CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081225

An Input-Output Approach for Environmental Life Cycle Assessment of Cement Production

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To evaluate the energy consumption and global warming impact of cement production at macro level, this work provided the 10 sectors Economic Input-Output Life Cycle Assessment (EIO-LCA) based on 1990 - 2010 Thailand national economic data. The estimating Thailand gross domestic product (GDP) and the environmental impacts from 1990 to 2010 were used to project the energy and greenhouse gas (GHG) emission of cement production chains in Thailand for 2015 - 2030. The results of EIO-LCA analysis found that the main energy input of the cement production was mainly associated with the use of fossil energy, including, coal, diesel, lignite, and electricity, which accounted for 74 % – 93 % in years 1995 - 2010 and 58 % – 59 % in years 2015 - 2030 of the total energy used. The highest contributor to the total GHG emissions of cement production was from diesel combustion emissions by 58 % – 65 % in years 1995 - 2010 and 44.2 % – 44.5 % in years 2015 - 2030. This was because various types of energy inputs were included in petroleum refineries sector. In comparison with the Process LCA, the main contributions of energy used (84 %) and GHG emissions (91 %) of cement production were from the limestone calcination in clinker production and fossil fuels used. The diesel consumption were excluded from the calculation because the amount of diesel used and combustion was relatively small. The obtained results showed that the disaggregated for the desired level analysis was particularly insufficient. The EIO-LCA analysis might be used for providing alternative way to estimate the environmental burdens associated with the life cycle of products at the macro level and relatively inexpensive.

1. Introduction

In 2017, global CO_2 emissions were 30 Gt/y, 7 % came from cement production. Between 2006 and 2050, cement production is projected to grow by 0.8 % – 1.2 %/y, reaching between 3,700 Mt and 4,400 Mt in 2050. This represents a 43 % – 72 % increase compared to production in 2006. The CO_2 emissions from cement production were expected to increase from 1.88 Gt/y in 2010 to 2.34 Gt/y in 2050, a 20 % increase (Rogeli et al., 2016). Following the above demand and environmental impacts, several life cycle assessment studies have been established for analysis greenhouse gas (GHG) emission and energy consumption of cement industry (Ke et al., 2012) or other products and services (Koch and Mihalyi, 2018). Life Cycle Assessment is widely used as a valuable tool to quantify the potential environmental impact of products or processes for supporting decision making in production and consumption. There are three approaches of LCA, namely, Process Life Cycle Analysis (PLCA), Economic Input-Output based Life Cycle Analysis (Economic IO-LCA) analysis and hybrid LCA containing PLCA and Economic IO-LCA (Guinee et al., 2002). Most of the LCA performed the system lifetime and examined using process life cycle analysis. Process product models are generally used to evaluate the life cycle assessment products or service from each stage. For example, Khongprom and Suwanmanee (2017) exaimed process life cycle analysis (PLCA) for environmental assessment of cement production in Thailand. Ke et al. (2012) estimated the GHG emission from Chinese cement industry and future emission. However, from a macro perspective and cost effective LCA, the

Paper Received: 21/06/2020; Revised: 18/07/2020; Accepted: 19/07/2020
Please cite this article as: Khongprom P., Champanoi S., Suwanmanee U., 2020, An Input-Output Approach for Environmental Life Cycle Assessment of Cement Production, Chemical Engineering Transactions, 81, 1345-1350 DOI:10.3303/CET2081225

Economic IO-LCA was applied for this study. A similar study was conducted by Hendrickson and Horvath (1998). They presented an application of the Economic Input-Output model for environmental life cycle assessment of steel-reinforced concrete. Albino et al. (2002) analysed the input-output approach based on production processes in global and local demand and supply chains of materials, energy, and pollution. By-product and waste outputs were also investigated. Kumar et al. (2016) evaluated greenhouse gas (GHG) emissions through the life cycle of the wind energy farm. The EIO was used as a tool for environmental analysis accounting. In this work, we adopted an enterprise Input-Output model to evaluate the use of energy and global warming impact of cement production and predict future emission. The results obtained from intrgrating of EIO and PLCA would enhance to develop data from the national statistics in typical cement sector.

2. Life Cycle Assessment (LCA)

The LCA is an important tool based on the ISO 14040 (2006) and 14044 (2006) standard for investigation environmental impacts, which can be described by four steps; goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1 Goal and scope definition

The objective of this study is to perform a life cycle analysis of global warming impact of cement production in Thailand during 1990 – 2030 based on the IPCC (2007) guideline, in comparison with PLCA results with a study by Khongprom and Suwanmanee (2017).

2.2 Process model requirement matrix for portland cement

In a combine EIO and PLCA, the production chain can be considered as the EIO system that described the product flows as the PLCA, energy and materials requirement for the production process analysis for all stages. The production of portland cement requires four raw materials including limestone (CaO, MgO), iron ore (Fe_2O_3), and gypsum. The productions of limestone or shale require ammonium nitrate (NH_4NO_3) as explosive materials and diesel. The limestone and shale obtained were milled to form a fine powder and then was burned to form clinker by the burning process. The clinker was mixed with gypsum to produce cement product. The majorities of energy sources are electricity, coal, lignite and diesel for transportation (Khongprom and Suwanmanee, 2017). Composition analysis of each material processing associated with the life cycle of portland cement was performed as below (Figure 1).

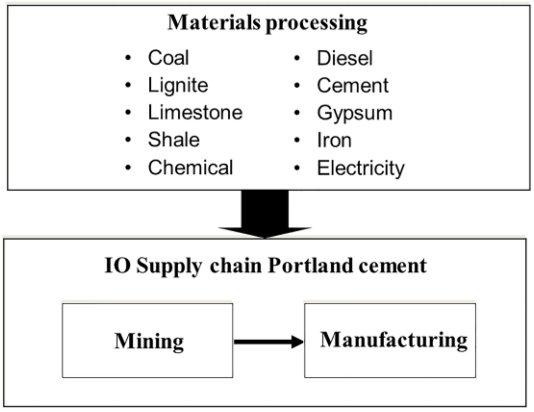

Figure 1: Composition (material processing) analysis for the portland cement production chains

Thailand gross domestic product (GDP), and Input-Output Tables (I-O Tables), were available from the Office of the National Economic and Social Development Board (NESDB, 2010) every 5 y with for 4 levels of sector, including 16×16, 26×26, 58×58 and 180×180 sectors. The input-output table represented the relationships between the total inputs (sale) and final demands (purchase). The total inputs are the sum of a intermediate transaction (x_{ij}) and primary inputs or value added (V_j) which can be calculated by using Eq(1). The value added was evaluated including, wages and salary, operating surplus, depreciation and indirect taxes less subsidies (NESDB, 2010) (Table 1). This study applied the top 10 economic sectors related with cement sector. The EIO-LCA for cement process could be established 10×10 matrix of direct process steps interaction from 1990 - 2010 to calculate the economiy's consomption matrix [A] for each year. The coefficients of matrix

(a_{ij}) can be calculated by using Eq(2) which was evaluated from intermediate transaction or original Input-Output Tables (x_{ij}) by dividing the total input (X_j). The element a_{ij} denoting the use input of process i per unit output of process j. Data entires in the matrix are expressed in M Thai Baht (THB).

$$\sum_{i=1}^{n} X_{ij} + V_j = X_j \tag{1}$$

$$a_{ij} = X_{ij}/{X_j}^{-1} \tag{2}$$

The matrix total output [X] for portland cement of each year was estimated by multiplying in the final demand with inverse Leontief matrixes for each process, which can be calculated by using Eq(3). The total output for year 2015–2030 was forecasted using historical data with method of least squares for estimating the regression coefficients $(\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x; x = \text{year}, \hat{y} = \text{total output year 2015 - 2030})$. The analysis of variance was used to test for significance of regression $(\hat{\beta}_1)$. The F-statistic was used for testing the hypothesis with 95% confidence level (Montgomery and Runger, 1999).

$$X = (I - A)^{-1} F \tag{3}$$

where X is vector of the total product (THB), F is the final demand the portland cement according to the production capacity of the chains (final consumption of cement production in this case), for the production X. A is the matrix of intermediate input coefficients. I is the identity matrix.

Table 1: Input-output table of portland cement

Inputs	Process$_1$	Process$_2$	Process$_3$	…	Process$_{10}$	Final demand F	Total product X
Process$_1$	$x_{1,1}$	$x_{1,2}$	$x_{1,2}$	$x_{1,.}$	$x_{1,10}$	f_1	X_1
Process$_2$	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,.}$	$x_{2,10}$	f_2	X_2
Process$_3$	$X_{3,1}$	$x_{3,2}$	$x_{3,3}$	$x_{3,.}$	$x_{3,10}$	f_3	X_3
…	$x_{.,1}$	$x_{.,2}$	$x_{.,3}$	$x_{.,.}$	$x_{.,10}$	$f_.$	…
Process$_{10}$	$X_{10,1}$	$x_{10,2}$	$x_{10,3}$	$x_{10,.}$	$x_{10,10}$	f_{10}	X_{10}
Value added	V_1	V_2	V_3	…	V_{10}	GDP^A	
Total inputs	X_1	X_2	X_3	$X_{..}$	X_{10}		

A is the gross domestic product (GDP) is the sum of all value added and final demands.

2.3 Environmental output calculation for portland cement

The total output for each process stage obtained was applied with assessing the environmental impact of cement production. The matix of environmental outputs for each process stage of cement production of each year was estimated by multiplying in the total output at each stage by the environmental impact factors per THB, which can be calculated by using Eq(4).

$$D_i = R_i \mathrm{X} = R_i (\mathrm{I} - \mathrm{A})^{-1} \mathrm{F} \tag{4}$$

where D_i is vector of environmental impacts for each process stage and R_i is matrix of environmental impact factors per THB for each process stage. The environmental impact factors were evaluated from the emission factors and cost of all materials. The emission factors of materials and energy sources, the net calorific value and GHG emissions, were taken from Khongprom and Suwanmanee (2017). The costs of materials and energy from 1990 to 2030 were reported in Table 2.

Table 2: Cost of materials and energy for portland cement (in THB per Unit)

Years	^{1}Coal	^{1}Lignite	^{1}Limestone	^{1}Shale	^{2}NH_4NO_3 (THB/kg)	^{3}Diesel	^{3}Cement	^{1}Gypsum	^{1}Iron	^{4}Electricity (THB/kWh)
1990 – 2000	1.124	0.500	0.085	0.090	0.333	15.212	2.071	0.438	33.33	2.695
2005	1.081	0.500	0.085	0.090	0.595	23.541	2.180	0.520	44.89	3.020
2010 – 2030	1.977	0.960	0.120	0.125	1.303	33.635	2.510	0.518	3.69	3.540

^{1}Department of Primary Industries and Mines (2010), ^{2}United States Department of Agriculture (2010), ^{3}Bank of Thailand (2010), ^{4}Metropolitan Electricity Authority (2010)

3. Results and discussion

3.1 Economic analysis

From Eq(1), the model requirement matrix for cement production was represented the total inputs, intermediate transaction, value added and final demand. The economic analysis of meterial processing was available from NESDB which was classified into three sources. The first source is a value of domestic products, including lignite, limestone, shale, electricity, lignite, gypsum and cement. The second is a value of import products, namely, coal, ammonium nitrate and Iron. The third is a value of diesel, which is a value at producer's price (domestic and import products). For example, the economic analysis was conducted for the base year 2010 (Table 3) and then the coefficients of matrix (a_{ij}) of each process stage was calculated by using Eq(2) as presented in Table 4. The negative values of final demand in limestone and shale (Table 3), which meant that there are stocks of limestone and shale at the previous year. From Eq(3), the inverse Leontief matrixes for each process was calculated $(I-A)^{-1}$ and then the total output [X] for portland cement from 1990 – 2010 was calculated as shown in Table 5. Table 5 revealed the major 10 sector contributors to cement production. Similarly, the negative values of the total output of limestone and shale were implied that there are stocks of those materials from the previous year. The results are disagree with Department of Primary Industries and Mines (2018), who reported that the use of limestone was 3.11 Mt/y in 2000 and 7.59 Mt/y in 2018, steady increasing 59 %.

Table 3: Process model requirement matrix (I-O Tables) for portland cement (in M THB)

Inputs	Coal	Lignite	Limestone	Shale	NH_4NO_3	Diesel	Cement	Gypsum	Iron	Electricity	Final demand
Coal	0	0	0	0	0	0	8,066	0	0	30,852	0
Lignite	0	0	0	0	0	0	201	0	0	956	12,695
Limestone	0	0	0	0	0	0	16,165	6.4	0	24.2	-5,371
Shale	0	0	0	0	0	0.581	3,423	465	0	0	-20,258
NH_4NO_3	0	1.1	245	158	0	31,473	321	306	0	1,250	0
Diesel	0	2,054	149	3,245	0	6,854	7,155	201	0	57,322	499,672
Cement	0	0	0	0	0	0	2,002	4,167	0	0	13,945
Gypsum	0	0	0	0.725	0	0	0	367	0	0	11,268
Iron	0	0	0	0	0	0	0	0	0	0	0
Electricity	0	155	21.3	1,366	0	3,122	14,303	786	0	15,316	135,170
Value added	0	11,235	9,858.5	18,168	0	217,468	43,987	6,147	0	288,889	0
Total inputs	0	13,445	10,273.8	22,937	0	258,919	95,622	12,444	0	394,610	150,289

Table 4: The coefficients of matrix (a_{ij}) of each process stage for portland cement

Inputs	Coal	Lignite	Limestone	Shale	NH_4NO_3	Diesel	Cement	Gypsum	Iron	Electricity
Coal	0	0	0	0	0	0	0.084355	0	0	0.078183
Lignite	0	0	0	0	0	0	0.002098	0	0	0.002424
Limestone	0	0	0	0	0	0	0.169048	0.00051	0	0.000061
Shale	0	0	0	0	0	0.000002	0.035795	0.037376	0	0
NH_4NO_3	0	0.000081	0.023796	0.006871	0	0.121557	0.003353	0.024590	0	0.003169
Diesel	0	0.152797	0.014553	0.141456	0	0.026474	0.074821	0.016182	0	0.145262
Cement	0	0	0	0	0	0	0.020934	0.334878	0	0
Gypsum	0	0	0	0.00003	0	0	0	0.029468	0	0
Iron	0	0	0	0	0	0	0	0	0	0
Electricity	0	0.011499	0.002072	0.05957	0	0.012059	0.149582	0.063053	0	0.038814

Table 5: The total output for each process stage for portland cement (in M THB)

Inputs	1990	1995	2000	2005	2010	2015	2020	2025	2030
Coal	-6.486	165	1,698	5,730	13,258	14,103	16,586	19,690	22,794
Lignite	1,467	2,547	4,158	4,256	13,096	13,094	15,092	17,589	20,085
Limestone	-5.416	540	2,709	2,010	-2,276	-387	-633	-940	-1,248
Shale	-4,057	-1,925	-288	-16,281	-19,171	-22,611	-26,178	-30,637	-35,095
NH_4NO_3	567	1,177	1,071	2,579	65,847	56,476	67,033	80,299	93,425
Diesel	19,435	64,092	172,659	419,208	536,459	686,903	798,037	936,953	1,075,869
Cement	-479	3,537	20,198	37,523	18,213	38,638	44,348	51,485	58,621
Gypsum	-307	923	3,699	8,133	11,609	14,745	17,228	20,332	23,437
Iron	-1.46	0	0	0	0	0.64	0.88	1.17	1.46
Electricity	16,016	39,518	83,896	147,655	149,928	207,711	237,788	275,384	312,980

3.2 Environmental impacts analysis

From Eq(4), the total output was calculated into environmental impacts, global warming and energy consumption using the total output (Table 6) and the environmental impact factors. Figure 2(a) presents the energy used per unit economic activity of cement industry which had a steady growth of energy from 1990 to 2030, increasing from 158 PJ in 1990 to 4,082 PJ in 2030. The highest contribution was from the use of fossil energy at 58 % – 91 % of the total energy used, followed by the use of chemicals at 8 % – 41 %. The obtained results found that 35 % – 57 % of the total energy input from diesel obtained in our study was required for cement production. This result disagreed with that of Khongprom and Suwanmanee (2017), who reported that about 1 % of the total energy input was from diesel at the stages of limestone and shale productions. Figure 2(b) shows the GHG emissions from various sources for the cement industry from 1990 to 2030, which increased by 357 Mt CO_2eq. from 1995 to 2030. The main contribution was from the use of ammonium nitrate from 2015 to 2030 at 35 % – 37 % of the total global warming impact, while the use of ammonium nitrate from 1990 to 2010 at 1 % – 33 % of the total global warming impact. For fossil energy, the GHG was emitted from lignite combustion (10 % – 26 %), coal combustion (8 % – 19 %), diesel combustion (27 % – 44 %), the electricity used (14 % – 25 %), and the CO_2 produced during decomposition of calcium carbonate ($CaCO_3$) to form clinker (3 % – 7 %). In comparison with PLCA results, the study by Khongprom and Suwanmanee (2017) reported the two highest contributors to the total GHG emissions of cement production were calcination and combustion emissions, accounting over 90%. However, the amount of diesel consumption and combustion was relatively small from the study by Khongprom and Suwanmanee (2017).

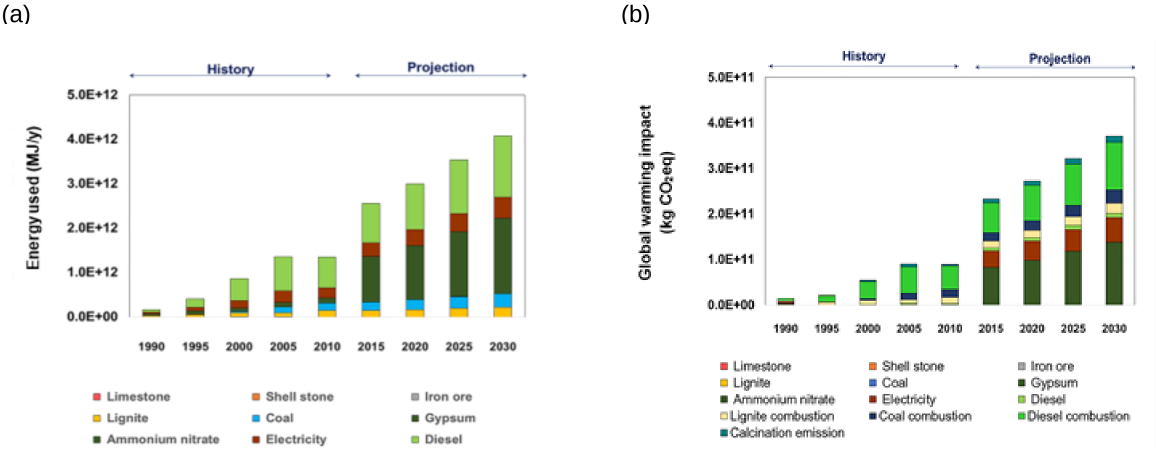
(a) (b)

Figure 2: EIO-LCA for cement production in 1990–2030: (a) energy used and (b) global warming impact

The results can be observed that the high usages of diesel and ammonium nitrate presented the high energy-related GHG emissions. This was because various types of energy inputs were included in petroleum refineries sectors, such as heavy oil, kerosene, gasogol and diesel. Similarly, many chemical industries produced from basic industrial chemicals sector were evaluated. The six sectors, coal and lignite, stone quarrying (shale), limestone, petroleum refineries, non-metallic products (gypsum), and electricity were involving the basic industrial chemical sector (ammonium nitrate) and petroleum refineries sector (diesel).

4. Conclusions

The EIO-LCA analysis provided cost-effective and alternative LCA to evaluate environmental burdens of a products or processes at a national level. Because the EIO approach has limitation for a specific process, the obtained results of cement production based on EIO analysis dentify that paticular sectors could be disaggregated for the desired level analysis, especially in the evaluation of basic industrial chemicals and petroleum refineries sectors. The obtained results suggested that the possibility of integrating Economic data with the LCA would be improving and making the methodological choices for environmental accounting at national-level under the life cycle sustainability assessment. For the next ten years (2021 – 2030), the results give a benefit to reflect the crucial policy on reducing the consumption of energy and the related GHG emissions and enhancing the sustainability of cement sector in Thailand.

Acknowledgements

This work has been supported by the Thai Research Fund (MRG6180218) Srinakharinwirot University Fund (SWU 314/2561).

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