Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings

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Introduction

As energy costs increase, controlling the cost of living will require reductions in energy demand. Furthermore, managing global green house gas emissions from property development is of key importance for minimising climate change. Life cycle energy analysis clearly identifies optimum strategies for reducing both energy demand and green house gas emissions.

In residential buildings, embodied energy represents between 30 and 100% of total life cycle energy consumption. This paper details the important contribution of embodied energy to global greenhouse gas emissions and explains in detail a comprehensive and repeatable approach to estimating the embodied energy in new developments. A case study is also presented to demonstrate outputs.

Life Cycle Analysis Explained

Life cycle analysis is a method of determining the real cost (or in this case, energy used) over the lifetime of a product, from cradle to grave. Life cycle analysis is particularly helpful for comparing a number of options, that is, identifying the most effective option available. It is also useful for benchmarking products. In this manner, the relative cost, or efficiency of a product can be identified.

Measuring Primary Energy

Life cycle energy consumption should be quoted in Primary Energy rather than delivered energy (or end use) units. The primary energy, or potential energy is defined as the intrinsic energy in a primary product or resource. The primary energy (potential energy) contained in a block of coal used to fire a power station will be many times greater than the delivered electrical energy at a premises due to heat losses at the power plant and transmission losses in the electricity grid (typically approximately 30% of the primary energy of coal actually reaches consumers).

In the case of residential construction, the total life cycle energy consumption is made up of two components:

- Operational Energy
- Embodied Energy

Operational Energy

Operational Energy is the energy requirement of the building during its life from commissioning to demolition (not including maintenance or renovations). For example, the energy used to heat and cool the premises, run appliances, heat water and light rooms.

Embodied Energy

The embodied energy is the energy requirement to construct and maintain the premises, for example, with a brick wall, the energy required to make the bricks, transport them to site, lay them, plaster them and (if necessary) paint and replaster over the life of the wall. Best practice would also include energy calculations for demolition and recycling. A summary flowchart detailing the elements required to estimate embodied energy is given in Figure 1.

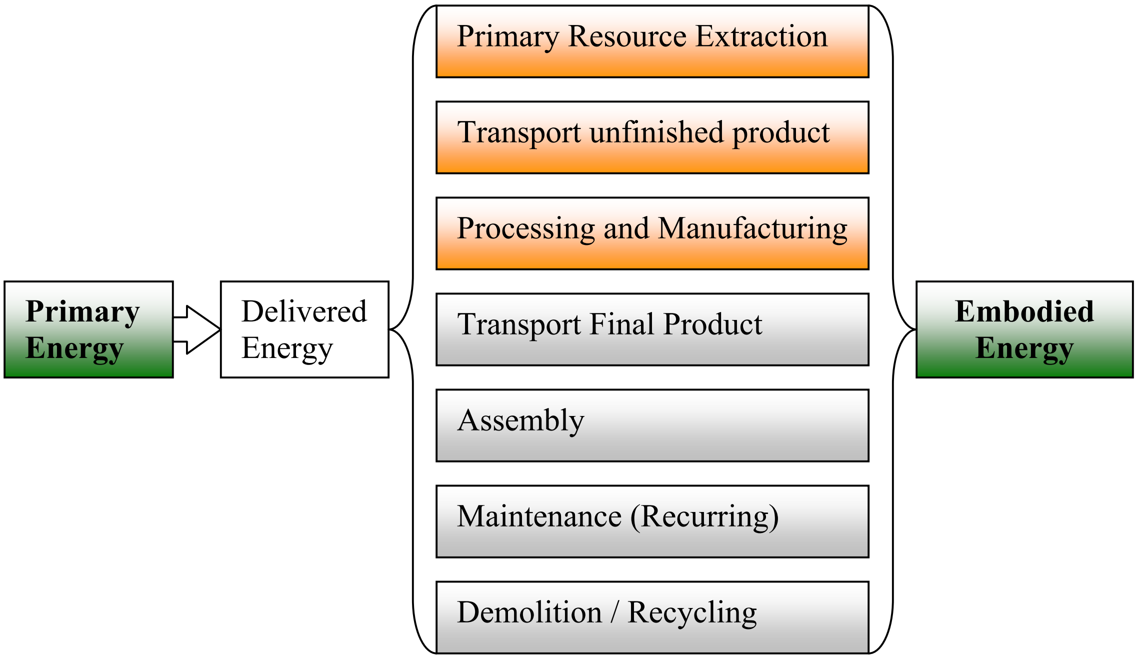

Figure 1: Breakdown of embodied energy calculations. Most embodied energy figures for specific materials are quoted using a "cradle to gate" boundary (includes orange boxes). Consumers must also consider transport, assembly, maintenance and demolition components of embodied energy. In addition, care should be taken to ensure that primary energy consumption is calculated, not delivered energy (which will understate the real energy cost).

Debate continues about the boundaries that should be applied to calculating embodied energy. Commonly, the most influential components of embodied energy are those bounded by the cradle to gate approach, that is, all the energy required to deliver the product to the gate of the factory ready for transport to the construction site. Even within an embodied energy calculation bounded "cradle to gate" the complexity of embodied energy could be extreme. For example, the energy used by the factory in the processing or manufacturing process may be easily identified, however what about the energy used by the employees:

- Transport Fuel (to and from work)
- Embodied energy of transport (to and from work)
- Energy of services (health, legal, accounting)
- Energy to produce food to feed the workforce (transport, agriculture, refrigeration)

Any one point in the processing and manufacturing chain can be analysed in detail chasing endless trail of energy calculations back to the stone age. With this in mind, it is important to remember the purpose of embodied energy calculations, it is to make informed decisions that lead to improvements in the way we use energy. At present, order of magnitude accuracy would generally satisfy this purpose. The approach discussed in this paper is built on this principal.

CO_2 and Embodied Energy

Embodied energy is a usually quoted in MJ or GJ units of energy. How this relates to carbon emissions depends on the primary energy utilised to drive the material processing, and the efficiency of this processing. For example, an aluminium product from a smelter driven with hydro power will have very little embodied carbon, yet a huge energy content. The aim is to quote both figures, however it should be noted accurate of carbon emissions is currently more difficult to estimate and subject to more variability. The embodied energy model is only ever as accurate as the material data inputs.

The Importance of Minimising Life Cycle Energy in Residential Development

In residential buildings, embodied energy typically represents between 30 and 100% of total life cycle energy consumption in papers focussing on this subject. The importance of embodied energy however is generally greater than these figures indicate. Driven by fashion and profit, redevopment of Australia's building stock usually occurs before design is reached.

Detail Analysis of Australia's Energy Demand

Operational energy of residences in Australia is easily calculated and its large contribution to Australian energy demand is well understood. Figure 2 represents Australian Energy Flows in 2009, Australia consumes approximately 4577PJ of energy domestically and exports more than predominantly in the form of black coal. This helps explained the following two factors:

- Low energy prices enjoyed by Australians compared to international trends due to an abundance of primary energy products
- Australia's position firmly in the top ten Green House Gas (GHG) producers per capita, ahead of the US and Canada due to a reliance on black coal

The next step is to analyse the energy demand more closely to identify where positive changes can be made.

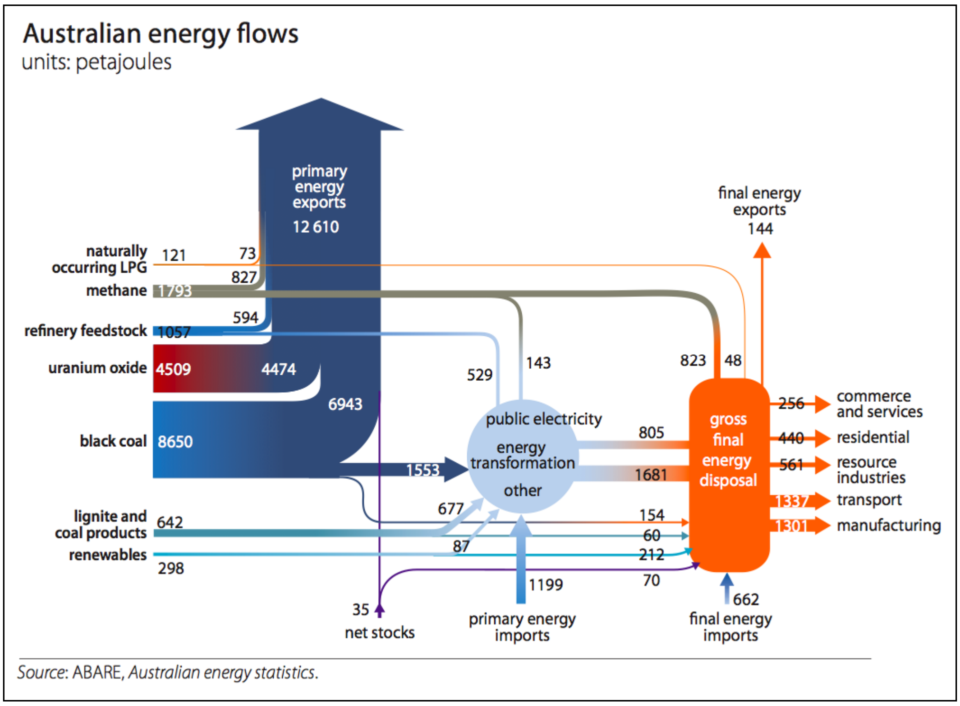

Figure 2 Australian Energy Flows (Petajoules). ABARE, "Energy in Australia, 2009"

Domestic energy consumption is summarised below in Table 1 and shows clearly that residential demand (the operational energy component of residential life cycle analysis) accounts for 9% of total energy requirement. Similarly, Table 2, from a separate source shows that two years earlier the residential demand was 14% of total energy demand in Australia. Either way, the importance of reducing residential energy demand is clear.

Table 1: Summary of Australian Domestic Energy Disposal, 2009 (ABARE Energy Study 2009)

Sector	Energy Consumed (PJ)	Energy Consumed (% of Total)
Commerce and Services	256	5%
Residential	440	9%
Resource Industries	561	12%
Transport	1337	28%
Manufacturing	1301	28%
Energy Exports	144	3%
Energy Imports	662	14%
Total Energy Disposal	4701	100%

Table 2: Summary of Australian Domestic Energy Disposal, 2007 (ABARE Year Book 2007)

Sector	Energy Consumed (PJ)	Energy Consumed (% of Total)
Trade and services	249	8%
Residential	433	14%
Agriculture	100	3%
Mining	342	11%
Manufacturing	1247	40%
Transport	1339	43%
Construction	28	1%
Other	84	3%
Total Energy Use	3140	100%

Table 3 shows that energy use correlates quite well with Green House Gas (GHG) emissions.

Table 3: Australia's Direct Greenhouse Gas Emissions by Economic Sector, 2007 Source: Department of Climate Change, Australian National Greenhouse Accounts, National Inventory by Economic Sector , 2007

Sector	Mt CO2	%
Primary Industries	207.0	34.6%
Manufacturing	71.5	12.0%
Electricity, Gas and Water	205.9	34.4%
Services, Construction and Transport	58.4	9.7%
Residential	54.3	9.1%
Total GHG Emmisions	597.1	100%

The embodied energy component of residential life cycle energy demand is made up of from Transport, Manufacturing, Commerce and Services, and Resource Industries from Table 1 and Table 2. It is a complex exercise determining just how much of this energy is directed to residential construction and maintenance. A number of studies identified by Harrington et al (2009) estimated that the embodied energy of the built stock accounts for 10% to 20% of Australia's total energy consumption. This would of course include commercial buildings, residential stock alone would be approximately half of these figures.

This supports the hypothesis that Australia's residential buildings (operations and embodied energy combined) contribute between 15 and 30% of total Green House Gas Emissions. Hence the importance of benchmarking, analysing and reducing life cycle energy demand and GHG emissions of residential buildings in a systematic manner.

Embodied Energy Calculations

The desired purpose of the described method of embodied energy calculations carried out on residential developments is to establish improvements in the design and compare design options prior to construction. The results are not designed for comparison with other studies due to the huge variations of calculation boundaries. The model developed in conjunction with this paper establishes key components in embodied energy contribution as follows:

- Cradle to gate embodied energy estimates from a range of databases
- Transport energy freighting the finished product to the construction site
- Major components of assembly energy (particularly when these differ between construction options)
- Recurring Embodied Energy (based on a 'churn rate' during the buildings life time)

This approach generally results in larger embodied energy calculations than associated methods which do not include the following in their boundaries:

- Transport or assembly energy
- Recurring energy (and associated transport / assembly energy)
- Embodied energy of services installation
- Fittings and finishes
- Landscaping and earthworks

Comparison is difficult as most reference material fails to define boundaries clearly.

Cradle to Gate Material Embodied Energy Estimates

Very little research has been undertaken on specific materials in Australia compared to countries of best practice such as the UK. The CSIRO has conducted research in this area and a small number of universities have conducted independent research. Not all of this is publicly available however where possible this research is used to verify the materials database in the model. Other key sources of data include:

- The ICE database (Inventory of Carbon and energy) compiled by the University of Bath, Sustainable Energy Research Team
- Numerous publications (conference papers and texts) listed in the references of this paper
- Australian Government National Green House Gas Inventory (for primary energy and carbon coefficients)
- ABARE (verifying modelling with input / output data)

Periodically new materials are added to the model's database by 'building' them from other material information and adding a processing energy assumption. Key elements for each material are embodied energy (MJ/kg), embodied carbon (kgCO_2/kg) and density. The database also stores information regarding the source and any verification that may have been carried out on local supplies of the material.

Material volumes or weights must then be calculated to determine the total embodied energy or carbon for a building component. The model allows a number of entry points:

- Direct weight
- Direct volume
- Volume or weight of individual components x number of components
- Custom tools to calculate specific materials (for example, paint weight from painted area and number of coats)

To identify the weight of materials for transport energy calculations the model must construct embodied energy information from first principals (rather than using generic embodied energy assumptions per m2 of building space for example).

Transport Energy

Transport energy is a function of material weight, transport method and the distance travelled. From these three factors very reasonably accurate calculations of transport embodied energy can be made. The model identifies the following main methods of transport:

- Light Commerial
- Rigid Truck
- Articulated Truck
- Rail
- Sea
- Air

Many materials involve two types of transportation method (eg import by sea, travel to site with rigid truck) and the model allows for this input.

Assembly Energy Embodied Energy Estimates

Where machinery or power tools are used in the construction process the energy and carbon is calculated in the model. The boundary here must be well defined. Typically an allowance is made for transport between jobs however it is normally restricted to the equipment itself and does not encompass trades person transport etc. Although this may slightly underestimate embodied energy calculations it allows for a good comparison between designs which si the purpose of the model. Furthermore it has been identified that transport component of embodied energy is rarely identified as the most influential component of a life cycle analysis. The transport energy is also calculated for recurring components (eg if it is estimated a building will be painted 20 times in its life, the transport energy for the paint will be multiplied by 20 as well as the material energy)

Recurring Embodied Energy

Any materials that will require maintenance or replacement during the life of the building are accounted for and modelled. The recurring energy is quite critical in embodied energy calculations, particularly for fittings. Fittings usually only comprise a small fraction of initial embodied energy but their high maintenance / replacement nature means that over the life cycle of the building their contribution to embodied energy is very large. As previously mentioned, the transport energy for these recurring materials is also calculated in the model.

To determine recurring embodied energy a churn rate is chosen for each material (number of times it is replaced during the building's lifetime). Churn rates are determined through experience and research and reflect the likely life of the material and or the maintenance requirement. Final recurring embodied energy is determined by multiplying material and transport energy by the churn rate. Transport energy related to embodied energy is reported as transport energy.

Case Study

A typical Australia spec built home was modelled and the estimated embodied energy calculations are shown in the below case study. The total embodied energy of the dwelling was calculated to be approximately 2,600GJ. The total greenhouse gas emissions was calculated to be 199tCO2e. This includes the recurring embodied energy over a life span of 50 years.

The Figure 3 shows a breakdown of the total embodied energy by construction area. These graphs, automatically generated by the model help to identify areas of improvement. Obviously for consideration in this building are the walls, floor and roof.

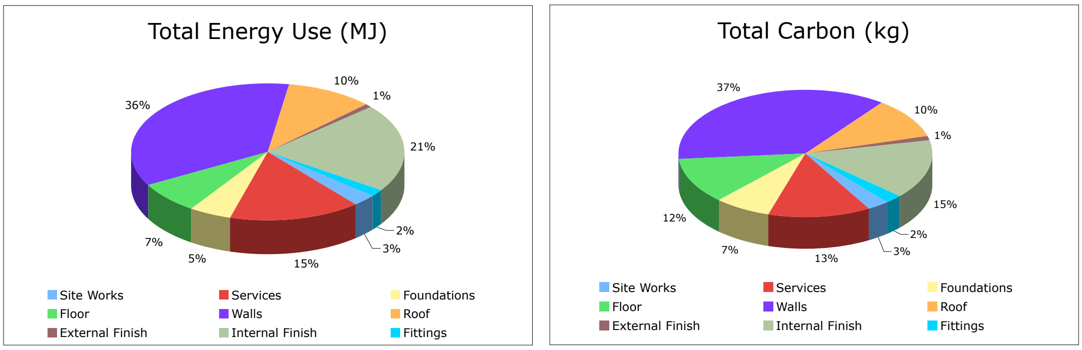

Figure 3: Energy and Carbon by Construction Category

Similarly Figure 4 shows the breakdown of embodied energy by type. The largest area for improvement is in materials, followed by recurring embodied energy. Having identified the major areas of improvement the full list of materials, travel distances and churn rates can be referred to shown in Table 4. The corresponding embodied energy calculations allow easy identification of materials or components that need to be targeted for improvement. In the case study, the large portion of embodied energy dedicated to "Internal Finish" and "Recurring Energy" is attributed to paint, given the high churn rate. An obvious way of reducing this would be to eliminate surfaces that require paint (rendering, raw timber ceilings, polished concrete etc). A list of assumptions used to calculate assembly energy is shown in Table 5. With a comprehensive and accurate Quantity Survey, the model can be run on most residential buildings in approx 16 hours.

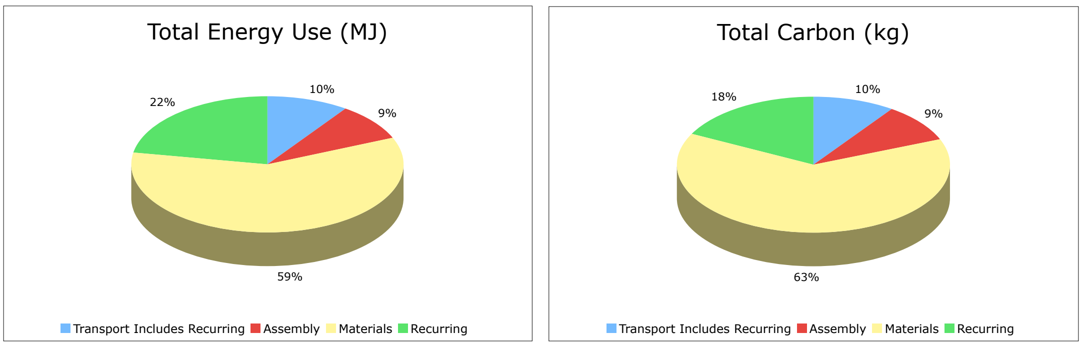

Figure 4: Energy and Carbon by Embodied Energy Category

Table 4: List of Materials for a 4 Bedroom Brick Veneer Home

Category	Description	Material	Churn Rate	Travel Category	Distance	Calculated Total Weight
			%		km	kg
Foundations	3 Bar F11 200 x 6000	Steel (virgin)	0%	Rigid truck	100	225
Foundations	300 x 200 R6 Ligatures	Steel (virgin)	0%	Rigid truck	100	
Foundations	Y12 600 x 600 Corner Bars	Steel (virgin)	0%	Rigid truck	100	
Foundations	Slab Tie	Steel (virgin)	0%	Rigid truck	100	
Foundations	TMS 65 Trench Mesh Chairs	PVC pipe	0%	Rigid truck	100	
Foundations	Footings	Concrete (1:1.5:3 eg in-situ floor slabs, structure)	0%	Rigid truck	100	34,560
Services	Electrical and Plumbing	Services "Electrical and Plumbing"	10%	Light Commercial	200	
Services	Air Conditioning	Services "Electical and Plumbing"	100%	Light Commercial	200	
Services	Air Conditioning	Services "Electical and Plumbing"	100%	Sea	10,000	
Floor	Slab	Concrete Steel Reinforced 1%	0%	Rigid truck	100	56,442
Walls	Garge Beam	Glue laminated timber				78
Walls	Facia Stiffenning	Timber (general)	0%	Rigid truck	400	14
Walls	Facia Stiffenning	Timber (general)	0%	Rigid truck	400	14
Walls	Lintels	Steel (virgin)	0%	Rigid truck	1,000	142
Walls	Ply wall Brace	Plywood	0%	Rigid truck	400	76
Walls	Pine Framing Long Lenghts	Timber (general)	0%	Rigid truck	400	551
Walls	Pine Framing Studs	Timber (general)	0%	Rigid truck	400	1,323
Walls	Pine Framing	Timber (general)	0%	Rigid truck	400	229
Walls	Facia Stiffenning	Timber (general)	0%	Rigid truck	400	10
Walls	Hoop Iron	Steel (virgin)	0%	Rigid truck	400	23
Walls	Bolts, Nails, Brackets	Steel (virgin)	10%	Rigid truck	400	
Roof	Prefab Roof Trusses	Timber (general)	0%	Rigid truck	1,000	3,192
Roof	Patio	Steel (virgin)	100%	Rigid truck	1,000	146
Roof	Timber for Patio	Timber (general)	100%	Rigid truck	1,000	
Roof	Gutters	(0.56mm) Painted Corrugated Zincalume Sheet	100%	Rigid truck	1,000	235
Roof	Gutters	(0.56mm) Painted Corrugated Zincalume Sheet	100%	Sea	10,000	235
Roof	Tile Valley	(0.56mm) Painted Corrugated Zincalume Sheet	0%	Rigid truck	1,000	13
Roof	Sarking for Concrete Tiles	MDF	0%	Rigid truck	1,000	2,940
Roof	Roof Tiles (Concrete)	Precast Concrete	20%	Rigid truck	500	
Roof	Downpipes and storm water	PVC pipe	20%	Rigid truck	2,000	63
Internal Finish	Bath	Steel (virgin)	100%	Rigid truck	150	
Internal Finish	Bath	Steel (virgin)	100%	Rigid truck	1,000	
Walls	Windows	Aluminium, extruded	0%	Rigid truck	1,000	
Walls	Windows	Glass	10%	Rigid truck	1,000	
Fittings	Door Knobs, stops, locks etc	Stainless Steel	100%	Sea	10,000	
External Finish	Front Door	Sawn hardwood	0%	Rigid truck	500	17
External Finish	Front Door Frame and step	Sawn hardwood	0%	Rigid truck	500	18
Roof	Attic covering	MDF	0%	Rigid truck	500	91
Internal Finish	Soffit Sheeting	Plasterboard	0%	Rigid truck	500	137
Internal Finish	Soffit Battons	Timber (general)	0%	Rigid truck	500	
Walls	Brick Facing	Bricks (facing)	0%	Rigid truck	500	
Walls	Galintal	Steel (virgin)	0%	Rigid truck	500	12,480
Internal Finish	Cielings	Plasterboard	20%	Rigid truck	500	2,800
Internal Finish	Internal Walls	Plasterboard	10%	Rigid truck	500	432
Internal Finish	Cornices	Plasterboard	10%	Rigid truck	500	360
Internal Finish	Wet Area Walls	Villa Board	0%	Rigid truck	500	4
External Finish	Garage Door	Steel (virgin)	100%	Rigid truck	1,000	80

External Finish	Garage Door	Steel (virgin)	100%	Rigid truck	1,000	93
Internal Finish	Pine Lenghts for internal finish (Door Frams etc)	Timber (general)	0%	Rigid truck	400	264
Internal Finish	Doors	Hardboard	10%	Rigid truck	1,000	
Fittings	Sink	Stainless Steel	100%	Rigid truck	1,500	3,900

Table 4 Continued

Category	Description	Material	Churn Rate	Travel Category	Distance	Calculated Total Weight
			%		km	kg
Category	Description	Material	Churn Rate	Travel Category	Distance	Calculated Total Weight
			%		km	kg
Internal Finish	All tiles throughout House	Ceramic tiles	100%	Rigid truck	1,500	100
Internal Finish	Mirrors	Glass	10%	Rigid truck	1,500	138
Fittings	Shower Screen and Doors	Glass	100%	Rigid truck	1,500	378
Internal Finish	Sliding Doors	MDF	10%	Rigid truck	1,500	23
Internal Finish	Sliding Door Frames	MDF	0%	Rigid truck	1,500	1
Fittings	Laundry Tub	Stainless Steel	100%	Rigid truck	400	
Internal Finish	Laundry Cabinets		100%	Rigid truck	400	
Fittings	Taps, shower heads etc	Stainless Steel	200%	Sea	10,000	
Internal Finish	Toilets	Ceramic sanitary ware	100%	Rigid truck	2,000	
Internal Finish	Carpet	Nylon carpet	500%	Rigid truck	3,000	
Site Works	Under concrete for future garden plumbing	PVC pipe	0%	Rigid truck	500	7
External Finish	Security Screens	Aluminium, extruded	0%	Rigid truck	2,000	20
Roof	Roof Insulation	Glass fibre insulation (quilt)	100%	Rigid truck	2,000	
Internal Finish	Paint		500%	Rigid truck	2,000	
External Finish	Clothes Line	Steel (virgin)	0%	Rigid truck	200	0
External Finish	Clothes Line	Steel wire	0%	Rigid truck	200	
External Finish	Fence Gates	Steel (virgin)	0%	Rigid truck	200	
External Finish	Letter Box	Steel (virgin)	250%	Rigid truck	200	

Table 5: Assumptions used for Assembly Energy

Category	Description	Equipment	Churn Rate %	Travel Catagory	Distance km	Power Source	Burn Rate (Per Hour)	Unit	Time used hrs
Site Works	Initial Leveling	Excavator (20t)	0%	Rigid truck	40	Diesel	60.0	L	20
Services	Services Trenches	Bobcat	0%	Rigid truck	40	Diesel	12.0	L	30
Foundations	Foundation Trenches	Bobcat	0%	Rigid truck	40	Diesel	12.0	L	48
Floor	Sand up for slab	Bobcat	0%	Rigid truck	40	Diesel	12.0	L	40
Site Works	Driveway	Bobcat	0%	Rigid truck	40	Diesel	12.0	L	10
Floor	Drill 450mm Slab Piers	Bobcat	0%	Rigid truck	40	Diesel	12.0	L	10
Foundations	Concrete Pump	Concrete Pump	0%	Rigid truck	40	Diesel	20.0	L	24
Roof	Crane (Raise Prefab Trusses)	Crane	0%	Rigid truck	40	Diesel	30.0	L	30
			0%						30
Site Works	Power Tools and Equipment	Electrical Equipment	0%	Light Commercial	40	Electricy	2.5	kWh	100
Foundations	Power Tools and Equipment	Electrical Equipment	0%	Light Commercial	40	Electricy	2.5	kWh	100
Floor	Power Tools and Equipment	Electrical Equipment	400%	Light Commercial	40	Electricy	2.5	kWh	100
Walls	Power Tools and Equipment	Electrical Equipment	0%	Light Commercial	40	Electricy	2.5	kWh	100
Roof	Power Tools and Equipment	Electrical Equipment	0%	Light Commercial	40	Electricy	2.5	kWh	100

Internal Finish	Power Tools and Equipment	Electrical Equipment	400 %	Light Commercial	40	Electricy	2.5	kWh	150

Comparative Reporting

Embodied energy must be reported in a manner that fairly compares different building designs. The number of occupants or dwellings must be considered for true comparison between designs. Furthermore the life span of a building is critical. To demonstrate this point, consider:

- A free standing building with a life span of 50 years and a total embodied energy of 2500GJ
- A conscientiously designed duplex with a life span of 150 years and a total embodied energy of 2500GJ

When considering the embodied energy per dwelling per year the embodied energy of the duplex will be 1/6 of the free standing house due to life span and the number of dwellings.

Australian houses are rarely demolished due to surpassing their design life or becoming structurally unsafe. More so they are demolished and re-developed to meet current aesthetic trends and fashions. Typically, spec built homes in Australia may only last 25 – 50 years before being re-developed. Strata developments with shared walls or floor and ceilings dramatically reduces the chance of early re-development as would be developers must purchase all strata units. Shared walls, as well as reducing the likelihood of an early demolition, also reduce the embodied energy (one wall between two dwellings). Generally, high density housing yields better embodied energy results for these reasons.

Consideration of the quality of design and the location's probably of redevelopment is also made in determining likely life span. Despite these factors, the durability ceiling is rarely used as the expected life span.

Having determined likely life spans and the number of dwellings in the designs, numerous options can be compared fairly to identify best cases.

Further Considerations to Embodied Energy

Subjective consideration of the ability to recycle and reuse products at the end of the building life can have an enormous affect on energy consumption. The model does not make allowance for demolishing and or recycling the building. This limitation is addressed with clients in consultation by making recommendations on materials that have a high recycled value and/or using materials that will last longer.

Appliances are not normally modelled due to the complexity of undertaking this task. Recommendations on appliance are however useful and the major considerations for ensuring good life cycle energy and carbon efficiency are life span and operational energy.

Conclusions

Despite the difficulty in calculating embodied energy, very estimates the life cycle energy and CO_2 emissions can be determined using sound modelling principals. These tools allow design options to be compared against one another, thereby providing a valuable decision making tool for developers, architects, builders and consumers. Given the significance of the embodied energy and CO_2 emissions within new residential buildings in Australia, establishment of modelling standards and inclusion of embodied energy considerations in all housing designs is overdue. Acceptance of embodied energy modelling principals will allow for relatively easy, immediate and significant reductions in total GHG emissions generated in Australia.

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