B-14.1.1 A study on the analysis of life-cycle CO_2 emission for technology assessment (Final Report)

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Abstract

The purpose of the study is to compile a life-cycle CO_2 emission inventory as a common database for the assessment of technological measures to arrest global warming, and to conduct case studies on life-cycle analysis for selected technologies. A methodology to calculate CO_2 emission intensity of each sector of industry based on the Input-Output table was established, and a database of emission intensity was compiled using this method and published for wide use for LCA studies. The "Processing-Material ratio" method, which is a hybrid of Input-output analysis and process analysis, was proposed to estimate CO_2 emission associated with production of equipments and facilities based on material composition data. Life cycle emission of CO_2 was estimated for two case studies; firstly for district heating and cooling system reflecting the difference in density and size of heat demand, secondly for the comparison between a gasoline vehicle and an electric vehicle with different source of electricity. Net reduction of emission during transition period towards widespread of EV was also simulated.

Key Words Carbon dioxide, Emission intensity, Life-cycle analysis, Input-output analysis, Electric vehicle

1. Introduction

Stabilization of CO_2 emission was set as both national and international short term targets, and longer term goals of the reduction of CO_2 emission is also being discussed. Assessment and implementation of concrete measures to reduce CO_2 emission are urgently required. Comprehensive and accurate emission inventory of Green House Gases (GHGs) is an essential tool to analyze current situation and trends of the emission by sectors and origins, as well as to assess technological and social measures to cope with the global warming issue. Emission inventory of GHGs is being compiled and reported as a part of a national communication report to the Framework Convention on Climate Change (FCCC).

On the other hand, the concept and the methodology of the Life Cycle Assessment (LCA) draws more and more attention in the world. So-called life-cycle-thinking is also essential in the technology assessment of measures to reduce GHGs emissions, as there often exist a trade-off between reduction of CO_2 emission in one stage and its increase in the others.

2. Research Objective

The life-cycle-thinking was adopted as a common concept of the entire research theme under the circumstances stated in the introduction. Therefore the first purpose of this sub-theme is to compile a comprehensive emission inventory of CO_2 as a common database for the assessment of technological measures to arrest global warming. During the preceding stage of the research project, two types of CO_2 emission inventory were compiled, using an energy balance table and the Input-Output (I-O) table. This study focuses on the compilation of I-O based emission inventory to be used for broader applications. The second purpose of the study is to show usefulness of the life cycle CO_2 emission analysis by conducting practical case studies.

3. Research Method, Result and Discussion

(1) Compilation of CO_2 emission inventory based on the Input-Output table

The Input-Output(I-O) table is a comprehensive statistics which describes transactions among different economic sectors by a monetary unit. As the most detailed edition of the table covers as much as some 400 sectors, the table is suitable for the sectoral disaggregation of emission inventory. The I-O table provides us with several supplementary tables, one of which, named physical amount table, covers physical amount of major fossil fuels consumed by sectors. For several types of fuel which were not explicitly described in physical amount table, data was supplemented by the energy balance table. The emission by industrial processes was also estimated using the limestone consumption data by sectors, which is also described in the physical amount table. By using these data and fuel-specific emission factors, we can compile the emission inventory of CO_2.

The I-O table provides us with further opportunity to analyze emission inventory in conjunction with the final demands of economic activities. Namely, we can analyze not only which sectors CO_2 is directly emitted from, but also which final demands the emission is imputed to. The concept of the "embodied emission intensity", being analogous to the "embodied energy intensity" used by the energy analysis was applied here.

First, CO_2 emission (C_i) by the sector *i* in the I-O table was calculated. A direct emission intensity per unit production was defined as follows;

$$d_i=C_i/X_i$$

where X_i denotes domestic production of the sector *i*. Then embodied emission intensity (t_j) of the sector *j* was calculated by;

$$t_j=\sum_i b_{ij}d_i$$

where b_{ij} denotes an *i-j* element of the inverse matrix $[I-(I-M)A)]^{-1}$ of the I-O table. The b_{ij} means induced production of the sector *i* so as to satisfy the unit amount of final demand for the sector *j*. t_i can be used for disaggregating a domestic emission. The emission (T_i) induced by the final demand of the sector *i* is calculated by;

$$T_i=(1-m_i)t_iY_i+t_iE_i$$

where m_i is the share of imports, Y_i and E_i are final demand from domestic and exports, respectively. Y_i can be further disaggregated to consumption expenditures, private and governmental fixed capital formation.

Slightly different embodied emission intensity t'_i was derived from the similar calculation employing the inverse matrix $(I-A)^{-1}$, that means we assumed the same industrial structure and the same energy efficiency for the production of imported commodities and services as those for domestic production. By using t'_i, we can estimate gross total emission to satisfy the final demand of Japanese economy, including the emission actually happens in Japan and the indirect emission happens in other countries1).

Using this methodology, emission inventory was compiled for 1975, 1980, 1985 and 1990. Then the direct emission intensity and the embodied total emission intensity were calculated by sectors. The results were edited and published2) as electronic spreadsheets for the convenience of LCA practitioners. The database covers both t_i and t'_i, both on producer's price basis and on consumer's price basis. In addition, contribution of electricity and industrial process (originated from limestone) was separately tabulated.

On the other hand, this inventory based on the I-O table was compared with two other CO_2 emission inventories; one is a top-down method based on the energy balance table, and another is a bottom-up method based on survey by the Environment Agency for emission inventory of SOx and NOx. Because of inconsistent classification of sectors, shares of sectors were more or less different. Amongst others, large differences were found in the transport sector. Classification of private cars and the boundary of "domestic" areas for aviation and navigation were major sources of discrepancies.

(2) A case study on detailed CO_2 emission intensity for aluminum production

Assumption in the I-O based emission intensity that the imported commodities are produced by the same industrial structure and the same energy efficiency is sometimes not realistic. Particularly, differences in electricity generation give big influence on the emission intensity of electricity-intensive products. Primary aluminum was chosen as the object of a case study, because it is a typical electricity-intensive product and exclusively provided by import. By using the statistics on fuel mix of electricity generation and the average electricity consumption data per unit amount of aluminum production, CO_2 emission factor per unit aluminum production was estimated for 6 regions of the world and Japan. The emission factors were very much different from one region to another, the lowest in South America where hydro-electricity was mainly used, and the highest in Australia where coal-fired electricity was used. An averaged emission factor for imports from all regions was similar to the factor assuming Japanese fuel mix, only because of a coincidence. We need to carefully examine the emission factors for the products which are mainly supplied by imports.

(3) "Processing-Material ratio" method - a hybrid of I-O analysis and process analysis -

Database of emission intensities based on the I-O table is practical tool for case studies of life cycle assessment of technological measures to reduce CO_2 emissions. For example, this is useful when estimating initial emission induced by the production of energy efficient equipment. However, disaggregation into 400 sectors is not enough to reflect detailed specification of the equipment. Moreover, because the equipment for CO_2 reduction measures are relatively expensive than mass-produced conventional equipment, application of emission intensities denominated by price tends to overestimate the emission. Process analysis method, which sums up CO_2 emission in all processes including material production, processing, assembly, etc., will encounter the limitation of data availability.

In order to tackle with these difficulties, a new method named "Processing-Material ratio (P/M) method" was proposed, which is a hybrid of the I-O analysis and process analysis.

In this method, material composition of the object to be assessed is investigated, and CO_2 emissions to produce these materials are estimated using emission intensities of materials, which are estimated either I-O analysis or process analysis. Then the P/M ratio of similar products is multiplied to the sum of these emissions for material production, in order to add emissions for processing materials to make final products. P/M ratios are in advance calculated by each sectors using I-O analysis by disaggregating embodied emission into two parts; the first is contributions from sectors in more up-stream than basic material industries like iron & steel, non ferrous metals, plastics, glass, etc., and the second is contributions from sectors in their down-streams. P/M ratio is low for the sectors with low level of processing, such as metal products, whereas the ratio is high for the sectors with higher level of processing such as electric machinery and precision machinery. Table 1 shows the examples of P/M ratios calculated from 32 aggregated sectors table.

Table 1. Processing/Material ratios of energy consumption for typical sectors

	Metal Products	General Machinery	Electric Machinery	Transport Machinery	Precision Machinery	Other Manufact.	Const-ruction
Energy for material production	0.992	0.564	0.289	0.467	0.234	0.288	0.466
Energy for processing	0.294	0.246	0.258	0.310	0.224	0.302	0.269
Processing/Material ratio	0.296	0.436	0.894	0.664	0.956	1.046	0.578

unit for Energy;10^7kcal/million yen

(4) A case study on the life cycle CO_2 emission analysis of district heating and cooling system

The first case study deals with district heating and cooling system (DHC) . DHC consists of central plants to generate hot and cool heat, and pipelines to transport heat to individual buildings. DHC can accomplish higher energy efficiency than conventional individual heat supply equipment under certain conditions. Spatial density of heat demand is thought to be the crucial factor of successful DHC, because of the high construction cost of pipelines. Eight types of hypothetical district configurations were set up by combining three levels of spatial density of heat demand and three levels of total heat generation capacity. Four different setups of heat generating equipment were prepared, including co-generation system and heat pump system using river water.

CO_2 emissions in an initial construction stage were estimated mainly by the process analysis method. The P/M method stated above was applied to the estimation of CO_2 emission for the production of heat generation facilities. Emission intensity database by I-O analysis was also used when any other appropriate data was not available. CO_2 emission in an operation stage was estimated based on the results from a simulation model of operation patterns. Heat losses from pipelines as well as energy consumption for pumps were also estimated reflecting configurations of the districts.

According to this study, emission in the initial construction stage of DHC systems is less than those by one year's operation, so the emission from operation stage is dominant in their lifetime. Whereas the cost of the construction stage equals to 10 to 15 years' cost of operation stage. Life cycle CO_2 emission of DHC is proved to be smaller than conventional systems where the spatial density of heat demand is higher than a certain level. However, if the density of heat demand is small, not only cost but also $LCCO_2$ of DHC are worse than conventional system. This is mainly because of increased pumping energy and heat losses associated with relatively long pipelines.

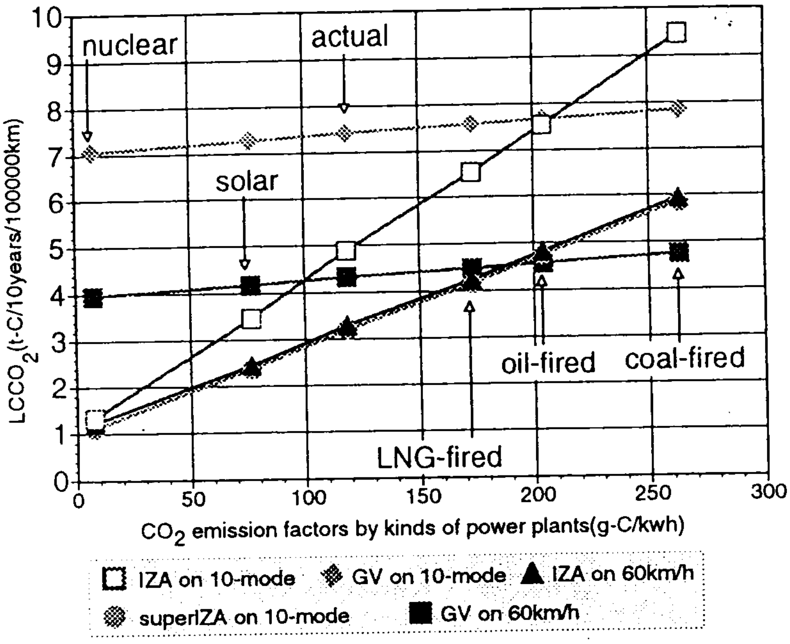

Fig. 1 $LCCO_2$ emissions for IZA and for GV by kinds of power plants

(5) A case study on the life cycle CO_2 emission analysis of an electric vehicle

The second case study deals with an electric vehicle (EV)[3]. The IZA, which was designed as a ground-up EV, and a gasoline-engined vehicle of the equivalent size were taken up for the comparison. EVs do not directly emit CO_2 in their operation, but indirect emissions by power plants should be accompanied with. Therefore, it is essential to consider the source of electricity generation when assessing $LCCO_2$ from EVs. In this study, five types of electric power generation were considered, namely, coal-fired, oil-fired, natural gas fired, nuclear and photo voltaic. Actual fuel mix of Japanese electricity generation was also referred to for comparison. CO_2 emission from electricity was calculated on life cycle basis, namely including fuel acquisition and refinery, as well as construction of power plants.

Life stages taken into account were production (material, parts and assembly), operation and maintenance of a vehicle itself, as well as extraction, transportation and production of energy for the operation of a vehicle. It was assumed that the vehicle's lifetime was 10 years, and the traveling distance per year was 10,000km.

CO_2 emission in production stage of the vehicle was calculated based on material composition. About three quarters of total weight of the GV is made of iron & steel, whereas only a quarter for the IZA. The IZA uses much more non-ferrous metals and resins. As a consequence, CO_2 emission of EV in production stage was higher than that of GVs. However, CO_2 emission of EV in operation stage was lower than GV, if electricity was supplied by low carbon fuels. In the case of current Japanese fuel mix of electricity, emission by EV was 40 % of GV. Consequently, $LCCO_2$ of EV including production and operation was 70 % of GV. Calculated $LCCO_2$ of EV and GV was plotted as a function of carbon intensity of electricity in Fig. 1. Despite the use of energy intensive materials for the IZA, lower emission in operation stage can compensate the excess emission in the initial production stage.

(6) CO_2 reduction during transition period towards widespread of technical measures

In the case studies of $LCCO_2$, the balance of the increase of emission in the initial production stage and reduction in later operation stage was simply calculated. However, in order to assess the emission reduction during transition period before the widespread of technical measures into the society, time-lags between introduction of measures and their operation should be considered. In the case of vehicles, for example, it takes considerable time to substitute current stock of GVs by EVs. Simple simulation was carried out to trace the net reduction of CO_2 emission in transition period, taking widespread of EVs as an example, with assumption that annual production of EVs increases 0.24 million vehicles per year. During first several years, emission increase for production of new EVs was larger than emission reduction by operation of EVs, because total stocks of EVs were still small. It takes considerable time before the net reduction of emission is fully accomplished.

4. Conclusion

A methodology to calculate CO_2 emission intensity of each sector of industry based on the Input-Output table was established by this study, and a database of emission intensity was compiled using this method and published for wide use for LCA studies. Case studies on electric vehicles and district heating and cooling systems proved the usefulness of $LCCO_2$ analysis as a comprehensive tool to assess effectiveness of technical measures to reduce CO_2 emissions.

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