (1982) also argue that embodied energy values can provide a consistent means for pricing environmental factors. Such prices may facilitate a more comprehensive consideration of the economic effects of many kinds of environmental policy decisions.

The most relevant previous research, and most recent, is Oka et al. (1993). The total energy consumption and environmental pollution caused by construction are quantified using input-output data (referred to as the Inter-Industry Relations Table). Six office buildings in Japan, varying from 1,502 m² to 216,000 m², are evaluated. The major results are:

- total energy consumption caused by construction of office buildings is 8-12 GJ/m² of floor area
- CO₂ production is 750-1140 kg, SO and SO₂ production is 720-1430 g, NO and NO₂ production is 700-1140 g, and dust is 70-130 g (per m² of floor area)
- the construction cost/m² of floor space is proportional to the energy consumption and production of pollutants
- structural work is shown to be high in energy consumption and CO₂ exhausted per unit cost of construction, industrial waste exhausted in finishing work is higher than the other two categories of work (structure and equipment), while equipment work is shown to be relatively low in energy consumption, CO₂, NO, NO₂ and industrial waste produced

They find that the average values of energy consumption and pollutants released due to the construction of the six buildings is 32 MJ/1000 yen for energy consumption, 3.0 kg/1000 yen for CO₂ production, 3.1 g/1000 yen for NO and NO₂ production, and 1.0 g/1000 yen for industrial waste production. Although correlation coefficients are not shown, all cost, energy and pollutant relationships reflect a tight linear pattern.

Research completed by Ding (2004) concerns the use of multi-criteria analysis as a selection tool for sustainable development. She obtained detailed information relating to twenty educational (high school) projects in New South Wales, Australia. Among this data are floor area, embodied energy (construction), operating energy (including the energy embodied in forecast maintenance and repair work), capital (construction) cost and operating cost. All data are based on real performance where possible. The mean initial embodied energy across all projects is 8.05 GJ/m², while the mean operating energy is 40.89 GJ/m² or 0.68 GJ/m²/annum (this falls to 32.92 GJ/m² or 0.55 GJ/m²/annum when recurrent embodied energy is removed). Floor area is measured as gross floor area (GFA¹). The mean capital cost (A\$2002) across all projects is \$1,360/m², while the mean operating cost is \$1,946/m² or \$32.43/m²/annum. The cost of maintenance and repair cannot be extracted from the data. Floor area is again measured as GFA.

METHOD

The characteristics of the relationship between energy and cost require further study. In particular, it is important to determine whether the relationship is robust and independent of the influence

¹GFA is defined as the fully enclosed floor area, measured to the internal line of external walls, plus the unenclosed covered area measured to the external face of external walls, at all floor levels of the building.

of building size. The selected research method adopted in this paper is sampling via case studies. Case study is an ideal methodology when a holistic in-depth investigation is needed (Feagin et al., 1991). It has been used in varied investigations, particularly in sociological studies but increasingly in construction. The procedures are robust, and when followed the approach is as well developed and tested as any in the scientific field. Whether the study is experimental or quasi-experimental, the data collection and analysis methods are known to hide some details. Case studies, on the other hand, are designed to bring out the details from the viewpoint of the participants by using multiple sources of data (Tellis, 1997).

The data for the research are drawn from actual case studies obtained courtesy of the Melbourne office of Davis Langdon Australia, a large national quantity surveying practice. Case studies are located across Greater Melbourne and are specifically intended to reflect a broad range of functional purpose.

Capital cost data and floor areas are obtained directly from the elemental cost plans prepared by Davis Langdon Australia. Embodied energy intensities are estimated from the composite items of work listed in these documents using the input-output-based hybrid method (Treloar, 1998; Crawford, 2004). Operating cost is estimated from reasonable cycles for future maintenance and replacement work using *LIFECOST™* software. Operating energy is based on data obtained from the Property Council of Australia for Melbourne office buildings, adjusted to allow for extended opening hours for other functional uses. All costs are adjusted and expressed in fourth quarter 2006 dollars using published building price indices (BPI) also supplied by Davis Langdon Australia. None of these data have a direct relationship with GFA, but an indirect relationship (i.e. bigger buildings use more energy and cost more money) is implied.

Thirty recent Melbourne projects are used as case studies. These projects represent diverse functions including provision of office workspace, health facilities, residential accommodation, teaching and laboratory space, retail, hotel accommodation and a number of specialist uses. Projects comprise both new construction (73.3%) and redevelopment (26.7%). So-called residential projects, comprising apartment buildings and aged care facilities, account for 23.3% of the case studies, and the remainder are constructed for various other commercial uses. One-third of the case studies are hospitals.

Projects range from 1997 to 2004, and vary in floor area from 249 m² to 18,821 m² GFA. The mean floor area is 3,749 m² (coefficient of variation of 110.75%). They comprise a wide range of materials and standards, some are air-conditioned and some not, some have fire sprinkler systems, some have loose furniture and special equipment, and some have substantial external works.

This mix decreases the likelihood that projects exhibit similarities in energy and cost performance. Economies of scale also play a part in larger projects, which tend to have lower unit costs than identical designs of smaller size. The mix is therefore effectively random, enabling a range of statistical techniques to be applied to the sample.

Table 1 lists the case studies used in this research by building type. Case studies are identified by a numerical code, as the name and location of projects needs to be kept confidential (this is a non-negotiable agreement made between the researchers and Davis Langdon Australia).

Data supplied by Davis Langdon Australia comprise GFA and elemental capital costs based on hundreds of abbreviated measured quantities extracted from design cost plans. The full

Table 1: Case study base information

Building ID	Year	Building Type	Gross Floor Area (m²)
1	2003	Residence (new)	1,409
2	2004	Residence (new)	450
3	2004	Residence (new)	1,791
4	2000	Office (new)	2,543
5	2003	Health Centre (redevelopment)	528
6	2003	Hospital (new)	6,761
7	2003	Residence (new)	328
8	2003	Information Centre (new)	1,223
9	2004	Hospital (redevelopment)	3,278
10	2003	Hospital (redevelopment)	3,760
11	2004	Library (new)	249
12	2004	Civic Hall (new)	625
13	2004	Primary School (new)	2,696
14	2001	Residence (new)	2,790
15	2001	Hospital (redevelopment)	5,677
16	2000	Hospital (new)	378
17	1999	Hotel (redevelopment)	652
18	2000	Car Parking Station (new)	5,412
19	1998	Hospital (new)	4,281
20	1998	Health Centre (new)	787
21	1998	Hospital (new)	1,159
22	1999	Hotel (new)	12,930
23	1999	Residence (redevelopment)	18,821
24	1999	University Building (new)	10,565
25	1999	Office (new)	4,704
26	1999	Hospital (redevelopment)	1,345
27	1999	Hospital (redevelopment)	5,940
28	1998	University Building (new)	2,502
29	1998	Residence (new)	5,223
30	1997	Hospital (new)	3,649

Source: Davis Langdon Australia (Melbourne Office)

project cost is presented, including Preliminaries, Site Works and External Services, and Special Provisions (such as allowances for loose furniture and equipment), but excluding contingencies, professional fees, land acquisition costs and goods and services tax. All other data are estimated using embodied energy models, promulgated operating energy targets (for Melbourne), expected maintenance and replacement cycles, and other operational assumptions.

Embodied energy, including both initial and recurrent embodied energy, is determined using a sophisticated spreadsheet model. The model is an input-output-based hybrid method that embraces both process analysis data (where it is available) supplemented with the input-output data from published government statistics (1996-1997 financial year), extracted and compiled at Deakin University by Dr Graham Treloar and Dr Robert Crawford. Looking at embodied energy, 41.65% of the overall calculation used process analysis data, varying between 25.56% and 62.60% across the thirty case studies (coefficient of variation equals 15.89%).

Operating energy is estimated using a simple model based on occupancy hours per year and 'good practice guidelines' for new buildings in Melbourne (PCA, 2001)². The latter translates to 0.56 GJ/m² net lettable area per year (or 155.5 kWh/m²/annum),

²Note that the good practice guidelines were used in preference to the new building design target (PCA, 2001) in this study. The latter is a 28.5% reduction from the former, yet in the short-term this is unlikely to be achieved for the general run of projects except those that are specifically designed as energy efficient.

comprising 70% electricity and 30% gas (where gas supply is present), or 100% electricity (where no gas supply is present). Delivered energy is converted to primary energy using a factor of 2.72 for electricity (based on 80% brown coal at efficiency=3.4 and 20% green power at efficiency=1) and 1.4 for gas. Office buildings assume nominal occupancy of 2,500 hours/annum (equivalent to 8am to 6pm Monday to Friday) as defined in PCA (2001). Hospitals, hotels, residential accommodation and car parking facilities are assumed to operate for 5,460 hours/annum (equivalent to 8am to 11pm Monday to Sunday), and this translates to an occupancy factor of 2.18 compared to office buildings.

Embodied and operating energy data are provided in Table 2. It is important to note that although an implied relationship exists between energy and GFA (i.e. bigger buildings use more energy both to construct and operate), the derivation of energy has no direct relationship to area. Embodied energy is modelled using energy intensities applied to hundreds of work items, and is effectively the true embodied energy of the project using the most comprehensive method available. Alternatively, operating energy is modelled more simplistically, and is a function of operating hours and occupancy profile in relation to useable floor areas. Neither embodied nor operating energy are directly computed from GFA.

Capital costs are converted to fourth quarter 2006 prices using a BPI provided by Davis Langdon Australia. Otherwise no adjustment to capital costs is undertaken and all unit rates are taken as correct and reflective of the project given applicable market conditions at the time. The BPI for fourth quarter 2006 is 175.0 (later indices were not used as they were still forecasts at the time of analysis).

Table 2: Case study energy summary

Building ID	Floor Area (m ² GFA)	Total Embodied Energy Initial (GJ)	Recurrent (GJ/yr)	Other Operating Energy (GJ/yr)
1	1,409	26,741	370	2,448
2	450	9,571	148	979
3	1,791	36,679	429	2,924
4	2,543	60,326	550	2,504
5	528	9,558	103	584
6	6,761	154,157	1,688	12,156
7	328	6,815	119	546
8	1,223	21,397	279	1,299
9	3,278	77,893	785	6,771
10	3,760	96,512	1,003	7,427
11	249	5,991	91	263
12	625	15,696	186	664
13	2,696	49,445	695	2,148
14	2,790	62,048	947	6,115
15	5,677	134,281	2,376	10,751
16	378	9,009	100	740
17	652	10,405	309	1,420
18	5,412	105,937	149	3,551
19	4,281	112,160	1,345	8,657
20	787	18,322	204	821
21	1,159	28,008	436	2,218
22	12,930	286,656	3,943	29,947
23	18,821	260,255	4,354	37,177
24	10,565	263,068	2,839	11,564
25	4,704	121,541	1,226	4,998
26	1,345	24,983	403	2,578
27	5,940	149,738	1,332	11,615
28	2,502	57,218	607	2,593
29	5,223	96,058	1,602	9,568
30	3,649	78,622	775	6,973

Source: Langston (2006)

Operating costs, on the other hand, are estimated using *LIFECOST™* software provided by Computerelation Australia Pty Limited. Maintenance and replacement cycles are determined using personal experience together with a number of useful references (e.g. Dell'Isola and Kirk, 1995), and priced by original unit rates with a suitable allowance for removal and disposal costs where applicable. All costs are adjusted to fourth quarter 2006 as before described.

Capital and operating cost data are provided in Table 3. It is important to note that although an implied relationship exists between cost and GFA (i.e. bigger buildings cost more to construct and operate), the derivation of cost has no direct relationship to area. Capital cost is estimated by the quantity surveyor based on hundreds of work items, and is effectively the real cost of the project. Alternatively, operating cost is modelled based also on hundreds of work items, and is a function of component life expectancies, cleaning and repair cycles. Neither capital nor operating cost are directly computed from GFA.

For all operating costs and operating energy, including recurrent embodied energy, a one-hundred-year time horizon has been assumed.

RESULTS

Base data are analysed in Langston and Langston (2007). The relationship between total life cycle energy (embodied + operating) and total life cycle cost (capital + operating) leads to a regression line of $y=0.0137x$, where y equals total life cycle energy and x equals total life cycle cost. As with all following correlations, the

y -intercept has been assumed at zero (i.e. no energy, no cost). Figure 1 shows the regression results for the Melbourne buildings.

The correlation between initial embodied energy and capital cost leads to a regression line of $y=0.0071x$. The Melbourne case studies are shown in Figure 2.

This is an important relationship for the prediction of embodied energy based on construction cost estimates. Provided costs are expressed in fourth quarter 2006 terms, the embodied energy can be derived in minimal time using the constant (gradient) of 0.0071. The reliability of this constant is investigated in Langston and Langston (2008).

Operating energy and operating cost, calculated over a one-hundred-year time horizon, leads to a regression line of $y=0.0150x$, as shown graphically in Figure 3. In all investigated cases, the relationships between energy and cost are clearly linear, and require no more complex regression method.

VARIABLE DEPENDENCY

An obvious criticism of this research is that both energy and cost are proxies for building area, and therefore all that has been shown is that bigger buildings use more energy and cost more money. In order to determine the 'goodness of fit' (r^2) for each relationship it is first necessary to remove area from the comparison. This can be done in one of two ways.

The first way is to express energy and cost as unit rates (i.e. energy/m² and cost/m²). The influence of building size is

Table 3: Case study cost summary

Building ID	Floor Area (m ² GFA)	Capital Cost (\$2006)	Operating Cost/yr (\$2006) Recurrent Expenditure	Energy Expenditure
1	1,409	2,999,243	75,221	33,654
2	450	1,198,625	44,716	13,462
3	1,791	3,881,208	102,215	43,189
4	2,543	6,321,146	293,590	42,622
5	528	832,897	34,125	8,033
6	6,761	20,213,443	790,532	211,057
7	328	575,722	45,054	8,301
8	1,223	1,984,097	106,580	17,863
9	3,278	10,932,154	308,775	112,286
10	3,760	13,188,297	379,602	119,721
11	249	577,654	27,142	3,622
12	625	1,710,606	65,176	9,129
13	2,696	4,140,979	265,684	29,723
14	2,790	7,901,075	456,106	103,254
15	5,677	16,603,374	750,830	212,207
16	378	1,174,502	60,533	15,183
17	652	1,325,701	107,333	25,804
18	5,412	5,857,972	207,995	60,434
19	4,281	12,754,657	501,092	191,499
20	787	1,806,207	97,070	15,450
21	1,159	3,042,888	213,702	48,087
22	12,930	43,838,966	1,609,751	539,706
23	18,821	41,392,112	1,670,800	792,257
24	10,565	36,750,343	1,043,406	215,991
25	4,704	16,328,325	597,484	90,831
26	1,345	3,143,639	160,966	54,933
27	5,940	19,778,684	612,987	247,515
28	2,502	5,796,121	238,294	47,947
29	5,223	13,119,590	660,692	179,993
30	3,649	9,032,456	393,959	156,952

Source: adapted from Langston (2006)

therefore limited to issues relating to economies of scale, where bigger buildings will tend to have slightly lower unit rates due to efficiencies caused by the larger scope of works. But this method has the disadvantage of clustering (bunching) the project data around the average, making any correlation specific to the effect of the economies of scale only. For this reason this method is not recommended as leading to a practical and valid outcome.

The second way is to compare energy with area (and cost with area) and then compare the residuals of both analyses, thus eliminating the GFA trends in each case. Thus, the underlying relationship between energy and cost is exposed after eliminating all dependency (whether direct or indirect) on building area.

Residual (or error) represents unexplained variation after fitting a regression model. It is the difference (or left over) between the observed value of the variable and the value suggested by the regression model. By comparing energy and GFA (or cost and GFA), the residuals for each represent the unexplained variation, and enable the independent relationship between energy and cost to be tested.

It is obvious that energy or cost is positively correlated with building size, and confirms the simple conclusion that bigger buildings demand more energy and cost more to construct or operate. The analysis of residuals, however, shows that even after building area is eliminated, there is still a strong relationship between energy

and cost. The original regression exercises provide a model for predicting energy performance based on cost, while the residual regression exercises demonstrate the validity of the comparisons.

The calculations for energy versus GFA residuals are presented in Table 4 and cost versus GFA residuals in Table 5. The energy versus cost scatter plots and regression details for each of total project, capital and operating data are shown in Figures 4, 5 and 6 respectively. The discovered correlation between energy and cost after eliminating any dependency on GFA is determined, and in each case the relationship has a *p-value* less than 0.05 (95% confidence level) and a sufficiently large *t-statistic*. Parametric line of best fit has been used in this analysis. However, a non-parametric line of best fit yields very similar results. In each case, a strong relationship between energy and cost, independent of GFA, has been proven. The r^2 value for total project energy and total project cost is 0.5959. The r^2 value for embodied energy and capital cost is 0.7081. The r^2 value for operating energy and operating cost is 0.6264.

DISCUSSION

In all observed instances, whether at project, elemental group or element levels, higher energy values give rise to higher costs and vice versa. This is obvious, but in addition it has been shown that cost is a strong predictor of energy. While at the work item level it is feasible to spend more capital to purchase materials or systems

Figure 1: Total project energy v cost correlation

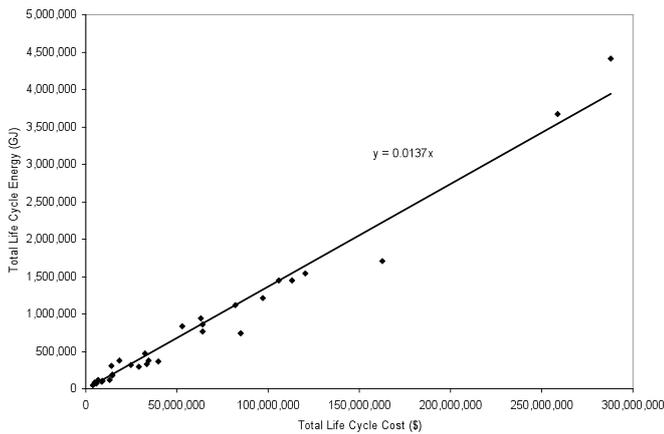


Figure 2: Embodied energy v capital cost correlation

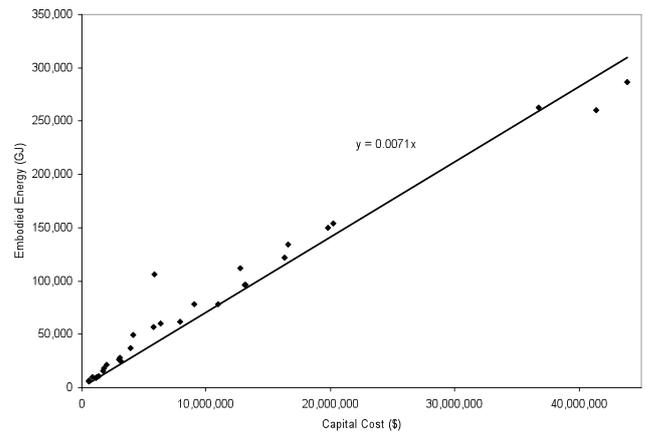
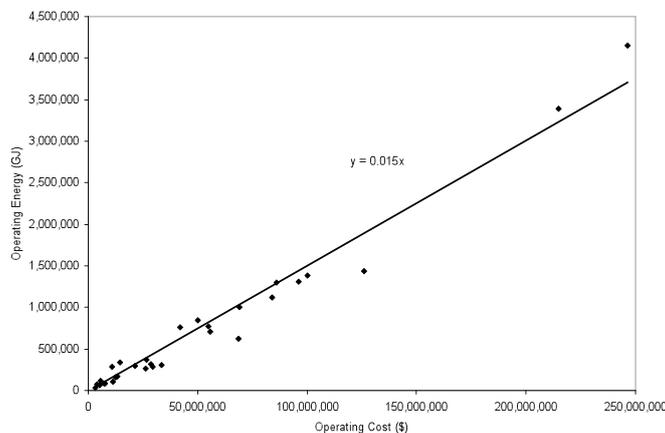


Figure 3: Operating energy v operating cost correlation



with lower embodied and/or operating energy demand, and thus introduce efficiency and value for money, at the higher levels of aggregation this is unlikely to be significant.

This finding leads to the conclusion that optimisation of energy and optimisation of cost are not mutually exclusive goals. The very strong correlations between energy and cost, and particularly between embodied energy and capital cost, suggest that this bond cannot be upset by individual decisions made at more refined levels of detail. It therefore may be more important to look elsewhere for efficiencies. In the case of embodied energy, savings can be found by building less. This may arise from more efficient floor plans (i.e. less non-functional area), more efficient plan shape (i.e. lower wall/floor ratios), more efficient internal layouts (i.e. more open plan design), and higher floor densities (i.e. people/m²). In the case of operating energy, savings can be found, in addition to building less, by reducing demand through use of natural lighting and ventilation, proper orientation, reduced operating hours (where possible) and intelligent control systems.

Having said that, this paper comprises case studies that did not have significant components of recycled or reused materials. Clearly where this is achieved, initial embodied energy can be markedly reduced since the upstream energy impacts would have been previously counted on another project (i.e. double counting is not valid). The cost of recycled and reused materials varies widely (for example, refer Treloar et al., 2003). In some

cases the cost can be higher than comparable new materials, and in many other cases the cost can be lower. The introduction of significant amounts of recycled and reused materials may upset the relationships found in this paper.

This issue also has implications for energy unit rates. In this paper 73.3% of projects represent new construction, and the remainder represent redevelopment projects. In many cases, redevelopment implies reuse of structure and other elements, so both embodied energy and capital cost are reduced. There is no discernible difference between the results for new and redeveloped projects, indicating that the inherent energy-cost relationship still appears to apply.

Current preoccupation with operating energy performance in Australia should be tempered with the understanding that embodied energy is significant, particularly in the context of a building's economic life, which is much less than the one-hundred-year time horizon adopted in this paper. Energy rating schemes should take embodied energy into account, simply by taking cost into account. Where the cost is high it is assumed the embodied energy is also. High performance in energy will then be dictated, at least in part, by the scale of the development. Large houses, for example, would be less likely to achieve high-energy performance than small houses, even though on a per-square-metre-basis the former are more efficient. This is a challenge for government authorities and policy makers.

Table 4: Case study energy residual summary

Building ID	Floor Area (m² GFA)	Total Project Energy Residual	Embodied Energy Residual	Operating Energy Residual
		(energy v GFA)	(energy v GFA)	(energy v GFA)
1	1,409	42,542	-10,763	53,305
2	450	82,437	-10,662	93,099
3	1,791	15,902	-7,704	23,606
4	2,543	-167,582	2,400	-169,983
5	528	20,023	-12,079	32,102
6	6,761	10,668	20,269	-9,601
7	328	62,258	-11,221	73,479
8	1,223	-42,899	-12,757	-30,142
9	3,278	126,832	6,730	120,102
10	3,760	119,224	16,669	102,555
11	249	49,003	-10,622	59,626
12	625	19,554	-7,689	27,243
13	2,696	-235,624	-11,236	-224,388
14	2,790	176,623	-326	176,950
15	5,677	174,622	19,915	154,707
16	378	70,110	-9,928	80,038
17	652	95,857	-13,466	109,323
18	5,412	-733,922	-3,657	-730,265
19	4,281	169,177	22,934	146,243
20	787	1,518	-7,980	9,498
21	1,159	86,414	-4,993	91,407
22	12,930	693,162	41,671	651,491
23	18,821	41,787	-90,821	132,608
24	10,565	-721,508	60,674	-782,183
25	4,704	-299,000	24,698	-323,698
26	1,345	72,178	-11,368	83,547
27	5,940	110,107	30,636	79,471
28	2,502	-146,454	31	-146,485
29	5,223	47,731	-10,132	57,864
30	3,649	59,259	778	58,481
sum		0	0	0

Source: Microsoft Excel Data Analysis Module

Table 5: Case study cost residual summary

Building ID	Floor Area (m ² GFA)	Total Project Cost Residual (cost v GFA)	Capital Cost Residual (cost v GFA)	Operating Cost Residual (cost v GFA)
1	1,409	-9,518,138	-872,695	-8,645,443
2	450	-493,883	-49,275	-444,608
3	1,791	-11,314,548	-1,035,967	-10,278,581
4	2,543	-2,257,512	-653,669	-1,603,843
5	528	-3,754,377	-628,429	-3,125,948
6	6,761	8,263,047	1,697,239	6,565,807
7	328	422,964	-338,359	761,323
8	1,223	-5,893,653	-1,378,904	-4,514,749
9	3,278	-1,343,587	1,946,215	-3,289,802
10	3,760	750,046	2,883,499	-2,133,453
11	249	-524,859	-120,265	-404,594
12	625	-1,269,675	-16,133	-1,253,542
13	2,696	-11,053,979	-3,252,478	-7,801,502
14	2,790	17,543,422	250,413	17,293,009
15	5,677	18,764,069	1,053,236	17,710,833
16	378	2,429,078	123,610	2,305,468
17	652	3,781,111	-474,917	4,256,027
18	5,412	-57,050,080	-8,967,066	-48,083,013
19	4,281	11,008,144	1,024,287	9,983,857
20	787	-37,609	-363,800	326,192
21	1,159	9,960,442	-144,994	10,105,436
22	12,930	44,429,824	8,443,003	35,986,821
23	18,821	-24,294,944	-10,122,940	-14,172,004
24	10,565	-12,467,150	7,825,548	-20,292,697
25	4,704	7,143,334	3,440,533	3,702,802
26	1,345	2,389,482	-553,181	2,942,662
27	5,940	7,326,774	3,508,920	3,817,854
28	2,502	-7,100,107	-1,066,509	-6,033,598
29	5,223	10,569,645	-1,188,302	11,757,947
30	3,649	3,592,718	-968,621	4,561,339
sum		0	0	0

Source: Microsoft Excel Data Analysis Module

Figure 4: Total project energy v cost residual correlation

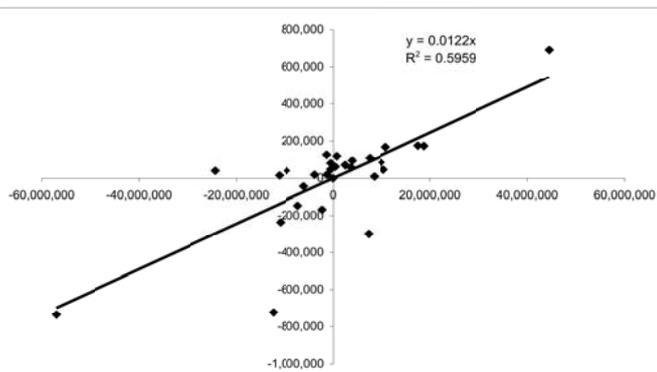


Figure 5: Embodied energy v capital cost residual correlation

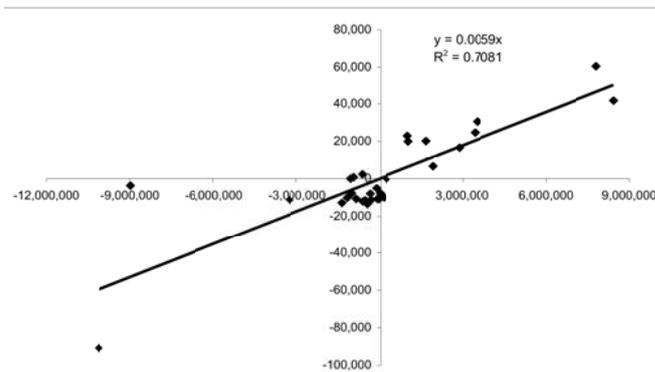
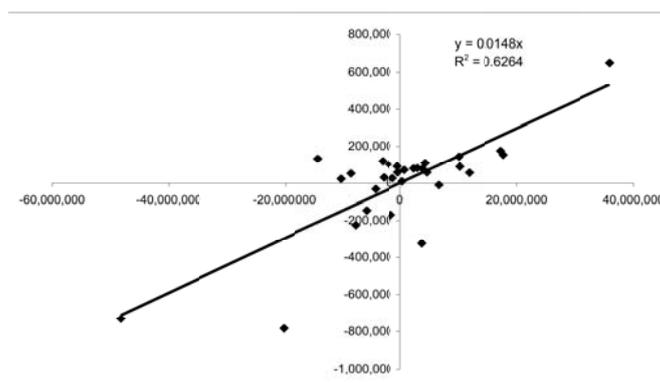


Figure 6: Operating energy v operating cost residual correlation



Sustainable development is a balance between progress and conservation, and most popularly defined as meeting the needs of the present generation without disadvantaging the ability of future generations to meet their own needs. But it can never be achieved. It is more likely to be approached by building less than building more. It is also important to maximise building life through adaptive reuse and recycling. Initial embodied energy, just like capital cost, is an indicator of project scope, and can be used therefore to gauge the impact of developments on the natural environment.

The lack of public knowledge about embodied energy has led to its absence from design decision-making and government policies. This situation has arisen as a direct result of the complexity of the calculations and the lack of reliable data upon which to base them. Over time, embodied energy models have become even more complex. This translates into specialist knowledge requirements and a considerable time commitment. The way forward is to develop models that practitioners can use and apply routinely to their projects. Only by putting useful tools into the hands of building designers and managers can a wider understanding of the importance of embodied energy be gained. This also enables life cycle energy and GGE calculation to be incorporated in the early design stages to reduce unnecessary environmental degradation.

CONCLUSION

The research objective was to discover the nature of the energy-cost relationship and other related heuristic rules by performing a thorough statistical analysis of the created dataset. This analysis included both initial and recurrent energy and cost considerations. Through a series of regression analyses, energy and cost are shown to have a high correlation, to the extent where an inherent relationship can be confidently claimed. While a dependency between energy and area, or between cost and area, has been shown to exist, after elimination of GFA using energy and cost residuals a strong correlation remains. The r^2 value for total project energy and total project cost is 0.5959. The r^2 value for embodied energy and capital cost is 0.7081. The r^2 value for operating energy and operating cost is 0.6264.

The overall relationship between embodied energy and capital cost can lead to the development of predictive models for energy based on cost. For example, embodied energy is given by the regression line $y=0.0071x$, where energy (y) is expressed in GJ and cost (x) is expressed in fourth quarter 2006 dollars. In this case it is therefore possible, by calculating construction cost (excluding contingencies, professional fees, land acquisition costs and goods and services tax), to derive embodied energy (including direct and indirect energy flows) at the project level.

But it should be remembered that this research was based on thirty 'ordinary' buildings. They had no special significance in terms of environmental performance or efficiency. They are representative of probably 90% of the existing commercial building stock in our cities. The challenge from this research, therefore, lies in trying to break the inherent energy-cost relationship by finding ways to minimise energy for new development even though the cost may have to rise. The heuristics promoted in this research apply where we make no effort to introduce improvements through innovation and better environmental design but rather follow traditional paradigms. Our ability to redefine the energy-cost relationship will ultimately be our success in realising more sustainable development.

In the developed world, where wants are routinely placed ahead of needs, the goal of sustainable development seems forlorn. The

marketplace will to some extent limit the use of energy as long as energy is appropriately priced. While it might be argued that development is important to meet present needs, this must be tempered with a regard for future generations and the legacy we leave them.

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