Variability in Embodied Energy and Carbon Intensities of Building Materials Using Hybrid LCA: Malaysian Experience

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Keywords: Embodied energy; carbon; variability; hybrid LCA; Malaysia

Abstract. This paper empirically investigates the variations of embodied energy (EE) and carbon (EC) intensities of materials and identifies their parameter variations in hybrid life cycle assessment (LCA). These parameters include energy tariff, primary energy factor, disaggregation constant, emission factor, and price fluctuation. Hybrid LCA has been conducted to expand the system boundary by filling the gaps in traditional LCA data inventories. The Malaysian Input-Output (I-O) tables are used to derive indirect energy and carbon intensities which are then combined to take advantages of detailed process LCA. The results revealed that maximum increase in energy tariffs and material price fluctuations were the key parameters and issues leading to higher variations in EE and EC intensity values. Other parameters – such as maximum increase in primary energy factor, emission factor and excluding disaggregation constant – have a slight impact upon EE and EC intensity variations. Building materials with high indirect energy in the upstream boundary of materials production have high influence on hybrid LCA variation. Therefore, any decision relating to these materials should be considered carefully.

Introduction

Building industry consumes 40% of primary energy during life cycle stages of material productions, transportation, operation, maintenance, demolition and disposal. Most of the energy consumed is mainly related to the operational phase of a building, while production of building materials such as cement, concrete and steel are attributed to the industry sectors such as concrete and other non-metallic mineral sector and iron and steel product sector. In developed countries, production of building materials contributes to 8-12% of the total carbon emission. In Asian countries such as Malaysia, the industrial sector (e.g. manufacturing and construction) accounts for 38.6% of total energy demand and was claimed to be a major contributor to the environmental impact [1]. The energy-intensive industries, for instance cement and steel, were predicted to be a major consumer in the future.

The literature on EE and EC intensities in materials production indicates a considerable discrepancy between the bottom-up (process LCA) and top-down (I-O LCA) analyses [2-4]. The high variations of EE and EC intensities can be found between the two analyses which in turn influence the LCA of building components and structures. Previous studies identified various parameters influencing variations in EE consideration such as methodological selection, primary and delivered energy, age of data, manufacturing technology, source of data, and completeness of data [5, 6]. Meanwhile, Crawford [3] also identified variation in top-down analysis due to homogeneity assumption, proportionality assumption, conversion of economic data to energy data, use of national average, capital equipment and sector aggregation.

Previous researches demonstrated the changes of EE and EC intensities of materials and products over a certain period of time [7]. The changes of EE and EC could be influenced by one or combination of the following parameters: system boundaries, method of EE analysis, geographic location, primary and delivered energy, age of data sources, sources of data, completeness of data, and temporal representativeness [5]. However, these factors have not been empirically studied to identify their relative contributions to the variation of EE and EC intensities. Currently, there are

limited researches have been conducted to empirically investigate and evaluate the impact of parameter variations in EE and EC intensities, particularly to study how these parameters can be incorporated into EE and EC analysis and to what extent this parameter influences the variations of EE and EE intensities. Therefore, the purpose of this paper is to identify factors and issues that have a strong influence on hybrid models resulting from material production, and to determine the different effects of parameter variations on hybrid LCA model.

EC intensity of material for reference case using hybrid LCA. Derivation of EC intensity involved identification of parameter variations in hybrid LCA model. Indirect energy and carbon per unit of final consumption were calculated using Leontief inverse matrix and parameters of energy and carbon in each sector. Each of parameters was derived based on the detailed energy balances provided by International Energy Agency (IEA) database and were validated by using Malaysian energy balances to ensure the reliability of data provided [8, 9]. These parameters convert the product flow in the supply chain (RM\$/RM\$) to physical energy values (GJ/RM\$) [10]. These values were further deflated to the base year 2005 according to the current Malaysian I-O tables for 2005 produced in 2010 [11]. The 2005 I-O tables have 5 years lag times thus influence the variability and consistency of EE and EC intensities of building materials. These variations were discussed in the next section.

The hybrid LCA combines the results obtained from the process LCA and I-O LCA so that the completeness in upstream boundary of materials production can be increased [2, 12]. The indirect carbon intensity of a particular material sector can be identified by subtracting Eq. 2 from Eq. 1 respectively. The difference between total and direct carbon intensity is then multiplied by material cost. In order to identify total EC intensity for a material (e.g. cement, aggregate, water and reinforcement steel), the indirect carbon intensity is combined with direct carbon intensity (i.e. extraction from process LCA) using hybrid LCA as given in Eq. 3 below.

$$DCO_{2-e}I_n = \sum_e^E D_{RCe} \times T_e \times PEF_e \times C_e \times I_e \quad (1)$$

$$TCO_{2-e}I_n = \sum_e^E T_{RCe} \times T_e \times PEF_e \times C_e \times I_e \quad (2)$$

$$ECO_{2-e}I_m = ECO_{2-e}I_D + [(TCO_{2-e}I_n - DCO_{2-e}I_n) \times C_m] \quad (3)$$

Where, $DCO_{2-e}I_n$ is the direct carbon intensity for a particular sector n or product output (GJ/RM\$); D_{RCe} is the direct requirement coefficient of energy sector e (RM\$/RM\$); E is the total number of energy supply sector e in I-O table; T_e is average energy tariff (GJ/RM\$); PEF_e is the primary energy factor of energy supply sector e (dimensionless); C_e is the disaggregation constant for energy sub-sector e ; I_e is the emission factor of energy supply sector e ; $TCO_{2-e}I_n$ is total carbon intensity for a particular sector n or product output (kg CO_{2-e}/RM\$); T_{RCe} is total requirement coefficient (Leontief inverse) of energy supply sector e (RM\$/RM\$); $ECO_{2-e}I_m$ is total EC intensity of a material or product using hybrid LCA; $ECO_{2-e}I_D$ is direct carbon intensity from process LCA; C_m is the cost of material or product (RM\$/kg).

Identification of parameter variations. Five parameters were identified to have impact on the variations of EE and EC intensities [5]. These include: (1) energy tariff for energy supply sector; (2) disaggregation constant; (3) primary energy factor; (4) emission factor; and (5) price fluctuation. Each of variation was quantified and incorporated into I-O LCA and hybrid LCA to identify key parameters that have influence to the variations in hybrid LCA model. Parameter variations were derived and quantified using coefficient of variation (COV) and percentage of range and then incorporated into the analysis. The detailed parameter variations are discussed in the following section.

Energy tariff for energy supply sectors. Energy tariff is used to convert monetary unit into physical unit of supply chain in Malaysian I-O tables. Each of energy tariffs for energy supply sector was derived from Malaysian energy balances obtained from International Energy Agency (IEA) and based on estimated individual energy tariff. These energy tariffs were compared to energy tariffs derived from the 2005 I-O tables. Based on Table 1, energy tariff for coal has 33.47% higher variation compare to others energy tariff. Crude oil was the second has 18.34% variation in

energy tariffs. Significant variation in energy tariff over period of time would have high influence on the EE and EC analysis.

Table 1. Malaysia's average energy tariffs for energy supply sector for the period of 2005-2008

I-O Sector ^a	Disaggregated energy supply sector	Average energy tariffs, T _e (GJ/RM\$)				Stdev.	Avg.	COV (%)	Max. of ET	Min. of ET
		2005	2006	2007	2008					
11100	Crude oil	0.0295	0.0253	0.0244	0.0186	0.004	0.02	18.34	0.0295	0.0186
11200	Natural gas	0.0820	0.0820	0.0820	0.0820	0.000	0.08	0.00	0.0820	0.0820
10100	Coal mining	0.1397	0.1400	0.1118	0.0598	0.038	0.11	33.47	0.1400	0.0598
23100	Petroleum refinery	0.0156	0.0179	0.0135	0.0135	0.002	0.02	14.04	0.0179	0.0135
40100	Electricity supply	0.0144	0.0144	0.0135	0.0125	0.001	0.01	6.59	0.0144	0.0125
40200	Gas supply	0.0820	0.0820	0.0820	0.0820	0.000	0.08	0.00	0.0820	0.0820

(a) Based on the Malaysian Standard Industrial Classification for 2000 (MSIC2000)

Disaggregated energy supply sector. Parameter used to disaggregate the energy supply sector aims to overcome double counting in EE and EC analysis. Disaggregation constant allows individual energy tariff to be used instead of average energy tariff [10]. In Malaysian I-O tables for 2005, the aggregated energy supply sectors can be found in crude oil (IOPI 1110) and natural gas sector (IOPI 11200) (aggregate natural gas and crude oil sector); and electricity (IOPI 40100) and gas supply sector (IOPI 40200) (aggregate electricity and gas supply sector). Disaggregated energy supply sector was derived from Malaysian energy balance obtained from International Energy Agency (IEA). The disaggregation constant was included or excluded in EE and EC analysis using hybrid LCA model to identify variability and consistency in EE and EC intensities of materials.

Primary and delivered energy. Primary energy is referred to as the energy required from natural resources (e.g. coal or natural gas) by producer (e.g. electricity or petroleum refinery) whereas delivered energy is the energy consumed by final consumers. Conversion of delivered energy to primary energy using primary energy factor (PEF) is site specific [13]. The consideration of primary energy takes into account the loss in transmission and distribution as well as for plant own use for specific countries. The variability of PEF leads to the variations in EE and EC intensities. The reliable and up-to-date energy database provided by International Energy Agency (IEA) was obtained to estimate PEF for Malaysian energy supply sectors. Table 2 presents derivation of PEF from Malaysian energy balances for the period of 2005 to 2008. The PEF for electricity supply has 4.14% variation higher than others energy supply sector due to own energy used in transformation processes (i.e. transformation of natural gas into electricity supply).

Table 2. Malaysia's PEF for the energy supply sector for the period 2005-2008

I-O Sector ^a	Disaggregated energy supply sector	Primary energy factor (PEF)				Stdev.	Avg.	COV (%)	Max. of PEF	Min. of PEF
		2005	2006	2007	2008					
11100	Crude oil	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
11200	Natural gas	1.62	1.62	1.64	1.74	0.05	1.66	3.31	1.74	1.62
10100	Coal mining	1.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00
23100	Petroleum refinery	1.01	1.04	1.04	1.06	0.02	1.04	1.95	1.06	1.01
40100	Electricity supply	4.18	4.04	3.96	4.37	0.18	4.14	4.28	4.37	3.96
40200	Gas supply	1.14	1.10	1.08	1.08	0.03	1.10	2.49	1.14	1.08

(a) Based on the Malaysian Standard Industrial Classification for 2000 (MSIC2000)

Emission factor. Emission factor was applied to estimate carbon intensity for specific materials or products. An emission factor converts indirect energy intensity into indirect carbon intensity from I-O tables per unit monetary value which is then multiplied with the material or product sector output. Emission factor for electricity depends on fuel mix into electricity generation plant. Electricity emission factor was derived from Malaysian energy balances and variation of electricity from Malaysian generation plants for the period of 2005 to 2008. The results are compared with previous studies and found to be slightly higher due to gross caloric value (GCV) and scope-3 emission are incorporated into emission factor calculation [14].

Price fluctuation. Previous researches proposed hybrid LCA model by using material and building prices to quantify total EE and EC intensity of building [2, 3]. However, using building prices with highly aggregated sectors (i.e. residential building and other construction in I-O tables used by Treloar [2] and Crawford [3]) tends to greatly impact upon the total EE and EC intensity of building due to two levels of problems in price variations: (1) the use of material price to convert economic flow into physical energy and product quantity; and (2) the use of building price to fill the remaining sideways and downstream gaps. In this research, variation of price from reference case was based on percentage range of maximum and minimum values over the period of 2005 to 2008. The building material prices in Malaysia were acquired from the Construction Industry Development Board (CIDB) database and found the material price for ready-mixed concrete increased by up to 42% over the period of 2005 to 2008.

Results and Discussions

The variations of EE and EC intensities of materials in Malaysia due to parameter changes compared with the reference cases are presented in Table 3. An increased energy tariff for the energy supply sector has a single high effect on EE and EC intensities of materials. The variations of EE and EC intensities of plasterboard were higher compared with other parameters, with results showing the variations of EE and EC intensities were up to 27.11% and 19.17% respectively. In particular, EE and EC intensities of plasterboard increased from 19.16 MJ/kg to 24.36 MJ/kg and 1.50 kg CO_{2-e}/kg to 1.79 kg CO_{2-e}/kg. This variation was due to the influence of indirect energy and carbon embodied in the upstream boundary of the supply chain in material production.

A single variation in PEF has less impact upon EE and EC intensities of materials. A maximum increase of PEF (i.e. particularly the natural gas and electricity supply sectors) has less impact on the hybrid LCA model. Using maximum PEF values between the periods of 2005 to 2008 showed the EE and EC intensities of plasterboard slightly increased from 19.16 MJ/kg to 21.74 MJ/kg and 1.50 kg CO_{2-e}/kg to 1.54 kg CO_{2-e}/kg, accounted for 13.02% and 4.80% of total EE and EC content. Meanwhile, the EE and EC intensities for clear float glass also slightly increased up to about 3.62% and 4.45% of total EE and EC content, ranged between 42.32 MJ/kg to 43.85 MJ/kg and 3.02 kg CO_{2-e}/kg to 3.15 kg CO_{2-e}/kg respectively. The parameter variations on energy intensive materials has less impact (e.g. cement, clay brick, steel virgin etc.), compared with less energy intensive materials such as clear float glass, plasterboard, or plastic products that have a large proportion of indirect energy and carbon embodied in the upstream boundary of materials production.

Using a disaggregation constant for aggregated energy supply sectors has less impact on variations of EC intensities of materials in the hybrid LCA model. Without disaggregation constants, EE and EC intensity values for clear float glass varied by up to 10.08% (10.08% reduction) and 11.78% (11.78% reduction) respectively. As shown in Tables 3, overall EE and EC intensities of materials in the hybrid LCA model slightly decreased from the reference cases.

An increase of material price also has a moderate impact on EE and EC intensities in the hybrid LCA model. The variation of material prices in Malaysia such as cement, ready-mixed concrete, and reinforcement steel were much higher compared with other material prices. Further increases of cement price of 32.95% led to the variation of EE and EC intensity values by up to 13.93% (from 9.01 MJ/kg to 10.26 MJ/kg) and 8.70% (from 1.01 kg CO_{2-e}/kg to 1.09 kg CO_{2-e}/kg) in the hybrid LCA model.

The variation in the electricity emission factor was due to the mix of fossil fuel in national energy policy, which has less impact on the hybrid LCA values. The maximum increase of emission factor has slightly increased EE and EC intensities of materials by approximately less than 3%. Therefore, using a disaggregation constant for the aggregated energy supply sector so that individual emission factors can be used instead of an average emission factor would result in less variation in the hybrid LCA model.

Table 3: EE and EC and changes in due to parameter variations compared with the reference case at materials and products level for Malaysia

Building material or product	Changed parameter	Embodied energy (MJ/kg)						Embodied carbon (kg CO _{2-e} /kg)					
		Process LCA	I-O LCA			Hybrid LCA	Change from ref. (%)	Process LCA	I-O LCA			Hybrid LCA	Change from ref. (%)
			Direct	Indirect	Total				Direct	Indirect	Total		
Ordinary Portland cement (OPC)	Reference case (minimum case)	5.200	1.024	3.807	4.831	9.007	0.000	0.740	0.106	0.265	0.372	1.005	0.000
	Maximum increase in ET	5.200	1.443	4.668	6.111	9.868	9.565	0.740	0.141	0.332	0.473	1.072	6.642
	Maximum increase in PEF	5.200	1.085	4.015	5.100	9.215	2.315	0.740	0.114	0.281	0.395	1.021	1.558
	Without disaggregation constant	5.200	1.030	3.149	4.180	8.349	-7.298	0.740	0.093	0.223	0.315	0.963	-4.259
	Maximum increase in material price	5.200	1.362	5.061	6.423	10.261	13.927	0.740	0.141	0.353	0.494	1.093	8.699
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.740	0.111	0.271	0.382	1.011	0.568
Concrete (35 MPa)	Reference case (minimum case)	1.074	0.145	0.777	0.922	1.851	0.000	0.142	0.015	0.055	0.070	0.197	0.000
	Maximum increase in ET	1.151	0.222	0.953	1.175	2.104	13.702	0.148	0.022	0.069	0.090	0.217	10.360
	Maximum increase in PEF	1.081	0.152	0.819	0.972	1.901	2.710	0.143	0.016	0.058	0.074	0.201	2.164
	Without disaggregation constant	1.075	0.146	0.644	0.789	1.718	-7.145	0.140	0.013	0.046	0.059	0.186	-5.418
	Maximum increase in material price	1.136	0.207	1.049	1.256	2.185	18.071	0.148	0.021	0.074	0.095	0.222	13.067
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.142	0.016	0.056	0.072	0.198	0.981
Plasterboard	Reference case (minimum case)	6.750	2.257	12.411	14.668	19.161	0.000	0.390	0.234	1.113	1.348	1.503	0.000
	Maximum increase in ET	6.750	3.488	17.605	21.094	24.355	27.109	0.390	0.338	1.402	1.739	1.792	19.174
	Maximum increase in PEF	6.750	2.390	14.906	17.295	21.656	13.021	0.390	0.249	1.186	1.435	1.576	4.800
	Without disaggregation constant	6.750	2.285	12.049	14.334	18.799	-1.889	0.390	0.207	0.929	1.136	1.319	-12.291
	Maximum increase in material price	6.750	2.415	14.990	17.404	21.740	13.458	0.390	0.249	1.183	1.431	1.573	4.614
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.390	0.245	1.151	1.395	1.541	2.478
Clear float glass	Reference case (minimum case)	15.000	7.879	27.323	35.202	42.323	0.000	0.910	0.995	2.106	3.101	3.016	0.000
	Maximum increase in ET	15.000	10.608	33.878	44.486	48.878	15.488	0.910	1.257	2.646	3.903	3.556	17.909
	Maximum increase in PEF	15.000	8.402	28.853	37.256	43.853	3.616	0.910	1.078	2.240	3.318	3.150	4.447
	Without disaggregation constant	15.000	7.957	23.057	31.014	38.057	-10.081	0.910	0.824	1.751	2.575	2.661	-11.775
	Maximum increase in material price	15.000	8.999	31.206	40.204	46.206	9.173	0.910	1.137	2.405	3.542	3.315	9.922
	Maximum increase in EF for elec.	-	-	-	-	-	-	0.910	1.062	2.173	3.235	3.083	2.209
Aluminium virgin	Reference case (minimum case)	155.000	11.364	86.025	97.388	241.025	0.000	9.160	1.696	7.509	9.205	16.669	0.000
	Maximum increase in ET	155.000	14.362	107.913	122.275	262.913	9.082	9.160	1.696	8.030	9.726	17.190	3.126
	Maximum increase in PEF	155.000	12.218	91.039	103.257	246.039	2.081	9.160	1.849	8.031	9.880	17.191	3.134
	Without disaggregation constant	155.000	11.523	75.056	86.578	230.056	-4.551	9.160	1.347	6.204	7.551	15.364	-7.830
	Maximum increase in material price	155.000	13.325	100.872	114.197	255.872	6.160	9.160	1.989	8.805	10.793	17.965	7.775
	Maximum increase in EF for elec.	-	-	-	-	-	-	9.160	1.832	7.831	9.663	16.991	1.930

Conclusion

Parameter or scenario uncertainty was conducted to empirically investigate and evaluate key parameters and issues that contribute to high variations in EE and EC intensities of building materials in Malaysian construction industry. This study found that maximum increase in energy tariff and material price fluctuation was the key parameters and issues leading to higher variations in EE and EC intensity values. Other parameters such as maximum increase in primary energy factor, emission factor and excluding disaggregation constant have a slight impact upon EE and EC intensity variations. The high variations of EE and EC intensities in hybrid LCA model can be clearly seen between energy and non-energy intensive materials due to the high contribution of indirect energy in non-energy intensive materials in upstream boundary of materials production. Therefore, any decision relating to these materials should be considered carefully. Thus one strategy to reduce uncertainty and increase reliability of hybrid LCA data is by firstly calculating EE and EC intensities of materials and products, and then computing EE and EC of the entire building by using actual quantities of material, labor and equipment (process LCA). This in turn can reduce the high variations of EE and EC intensity values caused by high dependency on the aggregated industry sectors in the I-O tables (i.e. residential and non-residential sector used in Malaysian I-O tables).

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