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Estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan

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Abstract

The purpose of this study is to quantify the total amount of energy consumption and CO_2 emission caused by the construction, operation, maintenance, and renovation of office buildings in Japan. In order to quantify the life cycle energy consumption and CO_2 emission of a building, it is necessary to obtain an estimate of the total quantity of domestic products and services used directly or indirectly (including the repercussion effect of the economy) during the life cycle of the building. The Input/Output (I/O) Table of Japan is used to calculate the total domestic product and then energy consumption and CO_2 emission are estimated by using energy consumption and CO_2 emission data for unit production of various categories of industries.

Keywords: Energy consumption; Repercussion effect; CO_2 consumption

1. Introduction

The past 5 years or so have seen a significant increase in interest and research activity in the development of environmental assessment methods for buildings. These methods were developed to serve the specific requirements of individual buildings but some of these do not meet the standards of quantitative analyses [1,2].

In other industrial sectors, life cycle analysis (LCA) [3] is currently widely used to assess the life cycle environmental impact of products. In order to use LCA methods to assess the environmental impact, it is necessary to perform an inventory analysis. The required databases and assessment methods for this type of analysis have been developed by various organizations [4,5]. However, in the construction industry, the materials used in construction, operation, and demolition are varied and the range of environmental criteria that are relevant to buildings is potentially enormous. This may serve as a severe limitation to the use of LCA methods in the building industry.

The Third Conference of The United Nations Convention on Climate Change paid a lot of attention to the issue of reduction of carbon dioxide emission in order to control global warming. As part of an effort motivated by the UN conference, it was felt necessary to develop a method to quantify the CO_2 emission caused by all activities related to buildings during their entire life cycles.

Modern day buildings are typically large-scale projects utilizing many different kinds of building materials so their constructions have a great impact on many other industrial sectors. The purpose of this study is to develop a simplified method to quantify the total amount of energy consumption and CO_2 emission caused during the life cycle of office buildings.

A former study [6] had been conducted on the energy consumption and CO_2 emission throughout building construction stages from producing materials to estimating the repercussion effect of the economy.

The operation of office buildings uses much energy and a lot of CO_2 is emitted in the process. In order to quantify the environmental effect during the entire life cycle of buildings, it is necessary to examine the full range of products and services consumed in the entire life cycle of buildings. In this study, a method for estimating the life cycle energy consumption and CO_2 emission of office buildings is proposed.

As a first step, it is necessary to obtain an estimate of the total amount of products and services that get consumed (referred to hereafter as 'final domestic products'). For this purpose, a set of Input/Output (I/O) Tables [7] are used. Currently, in the I/O Table the industries in Japan have been classified into approximately 400 groups.

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2. Analytical method [6]

In the analysis of the construction phase of the life cycle of buildings, the cost of each type of tasks was itemized and classified into two categories: (1) material cost (which includes the cost of materials and other items purchased from other industries), (2) labor cost (which includes labor cost and other value added). The cost of construction in Japan was estimated using a handbook of construction costs which lists the average material/labor cost for various categories of work (for example, ceiling work, ducting work, etc.) [8,9].

The total quantity and total price for major materials such as steel, concrete for various industrial sectors are given in the I/O Table. Therefore, it was possible to obtain the unit price of all major materials.

In this study, the total expenses for major materials such as steel and concrete were compensated by using their respective unit prices in the I/O Table for taking into consideration the differences in unit prices from one contract to another.

The costs for general management were calculated by taking the difference between the amount of the contract and the net construction cost. In this study, financial statements were analyzed to further sub-divide the costs for general management into categories such as mail and telegraph costs, advertising expenses, office supplies etc. The labor cost in general management ranked first and covers over 25% of the total general management cost. These costs were then put into their corresponding categories of the I/O Table.

The cost of materials, at this stage, is the price to the buyer. To convert this amount into the cost for the producer, the profit margin, transportation cost, and storage cost were deducted using the I/O Table which includes the average transportation cost, the average profit margin, and the average storage cost for various categories of industries and services.

Thus, the total demand was calculated and this cost of the producers (Y) was inserted into Eq. (1) to calculate the total value of all domestic products (X).

The data used in these calculations were taken from the 1985 I/O Table which provides data for over 406 different industries (excluding iron scraps and various metal scraps). In this study, the estimates of the costs of construction are for works from the period beginning in 1976 and ending in 1989. Therefore, the cost of the producers was brought to a common value of money, that used in the study is the 1985 yen, using the Construction Price Index [10].

$$X=[\mathbf{I}-(\mathbf{I}-M)A]^{-1}[(\mathbf{I}-M)Y+E] \tag{1}$$

where: X is production vector which is the final domestic product (yen/year); $\mathbf{I}$ is the unit matrix; A is the coefficient of input matrix; Y and E are the final demand vector and export vector (yen/year), respectively; Y_i and E_i are the final demand and export of i product (yen/year), respectively;

$$M=\begin{bmatrix} m_1 & & & 0 \\ & \cdot & & \\ & & \cdot & \\ 0 & & & m_i \end{bmatrix}$$

M_i is the import of i product (yen/year);

$$m_i=M_i/C_i=\frac{M_i}{\sum_j A_{ij}X_j+Y_i};$$

C_i is the domestic product + import − export) of i product (yen/year) and $[\mathbf{I}-(\mathbf{I}-M)A]^{-1}$ is the Leontief inverse matrix.

3. Estimation of energy consumption and CO_2 emission in construction

Data were collected from 10 buildings listed in Table 1 for the purpose of quantitative analysis using the I/O Table. The size of the buildings varied and ranged in size from 1253 to 22 982 m^2 in total area.

In Japan, large scale buildings are mainly built of steel while small buildings are mostly reinforced concrete structures [10]. Therefore, six out of the eight small buildings, those with area less than 2000 m^2, (A to F in Table 1) are RC structures and the relatively larger building (J in Table 1) is a steel structure.

In the accompanying figures and tables, four different tasks in the construction phase are identified: structural work, finishing work, equipment work, and general management work. The contribution of temporary works to structural work is also shown. Fig. 1 shows the energy consumption during

Table 1
Analysed office buildings

	A	B	C	D	E	F	G	H	I	J
Completion	1976	1979	1986	1987	1987	1988	1989	1989	1989	1987
Floor area (m^2)	1879	1404	1857	1340	1328	1253	1291	1358	8458	22 982
Stories	F7-B1	F7	F7-B1	F7	F7	F7-B1	F7	F7	F9-B1	F8-B2
Structure	RC	RC	RC	RC	RC	RC	RC/S	RC/S	SRC	S
Heat source for air-conditioning	packaged heat pump	packaged heat pump	TESHP	packaged heat pump	packaged heat pump	packaged heat pump	packaged heat pump	packaged heat pump	TESHP	district heating and cooling

TESHP: thermal energy storage type heat pump system

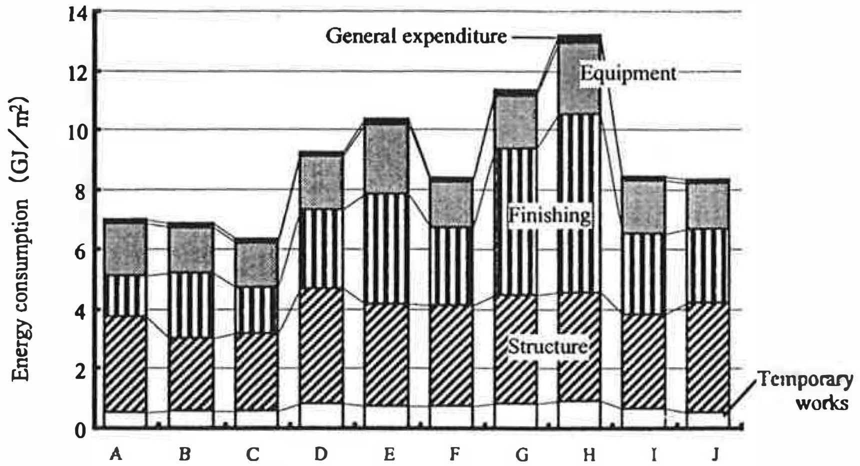

Fig. 1. Energy consumption for construction of office.

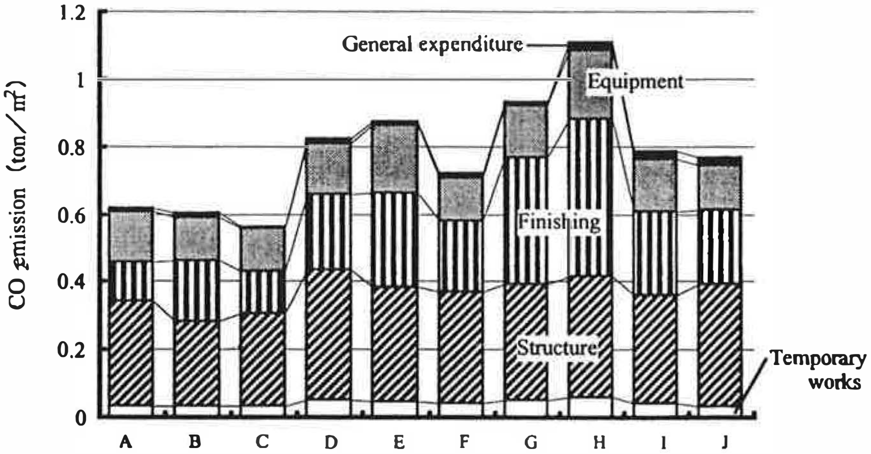

Fig. 2. CO_2 emission by construction of office.

Table 2
Energy intensity of construction (MJ/1000 yen)

	A	B	C	D	E	F	G	H	I	J	Average
Temporary works	30.38	35.65	34.34	37.59	35.32	34.83	36.85	36.52	108.87	34.41	42.47
Structure	77.36	60.02	53.06	48.50	52.79	49.57	54.50	51.93	70.75	94.85	61.33
Finishing	25.37	37.18	35.36	39.66	42.02	36.63	42.20	95.36	60.80	50.70	46.53
Equipment	30.39	30.65	25.13	29.78	29.68	28.76	29.95	29.14	27.13	29.05	28.97
General expenditure	5.86	5.88	5.87	5.88	5.86	5.86	5.79	5.87	5.87	6.76	5.95
Average	35.71	36.01	33.93	36.81	37.07	35.53	39.07	46.13	46.08	47.61	39.40

construction of the 10 office buildings and from this it can be seen that the energy required to construct 1 m^2 of floor area varied from 6.5 to 13 GJ/m^2 with an average value of 8.95 GJ/m^2. The energy consumption of buildings G and H is very high as a result of the higher energy consumed in their finishing works.

The amount of CO_2 emission was estimated by calculating the consumption of oil, coal, and, liquefied natural gas. In addition, the CO_2 emitted with the use of cement was added to calculate the total amount of CO_2 emitted by incorporating data [11] which showed that 0.3 ton of CO_2 is produced for every ton of cement as a result of dissolution of limestone. The results are shown in Fig. 2. The total emission of CO_2 was seen to vary from 650 to 1100 kg/m^2 (with an average of 790 kg/m^2). Our analysis found that the production of CO_2 was relatively proportional to the amount of energy consumed.

The energy intensity (energy consumption per unit construction price) and CO_2 intensity (CO_2 emission per unit construction price) are shown in Tables 2 and 3, respectively. The average energy and CO_2 intensity during the construction of office buildings is estimated as 39.4 MJ/1000 yen and average CO_2 intensity is 3.55 kg/1000 yen. Both energy intensity and CO_2 intensity are highest for structural work

Table 3
CO_2 intensity of construction (kg/1000 yen)

	A	B	C	D	E	F	G	H	I	J	Average
Temporary works	1.84	2.12	2.11	2.30	2.19	2.10	2.35	2.37	6.96	2.19	2.65
Structure	7.54	6.16	5.51	4.85	5.19	4.71	5.13	5.07	7.08	9.28	6.05
Finishing	2.09	2.98	2.81	3.32	3.18	2.95	3.20	7.51	5.65	4.47	3.82
Equipment	2.59	2.60	2.15	2.52	2.51	2.44	2.53	2.47	2.31	2.50	2.46
General expenditure	0.43	0.43	0.46	0.43	0.45	0.44	0.42	0.44	0.95	1.14	0.56
Average	3.15	3.15	3.03	3.26	3.12	3.04	3.21	3.88	4.28	4.37	3.55

and lowest for general expenditure. The reason for the lowest ranking of general expenditure is presumably the higher proportion of labor in this category of work.

4. Estimation of energy consumption and CO_2 emission during operation

The annual operating costs of a building include electric power rate, other energy rates, building cleaning cost, equipment maintenance cost, and cost of security for the building.

Fig. 3 shows the annual electric power rate for each building (A–J) from 1987 to 1993. These data were obtained by a survey of monthly bills of electric rates of each building. The average monthly cost of electric power is approximately 350 yen/m^2 of floor area of the buildings. The total annual operating costs for each building are shown in Fig. 4. These data were obtained by examining the owners' actual expenses for maintenance. The average total cost is 13 000 yen/m^2 of floor area and energy cost (electric power and gas) formed about 40% of the total operating cost. Equipment maintenance ranked second and formed about 25% of the total operating cost.

Energy consumption and CO_2 emission during operation were estimated following the procedure described in Section 2 and are plotted in Figs. 5 and 6, respectively. Energy consumption and CO_2 emission caused by the consumption of electric power was ranked first and formed approximately 90% of the respective totals except in the case of Building J. The energy (for hot water and chilled water) for Building J was supplied by a heat pump system in the district heating and cooling center located close to Building J, therefore, the relative proportions of the constituents differed from other nine buildings. The average annual energy consumption was determined to be 1.21 GJ/m^2 and average annual CO_2 emission was 87 kg/m^2.

5. Estimation of energy consumption and CO_2 emission in renovation

To obtain the life cycle figure of energy consumption and CO_2 emission of buildings, it is necessary to estimate the energy consumption and CO_2 emission from renovation works as well. However, because the buildings analyzed are relatively new, no major renovation has yet been made at the time we undertook a survey of those buildings. Therefore, for these buildings, expected life durations for each building material and/or system were hypothetically fixed (see Table 4) and following these hypothetical durations, the need for renovation work was calculated for an assumed life of the building. The life of the building was set at 40 years.

According to Table 4, the expected life period of lighting systems is 15 years, therefore, the renovation work for lighting systems was assumed to be carried out two times (15 and 30 years after construction) in the 40 years of building life. An assumption was made regarding interior finishing and structure of these buildings wherein these were assumed to

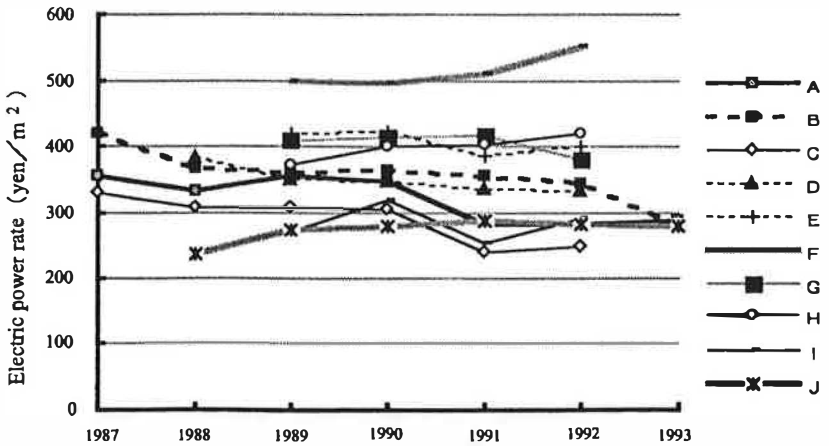

Fig. 3. Average monthly electric power rate of office buildings.

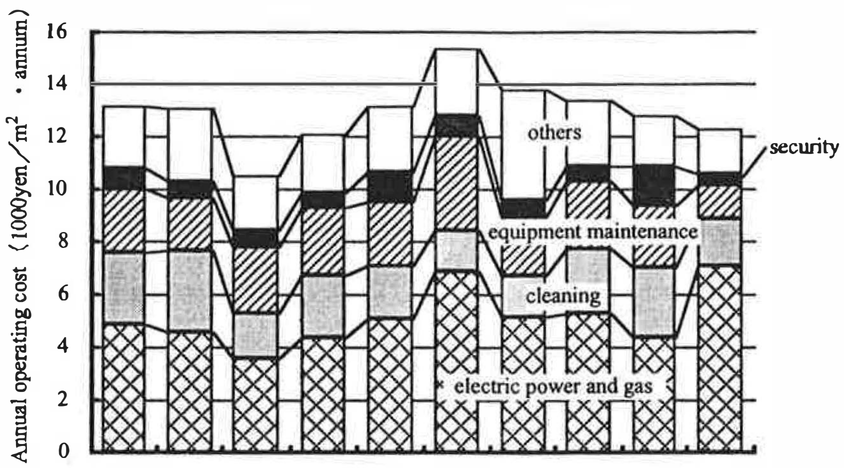

Fig. 4. Annual operating cost of office buildings.

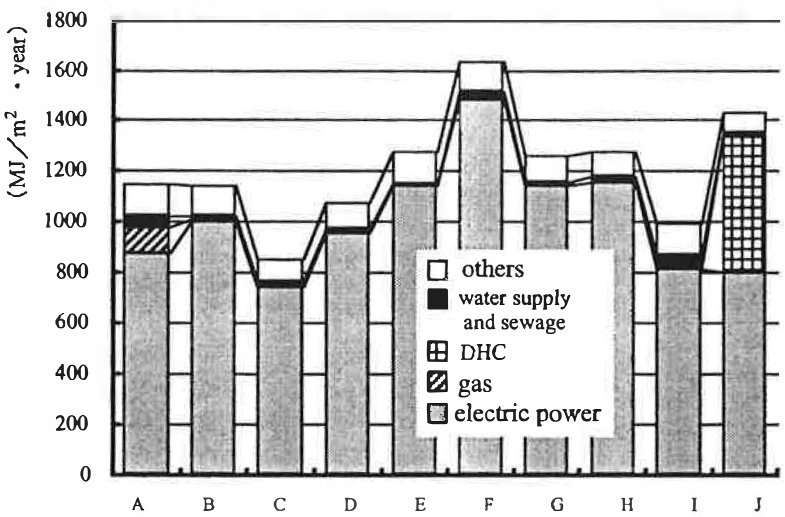

Fig. 5. Energy consumption by building operation.

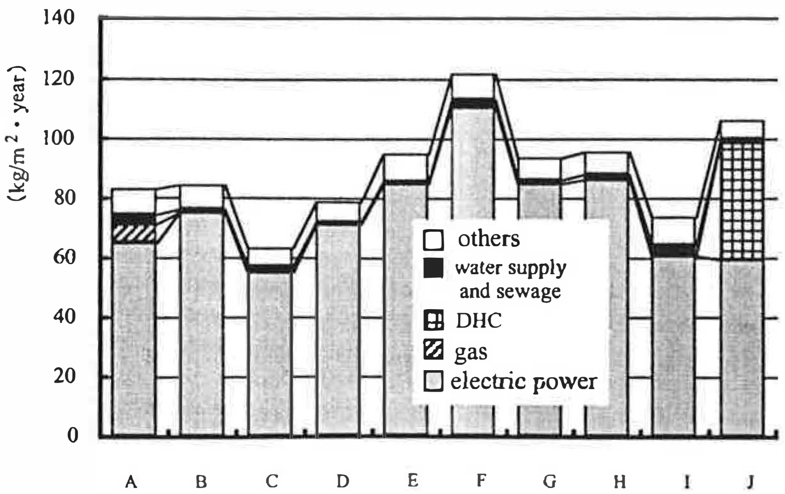

Fig. 6. CO_2 emission by building operation.

Table 4
Expected duration period

Part/equipment		Expected duration (years)
Roof	bituminous membrane waterproofing	25
	polyvinyl membrane waterproofing	15
	protecting tile	30
Outer wall	exterior gloss paint	20
Floor finishing	vinyl tile flooring	20
Substation	circuit breaker	20
	disconnecting switch	20
	transformer	20
	capacitor	20
Battery	lead storage battery	15
	alkaline battery	15
	battery charger	15
Electric cable	RN, BN	20
	CV 6.6/3.3 kV	20
	CV 600 V	20
	VV 600 V	20
	bus duct	20
Lighting system	fluorescent lamp	15
	incandescent lamp	15
	mercury lamp	15
Other electric systems	amplifier/speaker	20
	electric clock	20
	interphone	20
Sanitary pump	drain pump	20
	drain pump (submerged)	10
	water supply pump	25
	fire pump	30
	motor	20
Pipes	hot dip galvanized steel pipe (supply)	20
	hot dip galvanized steel pipe (drain)	20
	valve	20
Hot water supply equipment	storage type water heater (gas fired)	8
	instantaneous water heater (gas fired)	7
Ciller	centrifugal refrigerating machine (open type)	20
	centrifugal refrigerating machine (closed type)	20
	accessories	20
	absorption type chiller	20
Chilling unit		20
Cooling tower	fan	15
	motor	15
	casing	15
Air handling unit	casing, fan	15
	chilled and hot water coil	15
Packaged air-conditioner	coil, fan	20
	compressor	20
Ventilation equipment	supply fan	25
	exhaust fan	25
	motor	25
Air-conditioning pumps	hot and chilled water circulation pump	25
	motor	25

require no significant renovation. The materials used in renovation work were assumed to be the same as those used in the construction work and their cost was fixed at their respective values at the time of the initial construction.

These data were analyzed using the method described in Section 2 for estimating the energy consumption and CO_2 emission. Figs. 7 and 8 show the estimated energy consumption and CO_2 emission, respectively, in the renovation work. The average energy consumption was 1.54 GJ/m^2 and average CO_2 emission was 128 kg/ m^2 during the 40 years of building life. However, the energy consumption and CO_2 emission differed among these buildings because of the differences in the materials and systems used in the 10 buildings. The minimum energy consumption for total renovation work was 1.0 GJ/m^2 of floor area (Building B) and maximum energy consumption was 2.6 GJ/m^2 of floor area (Building

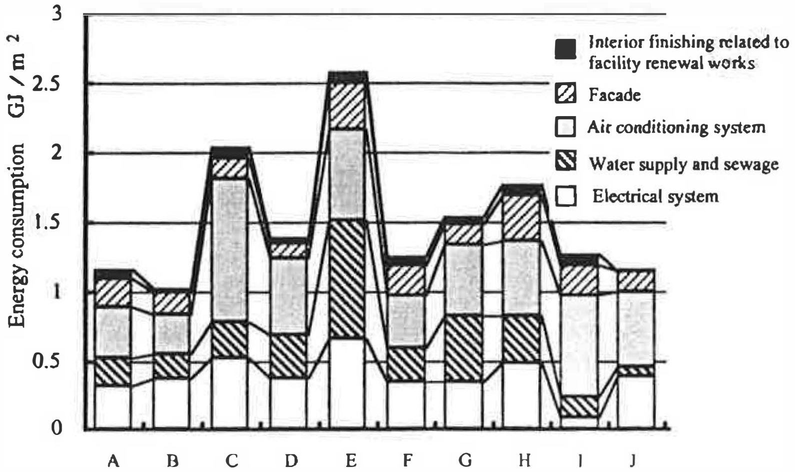

Fig. 7. Energy consumption for renewal works (total of 40 years).

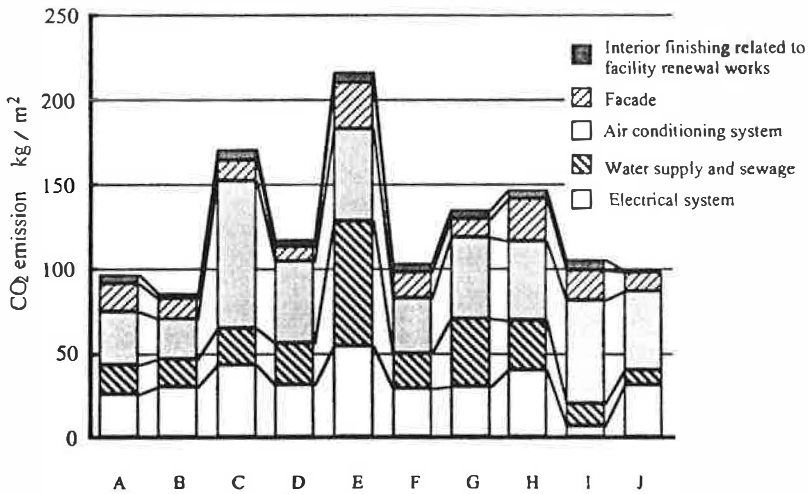

Fig. 8. CO_2 emission for renewal works (total of 40 years).

E). The large variation is mostly the result of the differences in the kind of systems used in the water supply and sewage works.

6. Conclusion

The energy consumption and CO_2 emission were estimated in each step of the life cycle of office buildings. In this study, the contributions in the demolition phase of buildings were not estimated. However, a former analysis [12] shows that energy consumption is 0.49 GJ/m^2 and CO_2 emission is 36 kg/m^2 for RC office buildings. Therefore, the energy consumption and CO_2 emission in the demolition work contribute relatively small amounts to their respective totals.

The life cycle figure of energy consumption and CO_2 emission are shown as follows.

Connection works
–Average energy consumption is 8.95 GJ/m^2
–Average CO_2 emission is 790 kg/m^2

Operation works
–Average annual energy consumption is 1.21 GJ/m^2 (48.4 GJ/m^2 for 40 years)
–Average annual CO_2 emission is 87 kg/m^2 (3480 kg/m^2 for 40 years)

Renovation works
–Average energy consumption is 1.54 GJ/m^2 for 40 years
–Average CO_2 emission is 128 kg/m^2 for 40 years

Demolition works
–Energy consumption is 0.49 GJ/m^2
–CO_2 emission is 36 kg/m^2

Entire life cycle
–Energy consumption is 59.4 GJ/m^2
–CO_2 emission is 4430 kg/m^2

The contributions to the life cycle energy consumption and CO_2 emission of each building are shown in Figs. 9 and 10, respectively. Overall figures are shown graphically by the pie charts of Fig. 11.

In this estimation, in terms of energy consumption, operation of office building is ranked first and contributes 82%

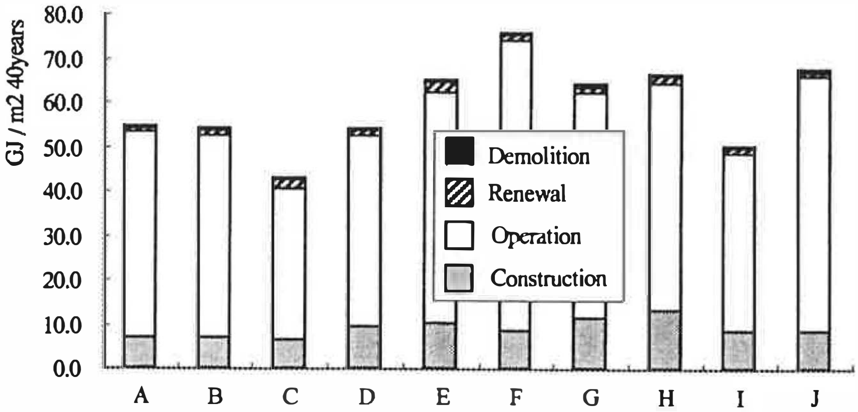

Fig. 9. Life cycle energy consumption.

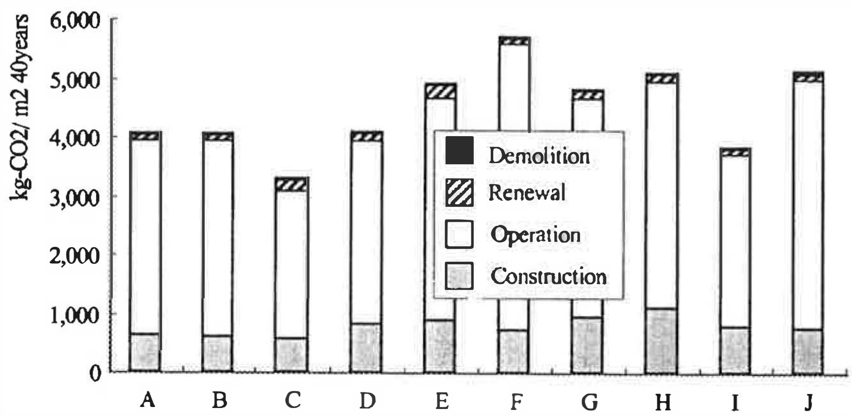

Fig. 10. Life cycle CO_2 emission.

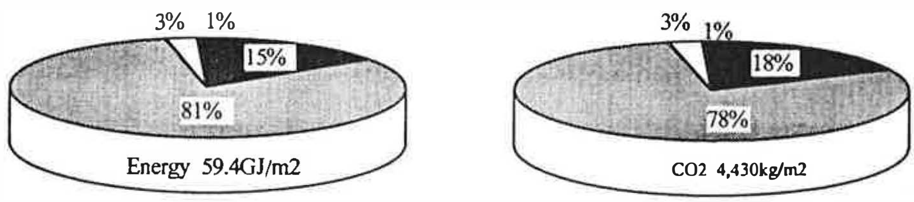

Fig. 11. Life cycle energy consumption and CO_2 emission (average of Buildings A–J).

of the life cycle energy consumption while construction work contributes only 15%. Therefore, energy saving in operation of buildings could be effective for securing a reduction in the life cycle energy consumption of office buildings.

7. Discussion

In this study, a method based on the use of I/O tables was applied to estimate the life cycle energy consumption and CO_2 emission of office buildings. The method is relatively easy to apply compared to LCA-based methodologies. However, there are a few items that may cause errors in the analysis. They are as follows.

(1) The I/O Table was based on the price of the producer while the cost in the estimate is the price to the buyer. Therefore, it was necessary to convert the cost in the estimate to the price of the producer using statistical data concerning the cost/labor information for various categories of work. However, if the nature of work for a specific building is different from the average, the use of the I/O table results will lead to undesirable effects on the result.

(2) Construction estimates are usually done using methodologies that are standard to individual firms. However, sometimes it happens that the prices are internally, intentionally manipulated.

In these cases, the analyzed result may be vastly different. In order to avoid such cases, the quoted price of major materials should be checked by comparing the average price written in the handbook of construction costs.

(3) The price information may not necessarily be from the same year as the year associated with the I/O table.

In this study, the costs were all brought to the same year using the Construction Price Index. However, Construction Price Index only reflects an overall change in the cost of all materials related to construction works and it does not accurately mirror the rise in prices of each individual material which may differ from the overall index. This could lead to significant error if there are significant asymmetries in the rise of prices of various construction materials.

(4) If the materials are from other countries, the analysis becomes complicated as one of the major limitations of the I/O method is the analysis of imported materials.

In this study, the analyzed buildings used only a few imported materials. Therefore, in this study the above limitation of the I/O method did not apply. In the future, studies comparing the results of the I/O- and LCA-based methods are required. In addition, precision of the results needs to be established by comparing results with data from actual buildings.

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