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Assessment of the Embodied CO2eq in Buildings towards a Sustainable Building Design and Construction

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1 Abstract

Research studies have shown that the initial energy embodied in a building can be as much as 67% of the operational energy over a 25 year period. With growing global concerns over material and resource consumption and the emissions of CO_2 into the atmosphere, the energy embodied in buildings constructed in town and cities becomes important and one of the key issues that needs to be tackled in the design stages in order to strive towards sustainable buildings design.

In this paper, a hybrid embodied carbon dioxide equivalent (CO_{2eq}) methodology used to assess the CO_{2eq} embodied in buildings is presented. The hybrid methodology consists of an Input-Output (I-O) and a process-based analysis. The I-O analysis is undertaken using re-derived Supply and Use and Input-Output data for Ireland which includes energy inputs into imported construction products and materials and construction sub-sectoral energy data. The Grand Canal Apartments in Dublin, Ireland is used as a case study. The buildings substructure, internal walls, floors, stairs, frame and roof was analysed in the study.

The Irish construction sector is divided into five different sub-sectors, each having direct input-output energy intensities and accounting for different construction activities. The construction sub-sectoral I-O direct energy intensities ranges from 25.61tCO_{2eq}/m€ for general fit-out to 493.27tCO_{2eq}/m€ for the use of construction machinery. When embodied CO_{2eq} analysis is carried out at the construction sub-sectoral level, there is a methodological improvement in the calculated values for the direct input-output as well as the total energy intensities over other traditional hybrid methods because of the use of disaggregated sub-sector construction data which can be more specifically applied to the type of construction project being considered. This hybrid methodology further makes use of disaggregates factors that disaggregate the energy supply sectors in the Input-Output analysis into individual sub-sectors supplying energy to the construction sector.

Increasing population in urban cities and town means that new building and other social infrastructure needs to be constructed. Embodied CO_{2eq} emissions of new buildings should be used as one of the sustainable indicators to measure the whole life sustainability of buildings. The embodied CO_{2eq} of a Grand Canal apartment building was estimated to be 0.00718tCO_{2eq}/€. Energy saving efforts and sustainability initiatives in the construction sector such as considerations to embodied CO_{2eq} of building materials, selection and design options can play a significant role in reducing the overall future CO_{2eq} of the country. Reduction in the CO_{2eq} embodied in buildings helps to tackle environmental pollution but needs however to be balanced with economic and social costs in order to achieve an overall sustainable urban solution.

2 Introduction

The construction industry typically consumes significant energy resources in an economy (Suzuki et al 1995). According to Perez-Lombard et al (2008) global contribution from buildings towards energy consumption has steadily increased reaching figures between 20% and 40% in developed countries. Consequently this causes substantially environmental emissions and environmental impacts and raises issues of sustainability (Cole 1998, Junnila et al 2003). In Ireland as in many other economies, the construction industry is very important economically but is also energy intensive. According to a report by the United Nations Economic Commission for Europe (UNECE 2006), Ireland had the highest level of construction activity between 2004 and 2007 although there has been a general slow down in the construction market locally and globally. By 2005 it contributed to 19% of GDP and 22% of GNP. This level of activity is likely to be associated with significant energy use and related emissions from the construction industry, raising questions about environmental sustainability.

The building and construction sector in Ireland consumed 25% of total primary energy consumption (Sustainable Energy Ireland 2007a). Hence to achieve security of supply, competitiveness and environmental sustainability as outlined in the Irish White Paper and the Irish Energy Policy Framework 2007-2020, energy use and emissions in the construction sector must be reduced. Also, in order deliver a sustainable building design and energy future for Ireland and fulfil national and European Union (EU) climate change targets under the Kyoto protocol, assessment techniques in energy intensive sectors such as building and construction must be developed so that emissions can be quantified and policy effectiveness assessed. Furthermore, as companies seek to obtain ISO 14000 environmental management accreditations, such assessment techniques and analysis would provide an effective way of quantifying and managing their environmental impacts.

Lack of environmental initiatives and research studies targeted at the Irish construction sector (Forum for the Construction Industry 2003, UCD Energy Research Group 2007) means that sustainable energy policy and regulatory measures are not fully incorporated with new environmental research knowledge to regulate whole life energy use in the building and construction sector. This study will therefore present a systematic analysis in the quantification of embodied CO_{2eq} emissions resulting from the total energy used in the construction of buildings.

Construction sector emissions intensities of three gases: CO_2, N_2O and CH_4 are analysed. These emissions are analysed because they are the major environmental emissions associated with energy use in the construction sector. CO_{2eq} emissions arise from the consumption of fossil-fuel derived electricity and the use of fuel such as diesel in plant and machinery. Impact assessment can aggregate CO_2, methane and other greenhouse gas emissions (GHG) into a single impact assessment parameter affecting climate change or global warming. CO_2 equivalent weighting known as global warming potential (GWP) is ascribed to each greenhouse gas which is then summed to give a total CO_{2eq}. Carbon dioxide equivalent, CO_{2eq} provides a universal standard of measurement against which releasing different green house gases can be evaluated as an impact of global warming (International Emissions Trading Association 2008). The six greenhouse gases, GHG specified in the Kyoto Protocol are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Of these, naturally occurring energy related GHG released into the atmosphere are CO_2, N_2O and CH_4

3 Methodological Assessment

A hybrid assessment used to calculate the embodied CO_{2eq} intensity of a building is presented. The hybrid assessment combines input-output analysis at a construction sector and sub-sectoral level and process analysis inventory.

3.1 Process Analysis

Process analysis is usually undertaken at an industrial level by measuring the inputs and outputs of energy and materials flow during the manufacturing processes of a product. The sum of all the energy used directly and indirectly during the manufacture of the product per unit output of the product is the process energy intensity for that particular product. According to Born (1996), process analysis suffers from truncation due to the setting of system boundaries but can be combined with I-O analysis into a hybrid model which has the advantages of the more accurate process analysis data and an I-O framework more complete in system boundary (Suh et al 2002, Mongelli et al 2005). The process analysis intensity in this study is calculated using database of inventory of carbon and energy, ICE published by Sustainable Energy Research Team (2008).

3.2 Input-Output Analysis

Embodied energy and CO_{2eq} I-O analysis is undertaken using national economic data whereby energy intensities are determined per unit monetary value of output. The energy and CO_{2eq} associated with activities in the building and construction sector can be characterized as direct and indirect and evaluated using I-O analysis. The former released directly due to activities undertaken on the construction site (for example structural works, fit-out, plant operation). Indirect emissions are associated with the upstream use of energy in construction-related activities (for example energy used to manufacture building materials, excavation of raw aggregate, design team activities).

3.2.1 Direct CO_{2eq} Intensity

The I-O direct energy intensity of construction is determined at a sub-sector level rather than at the aggregated sectoral level to improve accuracy. The direct emissions intensity is calculated from construction company data collected by the Irish Central Statistics Office which categorizes energy use according to five construction sub-sectors. The data collected was categorized into electricity and fuel used on site. It is assumed that fuel used was diesel since vast majority of plant and construction machinery uses operates on diesel fuel (Limerick Energy 2008).

A representative sample of 728 Irish construction firms was surveyed in a 2005 census and the electricity and fuel consumption of each was recorded. The primary energy in each construction sub-sector (Sub-Sector 1 to Sub-Sector 5) was derived from this. The CO_{2eq} intensities in tCO_{2eq}/€ was then derived for each Euro output of each sub-sector.

Irish electricity emission factors are derived taking into account the fuel type used in electricity generation and efficiencies of each generating plant. The electricity used in each construction sub-sector was therefore derived from each fuel type using the ratios of electricity generation mix in Ireland. The environmental emissions intensities (CO_2, N_2O, CH_4) due to electricity used on site was then calculated for each fuel type. Diesel emissions were also calculated using typical diesel emission factors and added to electricity emissions. The direct CO2eq intensity for the construction sector was then determined using the Global Warming Potential (GWP) of each gas and summing all CO_{2eqs}.

The construction sector in Ireland is divided into five sub-sectors namely: Sub-Sector 1 to Sub-Sector 5. Descriptions of the construction processes and activities undertaken in each sub-sector are outlined below;

Sub-Sector 1: Site preparation, demolition of buildings, earth moving, ground work, drilling and boring, etc

Sub-Sector 2: Building of complete constructions or part thereof; civil and structural construction works, etc

Sub-Sector 3: Building installation, installation of electrical wiring and fittings, insulation, plumbing and other installations, etc

Sub-Sector 4: Building completion, joinery installation, plastering, floor and wall, covering, painting, glazing and general fit-out, etc

Sub-Sector 5: Renting of construction equipments, etc

Because different construction activities are undertaken in each of the sub-sectors, their energy intensities will also vary. These represent the direct emissions intensity since these emissions are calculated using data on energy consumed on the construction site. According to Bullard et al (1978) and Tiwari (2000) the calculated I-O direct and total energy intensity of different but similar products such as a building belonging to the same I-O economic sector will be the same even though the production or construction processes undertaken in each is different. This hybrid analysis tackles this problem in traditional I-O analysis by calculating an I-O direct energy and CO_{2eq} intensity which is always unique to a building and consequently a unique total energy and CO_{2eq} intensity for every building even if they are similar and belong to the same I-O economic sector.

3.2.2 Indirect Emissions Analysis

Indirect emissions' intensities in the construction sector are estimated using data from the National Input-Output (I-O) tables. These are generated using data from the national accounts as well as other sources to show the economic transactions between all product sectors of the national economy. The input coefficients of the economy wide I-O tables are used to derive indirect energy and CO_{2eq} intensities in the building and construction sector. Because of the extended system boundary of I-O analysis, upstream energy inputs missed the process analysis are captured. The I-O intensities are calculated as GJ of energy consumed or tCO_{2eq} of CO_2 emitted per Euro output of the building and construction sector. The national I-O tables consist of supply and use tables together with symmetric input-output tables.

The indirect emissions intensities were evaluated as the difference between the I-O total and I-O direct emissions intensity as described by Treloar (1998). According to Bullard et al (1978), Lenzen et al (2000) and Stromman et al (2008) the total energy intensity is derived from the Leontief Inverse Matrix, $(I-A)^{-1}$ which is a binomial expansion estimate of the total deliveries or the sum of the zero order delivery to the infinite order delivery from one product sector of the economy to another.

Hence

$$\text{Leontief Inverse Matrix} = A^0 + A^1 + A^2 + A^3 + \ldots$$

$$= I + A^1 + A^2 + A^3 + \ldots$$

$$= (I-A)^{-1}$$

Where:

A= Matrix of direct requirement coefficients which shows the direct delivery from one product sector of the economy to another

This is employed using national I-O tables (Central Statistics Office 2006), average energy tariffs for Ireland (International Energy Agency, 2006) and primary energy factors (Sustainable Energy Ireland, 2006) and disaggregation factors (Wissema 2006) to determine energy intensities per unit monetary value of output from the construction sector.

Two further key features are incorporated into this methodology in order to improve its accuracy of calculated results from the available Irish data. These are:

- The addition of upstream energy inputs for imported goods and services and
- Disaggregation of the input-output energy supply sectors.

1. Energy Inputs of Imported Goods and Services

The main advantage of input-output analysis in energy and environmental research studies relates to the extended system boundary that the analysis offers over process-based approaches (Born 1996, Hayami et al 1997, Lenzen et al 2000). This is because in process analysis, because all the infinite energy inputs into a product can not be measured, a system boundary has to be set thus truncating some of the energy inputs. The direct requirement coefficient matrix of the Irish I-O tables used to evaluate the direct energy intensity and the Leontief inverse matrix used to calculate the total energy intensity (Treloar, 1998) is tabulated for domestic product flows. Hence, energy input into imported products has been omitted. According to EuroStat (2002), if input-output tables are to be used to calculate the total energy intensity used to produce one unit of a particular product then the energy used to produce imported inputs should also be included. This is particularly important given that Ireland and its construction sector is heavily dependent on imported products (SCCI 2006)

2. Disaggregation of Energy Supply Sectors

A limitation with I-O analysis is the aggregation of different products into one sector in the national I-O tables (Mongelli et al 2005). To tackle this problem, a constant called a “disaggregation constant”, is incorporated into the input-output analysis in order disaggregate the energy supply sectors because the energy supply sectors are aggregated together either with non-energy supply sectors or other energy supply sectors. A detailed analysis of the disaggregation of the energy supply sectors in Ireland was first undertaken by Wissema (2006) in a study to construct a Social Accounting Matrix for Ireland. The Irish I-O table consists of three aggregated energy supply sectors namely:

- Mining and Quarrying Products;
- Petroleum and Other Manufacturing Products; and
- Electricity and Gas

The energy sector peat, crude oil and coal are aggregated together with other quarrying products. The second energy sector, oil is aggregated together with ‘other manufacturing products’ while the third energy supply sector “electricity and gas” consists of electricity, natural gas and renewable energy.

The use of the disaggregation constants has a two-fold advantage. Firstly, non-energy supply sectors are eliminated from the analysis. Secondly, it enables individual primary energy factors and energy tariffs to be used instead of average values for two or more aggregated sector energy supply sectors (example electricity and gas).

3.3 Hybrid Embodied CO_{2eq} Assessment

The assessment of the hybrid embodied CO_{2eq} analysis is as follows;

- The bill of quantities of the building is analysed and the quantities of the main building materials identified. The CO_{2eq} [tCO_{2eq}] of the main building materials are calculated using process analysis from the database of inventory of carbon and energy, ICE (Sustainable Energy Research Team 2008).
- The CO_{2eq} of the rest of the entries in the bill of quantities of the building besides the main building materials which describes construction processes are calculated using I-O analysis. The total expenditure on all itemised construction processes undertaken are grouped under one of the five construction sub-sectors outlined. The direct sub-sectoral I-O part of the hybrid analysis is determined as follows.
- The primary energy intensity [GJ/€] representing direct energy use in each construction sub-sector (Sub-Sector 1 to Sub-Sector 5) was derived from the 2005 Irish construction census data
- The direct sub-sectoral CO_{2eq} intensity [tCO_{2eq}/€] was consequently calculated for each sub-sector using Irish emission factors published by Sustainable Energy Ireland (2007b) and global warming potential of the energy related greenhouse gases. The direct sub-sectoral CO_{2eq} intensity is calculated per Euro output of each sub-sector.
- The direct sub-sectoral $CO2_{eq}$ [t CO2eq] of the building is calculated from:

$$\text{Direct Sub - Sectoral CO}_{2\text{eq}} = \sum_{\text{j}=1}^{5} \text{I}_{\text{j}} E_j$$

Where:

j = Sub-sector

I = Direct sub-sectoral CO2eq intensity [tCO_{2eq}/€]

E = Economic output of each sub-sector for the building [€]

The indirect i-O part of the hybrid analysis is determined as follows.

- The direct requirement matrix and the Leontief Inverse Matrix were re-derived to include imported goods and services according to the methodology outlined by the European System of Accounts (EuroStat 2002). Upstream energy inputs into building and construction products are included in the analysis as a result of this analysis.
- The I-O direct and total energy intensities [GJ/€] of construction was calculated using the primary energy factors (Sustainable Energy Ireland, 2006), energy tariffs (International Energy Agency, 2006) and direct requirement coefficient and total requirement coefficient respectively (Central Statistics Office, 2006) as described by Treloar (1998).
- The direct and total I-O energy intensities of the overall construction sector were readjusted using disaggregation factors derived for Ireland by Wissema (2006)
- The I-O indirect energy intensities are calculated as a difference between the I-O total and the direct energy intensities of the whole construction sector. The I-O indirect CO_{2eq} intensity was then calculated for the whole Irish construction sector using Irish emission factors published by Sustainable Energy Ireland (2007b) and Global Warming Potential of the energy related greenhouse gases.
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The indirect I-O CO_{2eq} [tCO_{2eq}] of the building is calculated from:

$$\text{I - O Indirect } CO_{2eq} = I_{(I-O)} \times \sum_{j=1}^{5} E_j$$

Where: $I_{(I-O)}$ = I-O Indirect CO2eq intensity

- The hybrid CO_{2eq} intensity is evaluated as the ratio of the sum of the process CO_{2eq}, the direct sub-sectoral CO_{2eq} and the I-O indirect CO_{2eq} to the total expenditure of the building.

4 Results and Analysis

4.1 Direct Sub-Sectoral embodied CO_{2eq} of Building

Figure 1 show the quantities of electricity used by the sample of Irish construction companies classified by sub-sector in GJ of primary energy. By using the ratios of the electricity generating mix in Ireland: coal-25%, oil-13%, peat-9%, natural gas-46% and renewable energy-7%, the total amount of electricity by fuel type was calculated.

Figure 1: Sub-sectoral direct electricity use by fuel source

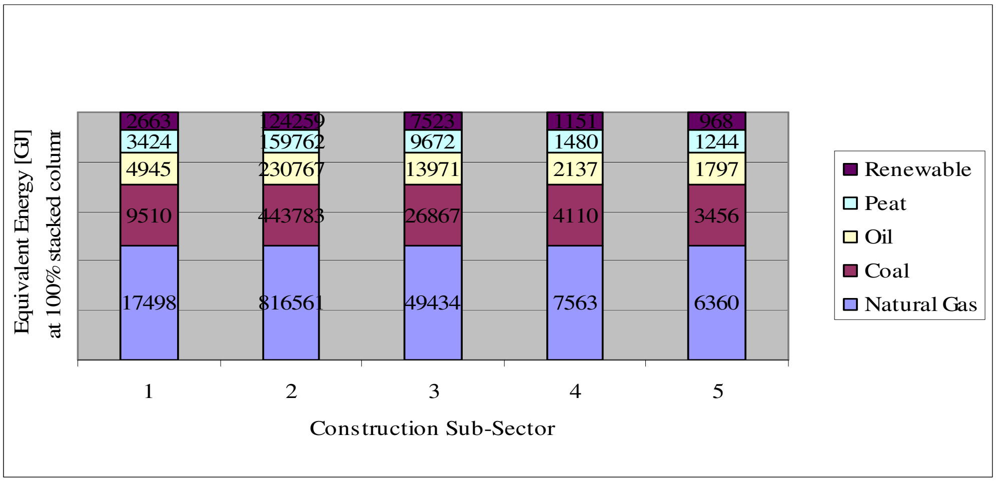
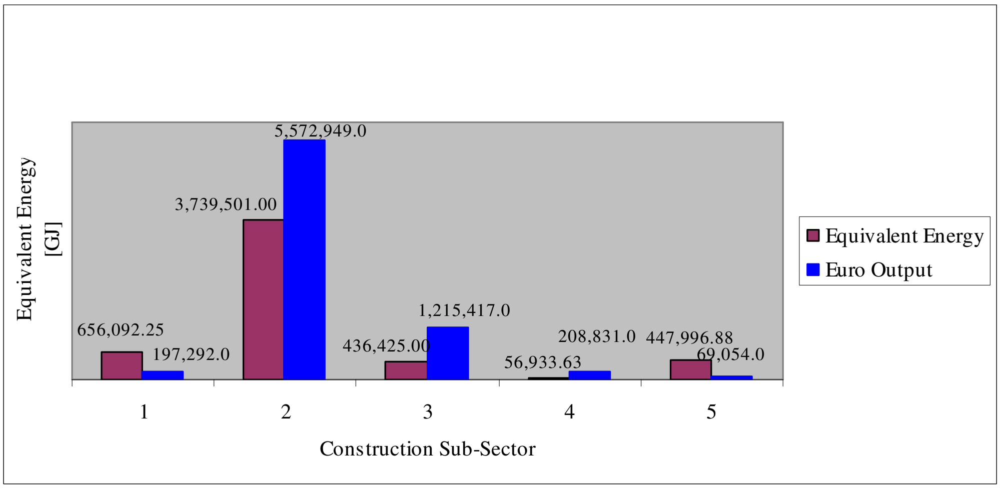


Figure 2: Sub-sectoral fuel consumption and economic output from census



Derived from: Central Statistics Office (2007)

Table 1: Electricity and Diesel emission factors in tonnes/GJ taking account of generating efficiencies

Electricity & Fuel	Gen. Eff.(η)	Fuel Mix Ratio	CO_2 [t/GJ] x 10^{-6}	N_2O [t/GJ] x 10^{-6}	CH_4 [t/GJ] x 10^{-6}
Electricity:					
Coal	0.370	0.25	88418.60	2.11	1.50
Oil	0.380	0.13	78500.00	2.00	3.00
Peat	0.385	0.09	105949.30	1.83	1.56
Natural Gas	0.414	0.46	55196.40	0.69	2.50
Renewable	1.000	0.07	0.00	0.00	0.00
Diesel	-	-	73300.00	1.77	3.95

Source: Sustainable Energy Ireland (2007)

The emissions intensity [t/GJ] presented in table 1 are multiplied by the quantities of electricity and diesel used [GJ] in each construction sub-sector and divided by the output of each sub-sector [€] to determine the direct emissions intensity for each sub-sector; these are presented in Table 2.

Table 2: The direct emissions intensities by construction sub-sector

Emission [t/m€]	Sub-Sector 1	Sub-Sector 2	Sub-Sector 3	Sub-Sector 4	Sub-Sector 5
CO_2	256.72	70.6	32.27	25.28	489
N_2O	0.006	0.002	0.001	0.001	0.012
CH_4	0.014	0.003	0.002	0.001	0.026
CO_{2eq}	258.87	71.28	32.62	25.61	493.27
Expenditure	29,324.30	2,019,047.33	487.80	177,640.67	14,655.68

Using:

$$\text{Direct Sub - Sectoral CO}_{2\text{eq}} = \sum_{\text{j}=1}^{5} \text{I}_{\text{j}} E_{j}$$

The direct sub-sectoral CO_{2eq} is estimated to be to be 163.3tCO_{2eq}

4.2 Indirect I-O embodied CO_{2eq} of Building

The primary energy factors (Sustainable Energy Ireland 2006), average energy tariffs (International Energy Agency, 1998) are presented in Table 3, the disaggregation constants in Table 4. Together with the re-derived direct requirement coefficients and the Leontief inverse coefficients of the 2000 National Supply and Use and Input-Output Table in Figures 5 and 6 (Central Statistics Office, 2006) the direct and total energy intensity of construction was calculated as described by Treloar (1998).

Table 3: Primary Energy Factors, Average energy Tariffs and Emission Factors for Ireland.

Energy Supply Sector	Primary Energy Factor	Average Energy Tariff [GJ/€]
Peat	1.01	0.1124
Crude Oil	1.00	0.5055
Coal	1.00	0.3681
Petroleum	1.01	0.1507
Natural Gas	1.03	0.2270
Electricity	1.11	0.0337
Renewable Energy	1.00	0.0686

Source (Sustainable Energy Ireland, 2006 and IEA, 2006)

Table 4: Disaggregation Constant for Ireland.

I-O Sector	Aggregated Energy Supply Sectors	Disaggregated Energy Supply Sectors	Disaggregated Constants
10-14	Mining and Quarrying	Peat Crude Oil Coal	0.136 0.175 0.116
23 & 36	Petroleum and 'Other Manufacturing'	Petroleum	0.700
40	Electricity and Gas	Electricity Natural Gas Renewable Energy	0.755 0.205 0.040

Source: (Wissema, 2006)

Figure 3: Comparison between the direct requirement coefficients of the construction sector to the energy supply sectors with and without imports

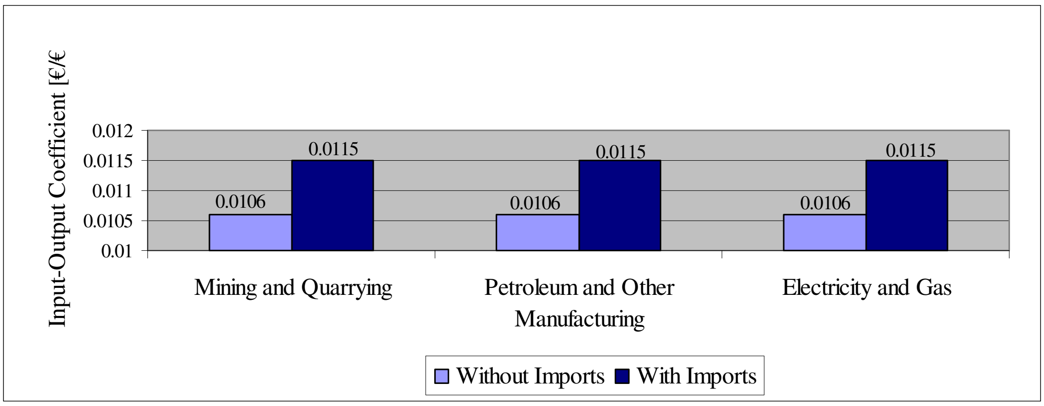
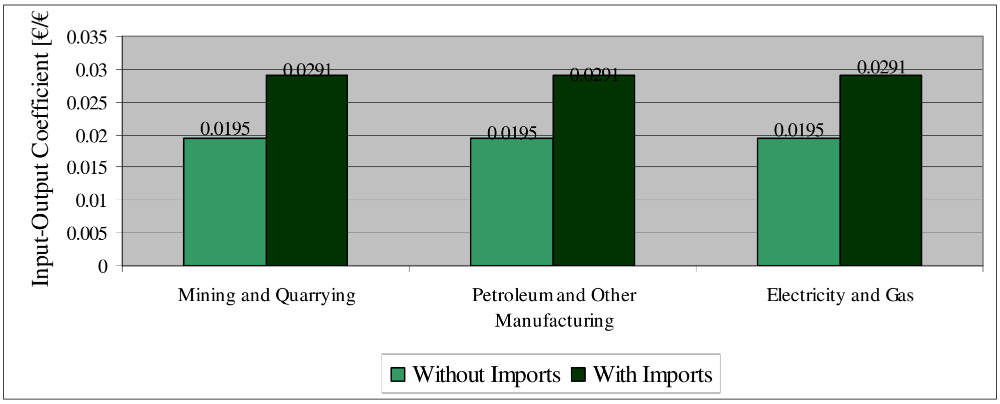


Figure 4: Comparison between the total requirement (Leontief) coefficients of the construction sector to the energy supply sectors with and without imports



The direct and total energy intensities of the Irish construction sector for each of the energy supply sectors are shown in Table 5. The direct and total energy intensities were found to be 0.00872 GJ/€ and 0.00373 GJ/€ respectively. Hence the I-O indirect energy intensity is estimated to be 0.00499 GJ/€.

Table 5: Direct, Total and Indirect I-O Energy Intensity of Irish Construction

Disaggregated Energy Sector	Direct Energy Intensity [GJ/€]	Total Energy Intensity [GJ/€]	Indirect Energy Intensity [GJ/€]
Peat	0.00018	0.00045	0.00027
Crude Oil	0.00102	0.00257	0.00156
Coal	0.00049	0.00124	0.00075
Petroleum	0.00086	0.00170	0.00084
Electricity	0.00027	0.00062	0.00036
Natural Gas	0.00046	0.00106	0.00060
Renewable Energy	0.00003	0.00006	0.00003

The indirect energy intensities presented in Table 5 is multiplied by the emissions intensities in Table 1 to obtain the indirect emissions intensities of energy use in the Irish construction sector.

Table 6: I-O indirect emissions intensity of the Irish construction sector

Energy Sector	CO2 [t/m€]	N2O [t/m€]	CH4 [t/m€]	CO2eq [t/m€]
Peat	28.7897	0.0005	0.0004	28.95
Crude Oil	122.2198	0.0031	0.0047	123.28
Coal	66.4477	0.0016	0.0011	66.97
Petroleum	66.0738	0.0017	0.0025	66.65

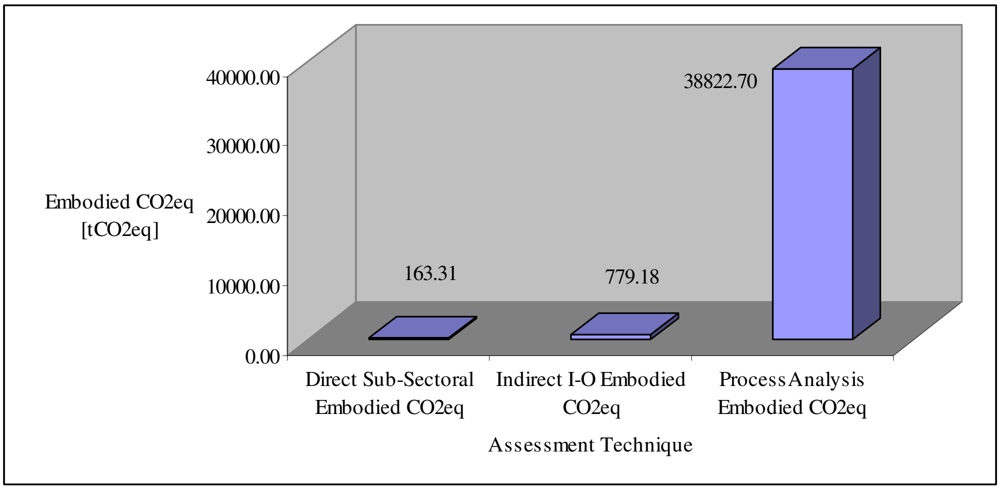
Electricity	28.1261	0.0006	0.0007	28.33
Natural Gas	33.3348	0.0004	0.0015	33.49
Renewable-Energy	0.0000	0.0000	0.0000	0.00
Total Indirect Emissions	344.9920	0.0079	0.0109	347.67

From:

$$\text{I - O Indirect CO}_{2\text{eq}} = I_{(I-O)} \times \sum_{j=1}^{5} E_j$$

The I-O indirect CO2eq is estimated to be 779.2tCO_{2eq}.

Figure 5: CO2eq of apartment building split into assessment technique



The hybrid CO_{2eq} intensity of a Grand Canal Apartment building is estimated to be 0.00718tCO_{2eq}/€ given that the total cost of the apartments was built at a cost of €5,536,402.60.

5 Discussions

With significant efforts been made to achieve very high efficiency with energy use in buildings, the energy and CO_{2eq} embodied in building becomes increasingly significant and the proportion of embodied energy to operational energy keep increasing. According to Yohanis et al (2002) initial energy embodied in a building can be as much as 67% of the operational energy over a 25 year period. The Commonwealth Scientific and Industrial Research Organisation, CSIRO (2006) also states that embodied energy approaches half the lifetime energy consumption in very energy efficient home. As cities expand and new urban centres spring up new buildings has to be built to accommodate growing population and services but its energy consumption has to be regulated. The New Building Regulation introduced in Ireland is one such newly legislation passed to improve energy efficiency of buildings in Ireland. While such an effort is commendable, a holistic approach has to be taken by not focussing solely on operational energy in order to achieve whole life sustainability. Hence embodied CO_{2eq} of buildings should be considered and used as a benchmark or sustainable indicator in regulatory measures. The 2007 Energy White Paper for Ireland which sets out the energy policy framework for Ireland from 2007 to 2020 reported the need to reduce total energy consumption by optimizing energy efficiency, reducing operational energy use but failed to directly point out the significant energy reductions that can be achieved through considerations to embodied energy in Ireland. This is especially important given that embodied energy research has not been undertaken in Ireland as is the case in other countries in Europe, Australia, United States, Japan and China.

The hybrid analysis indicates that for every Euro spent on a Grand Canal Apartment building, 0.00718 tonnes of carbon dioxide equivalent is emitted into the atmosphere. In this hybrid CO_{2eq} analysis the total embodied CO_{2eq} of the building does not only consist of the CO_{2eq} embodied in the building materials. All construction activities undertaken are accounted for and their embodied CO_{2eq} estimated using direct I-O sub-sectoral CO2eq intensities. The use of national I-O data also accounts for indirect energy inputs into the construction sector. The majority of embodied CO_{2eq} however is as the result of building materials such as steel, concrete, reinforced concrete, etc which have high embodied CO_{2eq}. The Grand Canal Apartment buildings was studied without work done on building installations and general fit-out. This may account for the lower contribution of I-O embodied $CO_{2eq.}$

I-O indirect energy intensity from the re-derived I-O table which includes energy inputs into imported goods and services in the construction sector was estimated to be 0.00441 GJ/€. This is almost double the I-O indirect energy intensity of 0.00227 GJ/€ obtained using direct requirements coefficients and Leontief Coefficients with imports goods and services discounted. The use of re-derived I-O tables therefore shows that energy inputs into imported goods are very significant although such indirect energy inputs can be difficult to control or regulate in any national energy policy measure. Greater control of indirect energy inputs can however be achieved when energy policy is formulated and implemented at a regional context such as the EU level.

6 Conclusions

The research shows that such environmental analysis can be used to quantify the CO_{2eq} emissions associated with buildings in the construction sector. Such quantitative measurements can be used to inform policy and regulatory measures. Building and activities in the construction sector contributes significantly to total national CO_2 emissions. The sustainable challenges confronting the design of new buildings call for complete sustainability tools which can assess such buildings. In order to achieve whole life sustainability, embodied CO_{2eq} assessment must be incorporated to any such tool or metrics.

A hybrid embodied CO_{2eq} analysis combining process, input-output and sub-sectoral construction sector analysis provides a comprehensive approach in estimating the CO_{2eq} embodied in buildings. Energy saving and CO_{2eq} limiting efforts can be achieved through such an analysis by identifying alternative building materials with lower embodied CO_{2eq} and employing energy efficient initiatives in construction sub-sectors with high energy and CO_{2eq} intensities.

Further research in embodied CO_{2eq} of buildings can lead to the formulation of regulations and standards comparable to operational energy use of buildings. In such a case, buildings could also be rated according to the amount of CO_{2eq} it embodies.

7 Reference

Born, P (1996) Input-output analysis: input of energy, CO_2, and work to produce goods. 'Journal of Policy Modelling ', volume 18, issue 2, 217–221

Bullard, CW, Penner, PS, Pilati, DA (1978) Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis, 'Resources and Energy' volume 1, 267-313

Central Statistics Office (2006) Supply and Use and Input-Output Tables, 'Published by the Stationary Office', Dublin, Ireland; ISSN 1649-5918, ISBN 0-7557-7134-606. 2006

Cole, R, J (1998) Energy and greenhouse gas emissions associated with the construction of alternative structural systems, 'Building and Environment', volume 34, issue 3, 335-348

Commonwealth Scientific and Industrial Research Organisation, CSIRO (2006) Embodied Energy-Sustainable Built Environment, Available for download at http://www.cmmt.csiro.au/brochures/tech/embodied/#

EuroStat (2002) The ESA 95 Input-Output Manual – Compilation and Analysis –'European Commission' Version 2002

Forum for the Construction Industry (2003) Applied construction innovation centre initial feasibility study, Ireland

Hayami, H, Nakamura, M, Suga, M, Yoshioka, K (1997) Environmental Management in Japan: Applications of Input–Output Analysis to the Emission of Global Warming Gases, 'Managerial and Decision Economics' volume 18, 195–208

International Emissions Trading Association (2008) What are carbon dioxide equivalents (CO2eq)? 'Market Solutions for Global Environmental Problems'

International Energy Agency (2006) Detailed Energy Balance for Ireland

Junnila, S, Horvath, A (2003) Life-Cycle Environmental Effects of an Office Building, 'J. Infrastruct. Syst', volume 9, issue 4, 157-166

Lenzen, M, Dey, C (2000) Truncation error in embodied energy analyses of basic iron and steel products, 'Energy', volume 25, 577-585

Limerick Energy (2008) Renewable diesel-Gen 2, Available for download at http://www.limerickenergy.com/renewable/index.html

Mongelli, I, Suh, S, Huppes, G (2005) A structure comparison of two approaches to LCA inventory data, based on MIET and ETH databases, 'Int J LCA', volume 10, issue 5, 317-324

Strømman, AH, Solli, C (2008) Applying Leontief's Price Model to Estimate Missing Elements in Hybrid Life Cycle Inventories, 'Journal of Industrial Ecology' volume 12, issue 1, 26-33

Suh, S, Huppes, G (2002) Missing inventory estimation tool using extended input-output analysis, 'Int J LCA', volume 7, issue 3, 134-140

Sustainable Energy Ireland, SEI (2006) Energy Statistics for Ireland, 'Energy Policy Statistical Support Unit', Cork, Ireland

Sustainable Energy Ireland, SEI (2007a) Energy in Ireland 1990 – 2006 Report, 'Energy Policy Statistical Support Unit', Cork, Ireland

Sustainable Energy Ireland (2007b) Emissions Calculator-Ireland, version 5, 'Energy Policy Statistical Support Unit', Cork, Ireland

Sustainable Energy Research Team (2008) Inventory of carbon and Energy, ICE, version 1.6a,' University of Bath' United Kingdom

Suzuki, M, Oka, T, Okada, K. (1995) The estimation of energy consumption and CO2 emission due to housing construction in Japan, 'Energy and Buildings' volume 22, issue 2, 165-169

Swedish Chamber of Commerce Ireland, SCCI (2006) Spotlight Sweden, 'SCCI News' volume 7, 1-10

Tiwari, P (2000) An analysis of sectoral energy intensity in India, 'Energy Policy', volume 28, issue 11, 771-778

Treloar, GJ (1998) "A Comprehensive Embodied Energy Analysis Framework", PhD thesis, Deakin University, Australia

United Nations Economic Commission for Europe, UNECE (2006) Republic of Ireland-National Market Report 2006, 'Annual Meeting of Timber Committee' 3rd-4th October 2006.

University College Dublin, UCD, Energy Research Group (2007) Green Paper: Towards a Sustainable Energy Future for Ireland, 'Department of Communication, Energy and Natural Resource', Ireland

Wissema, W (2006) Building Social Accounting Matrix for Ireland with specific details in relation to energy and carbon dioxide emissions, 'Institute for International Integration Studies', Dublin-Ireland, Number 170, 1-28

Yohanis, YG, Norton, B (2002) Life-cycle operational and embodied energy for a generic single-storey office building in the UK, 'Energy', volume 27, issue 1, 77–79

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