CO_2 Emission of an Alternative Technology and Bilateral Trade between Japan and Canada:

Relocating production and an Implication for Joint Implementation*

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Abstract

Japan heavily depends on materials such as coal, pulp, and woods from Canada, while Canada imports manufacturing goods from Japan. Both countries consume energy and generate CO_2 in order to produce exporting goods and materials. Using trade data, we have linked the two countries input-output tables, and estimated CO_2 emission through bilateral trade between from each sector. For example, one Japanese automobile (US 10,000 dollar) exported to Canada generates CO_2 4.58 tonnes in Japan and 7.76 kg in Canada. On the other hand, pulp export (US 10,000 dollar) from Canada to Japan generates CO_2 17.2 tonnes in Canada and 7.71 kg in Japan. CO_2 emission would have increased by 6.55 million tonnes in Japan (Canada generates CO_2 5.44 millions tonnes for exports to Japan), and by 5.34 million tonnes in Canada (Japan generates CO_2 2.83 millions tons for exports to Canada), if there had been no trade between the countries and the same amount of commodities had been produced domestically.

We have also found there are significant differences of CO_2 emission per production between these countries. CO_2 emission from electricity per kWh in Canada is 0.44–0.46 times Japan's CO_2 emission from electricity. There are rooms to reduce CO_2 emission re-allocating alternative technologies between these two countries. We estimated CO_2 emission from production of photovoltaic cells for these countries. Canadian photovoltaic cells are considerably lower CO_2 emission (0.725 times) than Japanese, mainly because Japan's electric power has higher CO_2 emission than Canada's.

1 Introduction

The bilateral trade between Canada and Japan has a specific character: Canada exports natural resources, and Japan exports manufactured goods. Coal, pulp and woods are three major exports to Japan, their values are about 46% of the total export from Canada to Japan. Machinery, electric machinery, and automobiles are three major exports to Canada, their values reach 75 % of the total export from Japan to Canada. Each country emits CO_2 on behalf of exports to the other countries, while every country saves domestic CO_2 emissions by importing tradable goods.

Our objectives of this paper are three folds. Firstly, we try to find differences of CO_2 emission generated by unit production both in terms of value and in terms of volume. The findings will show whether CO_2 can be reduced by producing some commodity in the partner country. Especially we expect that non-tradable commodities, such as electric power and transportation, have large differences of CO_2 emission. Because major differences exist in CO_2 emissions of non-tradable commodities, we must use the input-output technique in order to identify direct and indirect CO_2 emissions from tradable goods.

Our second question is how much the international trade and transactions increase CO_2 emissions in both of the countries. Even if we may find the significant differences of CO_2 emission from some tradable goods, the international transactions could add considerable CO_2 emissions after relocating production sites. This side effect is also analysed by input-output tables extended to bilateral trade.

Finally, we evaluate a typical alternative technology, i.e. photovoltaic cells, in case that the production is operated in Canada, and in Japan. We will compare direct and indirect CO_2 emissions of Canadian photovoltaic with those of Japanese photovoltaic. The photovoltaic technology we evaluated here is not new, but the polycrystalline silicone solar cell has been produced most in recent years.

The evaluations on CO_2 emission generated by unit production are simple comparisons, still might include uncertain errors, which we do not know. We will describe the procedures in detail as possible. The next section presents the data sources and the basic input-output model, and our analyses are explained sequentially as described above.

2 The data sources and the basic model

2.1 Data for Japan

We use 1995 input-output tables and 1990 input-output tables, both complied by Ministry of Public Management, Home Affairs, Posts and Telecommunications ([1994] and [2000]). We estimated CO_2 emission following the sectoral definition of the input-output tables, extended the input-output tables, and call them the environmental input-output tables (Japan).[2] Figure 1 shows the conceptual framework of our 1995 environmental input-output table for Japan.

We aggregated the Japan's non-squared intermediate transaction matrix into the 397 $\times$ 397 squared matrix for convenience. We also aggregated 53 different energy and other sources of carbon emission into CO_2 emission volume vector ($\mathbf{co_2}'$) of 1 $\times$ 397 columns. The same procedure was applied to our 1990 environmental input-output tables of Japan, and we obtained the 405 $\times$ 405 squared intermediate transaction matrix, and CO_2 emission vector of 405 columns.

2.2 Data for Canada

Statistics Canada provides the input-output tables every year, and the greenhouse gas emissions by sector every year. Canada's input-output tables consists of three matrices, i.e. use matrix, make matrix and final demand matrix. The 1995 use and make matrix has 469 commodities and 166 activities, and the 1995 final demand matrix has 469 commodities and 122 institutions. We assumed the industry technology assumption and obtained the 469 $\times$ 469 squared matrix for intermediate transactions. In the calculation procedure, we had to estimate truncated figures due to the confidentiality problem. After filling self-evident figures estimated from row total and column total, we applied the RAS method with the Lagrange multiplier method to the 1995 input-output tables, and obtained the balanced intermediate transaction matrix.[3]

2.3 The basic model

We applied the possible simplest model to compare direct and indirect CO_2 emission between the two countries. The definitions of the variables are as follows:

- x_i : the ith output value, $i = 1, \ldots, n$.
- $\mathbf{x}$: the output column vector with its ith element of x_i.
- X_{ij} : the ith input value of the jth sector, $i, j = 1, \ldots, n$.
- A_{ij} : the ith input coefficients of the jth sector, $A_{ij} = \frac{X_{ij}}{x_i}$, $i, j = 1, \ldots, n$.
- $\mathbf{A}$: the input coefficients matrix with its ij element of A_{ij}.
- fd_i : the ith domestic final demand, $i = 1, \ldots, n$.
- $\mathbf{fd}$: the domestic final demand vector with its ith element of fd_i.
- ex_i : the ith export final demand, $i = 1, \ldots, n$.
- $\mathbf{ex}$: the export final demand vector with its ith element of ex_i.
- im_i : the ith import, $i = 1, \ldots, n$.
- M_i : the ith import coefficient, $M_i = \frac{im_i}{\sum_j^n X_{ij} + fd_i}$, $i = 1, \ldots, n$.
- $\hat{\mathbf{M}}$: the import matrix (diagonal) with its diagonal element of M_i.

[2] The estimated procedure is given in Asakura et al. [2001] for example, and the other our papers. We have been estimated the environmental input-output tables for Japan every 5 years since 1985, which was first published in 1992 and presented at the 10th conference on IIOA at Sevilla on 29th March 1993. See Hayami et al. [1993].

[3] We applied different procedure for the 1990 input-output tables, due to lack of row total data. We hypothetically set a residual activity and a residual commodity to obtain balanced matrix. See for detail Hayami, Nakamura, Asakura, and Yoshioka [1999].

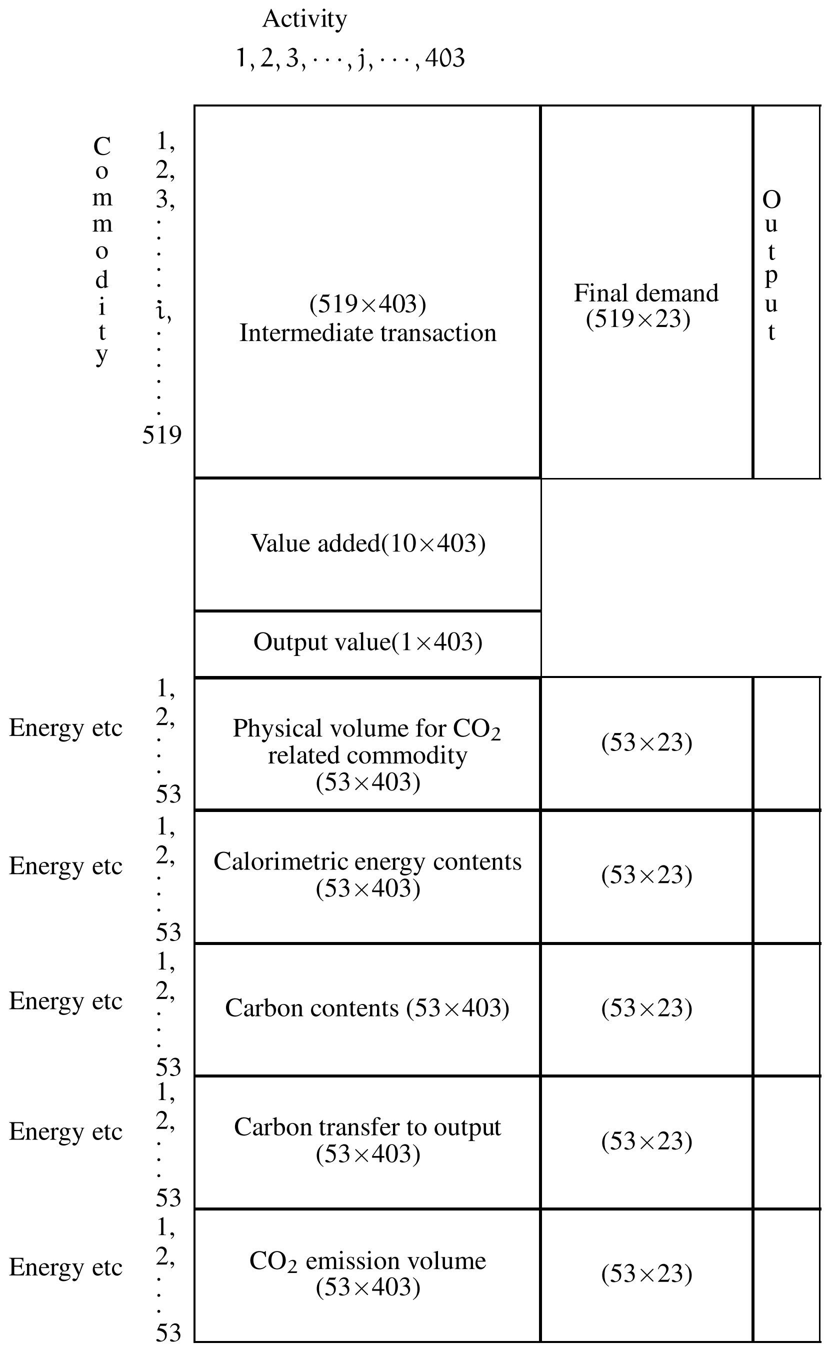

Figure 1: Conceptual framework of 1995 environmental input-output table, Japan

CO_{2i}	:	the i th sector's total CO_2 emission volume, $i = 1, \ldots, n$.
$\mathbf{co_2}$	:	the CO_2 emission volume vector $n \times 1$ with its ith element of CO_{2i}.
E_i	:	the ith emission coefficient, $E_i = \frac{CO_{2i}}{x_i}$, $i = 1, \ldots, n$.
$\boldsymbol{e}^{\mathsf{T}}$	:	the emission coefficient vector $1 \times n$, with its diagonal element of E_i. $^{\mathsf{T}}$ means transpose of vector or matrix.
$\hat{E}$	:	the emission coefficient matrix (diagonal) with its diagonal element of E_i.
f_i	:	an ith final demand, $i = 1, \ldots, n$.
$\mathbf{f}$	:	a final demand vector with its $i$the element of f_i.
$\mathbf{I}$	:	the identity matrix with its diagonal element of 1.
$\mathbf{1}$	:	the vector of one $n \times 1$ with its element of 1.

The balanced commodity flow is expressed as follows:

$$x_i + im_i = \sum_{j=1}^{n} X_{ij} + fd_i + ex_i, \quad i = 1, \ldots, n.$$

If we assume the import volume is proportional domestic demand under the competitive import scheme, we can introduce the import coefficient defined as above. Following the standard procedure, we can denote the above equation in vector form.

$$\mathbf{x} + \hat{M}(\mathbf{x} + \mathbf{fd}) = \mathbf{Ax} + \mathbf{fd} + \mathbf{ex},$$

or

$$\mathbf{x} = (\mathbf{I} - (\mathbf{I} - \hat{M})\mathbf{A})^{-1}((\mathbf{I} - \hat{M})\mathbf{fd} + \mathbf{ex}).$$

We can derive sectoral CO_2 emission volume by its definition, using the emission coefficient matrix $\hat{E}$.

$$\mathbf{co_2} = \hat{E}\mathbf{x} = \hat{E}(\mathbf{I} - (\mathbf{I} - \hat{M})\mathbf{A})^{-1}((\mathbf{I} - \hat{M})\mathbf{fd} + \mathbf{ex}).$$

We can also derive the total CO_2 emission volume $CO_2 = \mathbf{1}^{\mathsf{T}}\mathbf{co_2}$, using the emission coefficient vector $\boldsymbol{e}^{\mathsf{T}}$.

$$CO_2 = \mathbf{1}^{\mathsf{T}}\mathbf{co_2} = \boldsymbol{e}^{\mathsf{T}}\mathbf{x} = \boldsymbol{e}^{\mathsf{T}}(\mathbf{I} - (\mathbf{I} - \hat{M})\mathbf{A})^{-1}((\mathbf{I} - \hat{M})\mathbf{fd} + \mathbf{ex}).$$

We often use direct and indirect CO_2 emission generated by unit production of ith commodity ($CO_2{}^{(i)}$), which can be derived following calculation. Let $\mathbf{f}^{(i)}$ the final demand vector with its $i$the element of 1 and the other elements of 0. And domestic productions induced by $\mathbf{f}^{(i)}$ is $(\mathbf{I} - (\mathbf{I} - \hat{M})\mathbf{A})^{-1}\mathbf{f}^{(i)}$, which is direct and indirect production generated by unit production of ith commodity. Thus direct and indirect CO_2 emission generated by unit production of ith commodity ($CO_2{}^{(i)}$) is given as follows:

$$CO_2{}^{(i)} = \boldsymbol{e}^{\mathsf{T}}(\mathbf{I} - (\mathbf{I} - \hat{M})\mathbf{A})^{-1}\mathbf{f}^{(i)}. \quad (1)$$

3 Canada and Japan comparison of CO_2 emission by commodity

The purpose of this section is to identify differences of CO_2 emission from unit commodity production between the two countries. We first compare CO_2 emission from one million US dollars worth of production, using equation (1) and the exchange rates. Exchange rates used are 94.06 yen per one US dollar, and 1.3724 Canadian dollar per one US dollar for 1995. In 1995, Japanese yen was extraordinary strong to US dollar, and Canadian dollar was weak to US dollar, as compared to the preceding years and to the following years. OECD's purchasing power parity (PPP) indices for GDP in 1995 were 170 yen per one US dollar for Japan and 1.18 Canadian dollar per one US dollar for Canada. In comparison of CO_2 emission from unit commodity production in terms of PPP, we just multiply 1.807 to the Japanese CO_2 emission, and 0.8598 to the Canadian CO_2 emission stated in Tables 1 and 2.

Sorting sectors by volume of CO_2 emission from one million US dollars worth of production, Table 1 shows 40 commodity sectors with most CO_2 emissions for each country. In spite of wide differences of the CO_2 emission volume, the ranking order of sectors shows strong similarity between the two countries. For example, Cement is the most CO_2 intensive sector for both countries in one dollar worth of production, and electric power is the second most CO_2 intensive sector. The difference is appeared in the third place: pipeline transportation is the third largest CO_2 for Canada, and coal products for Japan. Coal in Canada's classification means coal mining, whereas coal products in Japan mean mainly coke for steel production and gas distribution. There is no significant pipeline transportation in Japan. Iron steel and its products have large (direct plus indirect) CO_2 emissions for both countries regardless of the difference of the classification. Salt, sodium chlorate, caustic soda, and soda chemistry all related soda have relatively large CO_2 emission in terms of one dollar worth of production for the two countries. And it can be found that transportation and petrochemical sectors have high CO_2 emission. In Canada, CO_2 volume per one dollar worth of production in petrochemical sectors is larger than the other chemical sectors, but in Japan, CO_2 from one dollar worth production of ammonia and pulp is larger than from one dollar worth production of petrochemical products.

Table 2 shows 40 commodity sectors with least CO_2 emission. The similarity of sectors appeared in the table is apparent. Rent, telecom, finance, insurance, and information service are all appeared in least 40 commodities in both countries. In Canada, apparel sectors and electronic sectors are appeared in the table, but in Japan no such sector ranked in the table.

These similarities and dissimilarities are common to the results from the 1990 input-output tables. Table 3 shows direct and indirect CO_2 emission from one million US dollar worth of production, which is in the same definition as in 1995. Cement is the most CO_2 intensive commodity, and electric power is the second most. In the 1990 Canadian input-output tables, coke, tar and pitch appear in the table, while coke, tar and pitch does not appear in Table 1 1995. In the 1995 Japanese input-output tables, tar and pitch are classified in coal products as well as coke, and in 1990, coal products (coke) and coal-tar products are separated. There were changes of CO_2 emission from coke and tar in the Canadian environmental input-output tables, as a result, the difference of CO_2 emission from coke in 1995 was appeared.

Table 4 shows the 20 commodity sectors with least CO_2 emissions from one million US dollar worth of production. The similarity of the sectors appeared in the table are apparent. There was no significant change for these 5 years. We can conclude that the ranking order of CO_2 emission across sectors are stable.

When we try to compare the absolute volume of CO_2 emission in terms of one unit of production, the above coefficients observed in Tables 1–4 are not easy to understand. The figures in Tables 1–4 include price differences between the two countries. The same one million US dollar worth of production does not mean the same volume of production, unless the price of a commodity in US dollar is the same for both countries. In some commodities freely traded with proper exchange rates, the same value could mean the same amount of volume.

But the commodities such as services, rent and the other non-tradables are almost impossible to measure proper volume produced. We can only compare CO_2 emission from one dollar worth of production for services and non-tradables, without assuming how much the price difference of

Table 1: 40 commodity sectors with most CO_2 emissions: Canada and Japan, 1995[a]

Canada			Japan		
No	Sector	CO_2	No	Sector	CO_2
286	Cement	13.75831	157	Cement	10.15797
409	Electric power	4.88112	291	Self-Power gener.	9.27398
403	Pipeline transport.	3.74188	144	Coal products	7.51402
304	Diesel and fuel oil	3.31421	166	Pig iron	6.23060
303	Motor gasoline	3.28686	111	Ammonia	3.57451
287	Lime	3.14001	168	Crude steel(conv)	3.38980
294	Natural stone prod.	3.14001	116	Salt	2.25561
296	Mineral wool build.	3.14001	167	Ferro alloy	2.22812
289	Ready-mix concrete	2.93711	158	Ready mixed concret.	2.19612
309	Asphalt compound etc	2.85624	290	Electric power	2.19214
305	Lubricating oils etc	2.58152	170	Hot rolled steel	2.08548
027	Iron ores and con.	2.54415	113	Industrial soda chem.	1.94210
179	Flat iron and steel	2.45499	297	Other sanitary serv.	1.84905
031	Crude mineral oils	2.38400	176	Cast and forged mat.	1.80617
032	Natural gas, excl.	2.38353	165	Miscellaneous ceram.	1.74899
393	Air transportation	2.31375	169	Crude steel(electr.)	1.64915
307	Liquid petroleum gas	2.30844	099	Pulp	1.55672
310	Petrochemical feed	2.24676	317	Air transport	1.41018
322	Chlorine	2.24343	100	Foreign paper etc	1.40557
323	Oxygen	2.24343	101	Paperboard	1.34620
329	Caustic soda	2.24343	175	Cast iron pipes etd	1.31608
330	Sodium chlorate	2.24343	172	Cold-finished steel	1.29832
337	Butadiene	2.24343	132	Rayon,acetate	1.18990
349	Carbon	2.24343	171	Steel pipes and tube	1.18271
396	Water transport	2.01159	120	Aliphatic intermed.	1.18228
335	Ethylene	1.96286	180	Lead Zinc(inc.regen.)	1.18025
397	Services incidental	1.90406	298	Other sanitary serv.	1.17594
399	Truck transportation	1.78436	314	Ocean transport	1.10471
178	Reinforcing bars etc	1.70420	122	Synthetic rubber	1.04009
250	Aircraft service etc	1.69742	313	Self-freight tran.	1.02479
033	Sulphur, crude etc	1.64836	293	Steam and hot water	1.01283
398	Railway transportat0	1.58832	159	Cement products	1.01250
444	Transportation marg.	1.53816	127	Other industrial org	0.96829
401	Urban transit	1.48543	174	Cast and forged steel	0.95555
311	Fertilizers	1.46365	312	Self-Passenger trans	0.94928
400	Bus transport, inter	1.44349	177	Iron and steel shear	0.93637
034	Asbestos, crude etc	1.42065	118	Petrochemical basic	0.92464
035	Gypsum	1.42065	131	Other resin	0.91009
004	Other live animals	1.33401	115	Compressed gas etc	0.90841
015	Canola, soybeans etc	1.32498	315	Coastal and inland	0.88464

[a] Numbers are estimated amounts of emissions of CO_2 in kilo tonnes generated by one million U.S. dollars worth of production; direct and indirect CO_2 emission, using $(I - (I - \hat{M})A)^{-1})$.
The sector names are abbreviated, for details refer to the sector identification number.
Exchange rates used are 94.06 yen/US dollar, 1.3724 Canada dollar/US dollar

Table 2: 40 commodity sectors with least CO_2 emissions: Canada and Japan, 1995[a]

Canada			Japan		
No	Sector	CO_2	No	Sector	CO_2
431	Accommodation servic	0.32426	334	Private broadcasting	0.09325
447	Advertising and prom	0.31887	379	Truck operations etc	0.09288
423	Private education se	0.31826	362	Private non-profit o	0.09280
391	Railway and telecomm	0.31614	372	Civil engineering an	0.09259
385	Repair construction	0.30968	394	Individual instruct.	0.09207
172	Advertising in print	0.34573	388	Barber shops	0.08898
168	Newspapers, magazine	0.34522	326	Oth. serv. r to air	0.08674
392	Oth.engineer. const.	0.34426	023	Silviculture	0.08653
387	Non-residential buil	0.33690	339	School education(pri	0.08452
435	Services to building	0.33405	019	Other livestock-rais	0.08158
427	Other recreational s	0.32949	389	Beauty shops	0.08151
100	Beer, incl. coolers	0.32589	327	Travel and other ser	0.07837
441	Spare parts and main	0.32487	299	Wholesale trade	0.07805
429	Advertising services	0.30907	364	Information service	0.07541
390	Electric power, dams	0.30515	331	International telecom	0.07483
455	Gov. funding univ.	0.29418	260	Repair of aircraft	0.07371
138	Clothing and accesso	0.28360	365	News syndicates, etc	0.07305
141	Custom tailoring	0.28202	338	School education(pub)	0.07289
449	Welfare organization	0.27184	346	Research inst. (NPO, nat)	0.07250
275	Electronic equipment	0.27172	305	Real estate rent	0.07125
272	Telephone and relate	0.26042	349	Research inst. (Ind, soc)	0.07117
459	Other provincial gov	0.25703	304	Real estate agencies	0.06748
460	Other federal gov	0.24460	302	Life insurance	0.06517
456	Gov. funding oth edu	0.23864	329	Domestic telecomm.	0.06444
116	Leather gloves	0.22755	374	Other business serv.	0.06382
140	Fur apparel	0.22755	332	Oth. serv. relat comm	0.06310
445	Laboratory equipment	0.21574	371	Judicial,financial	0.06242
437	Other services to b	0.21514	323	Serv. r to water tra	0.05715
251	Automobiles	0.21096	370	Building maintenance	0.05660
433	Personal services	0.20984	303	Casualty insurance	0.05656
406	Radio and television	0.20885	347	Research inst.(NPO, soc)	0.05136
419	Insurance	0.20125	367	Car renting	0.04774
425	Other health and soc	0.20032	345	Research inst.(Pub, soc)	0.04725
436	Software development	0.17354	330	Mobile telecomm	0.04710
407	Telephone and other	0.16916	366	Goods renting etc	0.04708
424	Priv. hospital serv	0.16531	075	Tobacco	0.04515
453	Gov. funding hosp.	0.16531	301	Financial service	0.04388
428	Engineering, scien.	0.16175	292	Gas supply	0.03181
454	Gov. funding resid	0.11843	306	House rent	0.01917
420	Gross imputed rent	0.02542	373	Worker dispatching	0.01298

[a] Numbers are estimated amounts of emissions of CO_2 in kilo tonnes generated by one million U.S. dollars worth of production; direct and indirect CO_2 emission, using $(I - (I - \hat{M})A)^{-1})$.
The sector names are abbreviated, for details refer to the sector identification number.
Exchange rates used are 94.06 yen per US dollar, and 1.3724 Canadian dollar per US dollar.

Table 3: 20 commodity sectors with most CO_2 emissions: Canada and Japan, 1990[a]

Canada			Japan		
No	Sector	CO_2	No	Sector	CO_2
305	Cement	11.53425	167	Cement	12.28640
430	Electric power	5.43939	301	Self power generation	12.24309
308	Ready-mix concrete	3.79629	176	Pig iron	6.10124
187	Ferro-alloys	3.27569	154	Coal products	5.41976
188	Iron and steel ingot	3.27569	063	Salt	4.15599
192	Iron and steel railway	3.27569	177	Ferro alloy	4.10248
191	Flat iron and steel including galv. tinplate	3.26846	178	Crude steel	4.03879
189	Steel castings	3.26551	300	Electric power	3.46890
223	Flat iron and steel, alloy, other coated	3.26137	175	Miscellaneous ceramics	3.37598
432	Coke	3.03469	168	Ready mixed concrete	3.14191
028	Iron ores and concentrate	2.95383	131	Coal-tar products	3.11763
193	Tar and pitch	2.81836	307	Other sanitary service	3.05860
322	Gasoline	2.79369	121	Industrial soda chemicals	2.89904
323	Diesel and fuel oil, aviation fuel	2.79369	179	Crude steel(electric furnace)	2.87393
329	Petrochemical feed s	2.79090	180	Hot rolled steel	2.82962
324	Lubricating oils and	2.77975	118	Ammonia	2.30210
328	Asphalt and products	2.73931	190	Lead (including regenerated)	2.26170
190	Steel bars and rods	2.73511	107	Western and Japanese type paper	2.19081
424	Pipeline transportation	2.71311	186	Cast and forged mate	2.06145
321	Abrasive products	2.50007	325	Ocean transport	1.92455

[a] Numbers are estimated amounts of emissions of CO_2 in kilo tons generated by one million U.S. dollars worth of production; direct and indirect CO_2 emission, using $(I-(I-\hat{M})A)^{-1})$ for Japan. Because some sectors of the export include the re-export in Canada's input-output tables, it does not satisfy the condition that the positive import coefficient $M_i > 0$ for some i, where M_i is defined as $\frac{im_i}{\sum_j X_{ij}+fd_i}$. Thus we use the formula that permits the export included the re-export, that is, $M_i^* = \frac{im_i}{\sum_j X_{ij}+fd_i+ex_i}$. The above $\hat{M}$ has its diagonal elements of M_i^*.

Exchange rates used are 144.79 yen per U.S. dollar, and 1.1668 Canadian dollar per U.S. dollar. The sector names are abbreviated, for details refer to the sector identification number.

Table 4: 20 commodity sectors with least CO_2 emissions: Canada and Japan, 1990[a]

Canada			Japan		
No	Sector	CO_2	No	Sector	CO_2
440	Insurance and workers' compensation	0.29193	339	International telecommunications	0.11140
293	Radar and radio navigation equipment	0.29139	353	Research institute(private, social science)	0.10906
292	Broadcasting and radio communi. equip.	0.29117	025	Silviculture	0.10894
295	Electronic alarm and signal systems	0.29117	379	Judicial, financial, accounting	0.10794
429	Postal services	0.27622	343	Cable broadcasting	0.09866
427	Radio and television	0.26890	315	Real estate rent	0.09832
262	Scales and balances	0.26747	355	Research institute(private, NPO)	0.09691
334	Pharmaceuticals	0.26720	338	Domestic telecommunications	0.09228
290	Radio, TV, stereo, VCR and unrec. tape	0.26263	079	Tobacco	0.09178
263	Vending machines	0.25126	314	Real estate agencies	0.09068
264	Computers,office machines excl. photo and fax	0.24638	346	School education (public)	0.08991
456	Personal services, incl. childcare	0.24260	374	Goods renting and leasing (excl.car)	0.08848
459	Computer services	0.24254	378	Building maintenance	0.08837
291	Telephone and related equip. incl. fax	0.21065	313	Casualty insurance	0.08706
460	Other services to business and persons	0.20989	375	Car renting	0.07770
447	Other health and social services	0.20498	333	Service relating to water transportation	0.06575
438	Imputed service, banks	0.17571	311	Financial service	0.06486
428	Telephone and other telecommunications	0.15482	312	Life insurance	0.06171
450	Professional service to bus. management	0.14845	316	House rent	0.04504
441	Imputed rent, owner occupied dwellings	0.02586	381	Worker dispatching service	0.01697

[a] Numbers are estimated amounts of emissions of CO_2 in kilo tonnes generated by one million U.S. dollars worth of production; direct and indirect CO_2 emission, using $(I-(I-\hat{M})A)^{-1})$ for Japan. Because some sectors of the export include the re-export in Canada's input-output tables, it does not satisfy the condition that the positive import coefficient $M_i > 0$ for some i, where M_i is defined as $\frac{im_i}{\sum_j X_{ij}+fd_i}$. Thus we use the formula that permits the export included the re-export, that is, $M_i^* = \frac{im_i}{\sum_j X_{ij}+fd_i+ex_i}$. The above $\hat{M}$ has its diagonal elements of M_i^*.

Exchange rates used are 144.79 yen per U.S. dollar, and 1.1668 Canadian dollar per U.S. dollar.

The sector names are abbreviated, for details refer to the sector identification number.

service reflects volume of service. Even when complete volume data are available, there remains the problem of quality adjustment.

Nonetheless, comparing CO_2 emission by the same physical volume of production provides us some insights and information, assuming that both countries are producing the same quality of products. Table 5 presents CO_2 emission per unit volume of production. For example, Canadian wheat generates 0.140 ton-CO_2 every 1 ton of the production, while Japanese wheat emits 0.342 ton-CO_2 every 1 ton of the production. In agricultural, fishery and forestry, Canada has lower CO_2 emission per unit volume of production than Japan. Corn is an exceptional case, but corn, canola and soybeans are all the same CO_2 emission per one million dollars worth of production in Canada. This means the number of activities in the Canadian matrix is not large enough to separate these activities, as indicated IO No at the first column of Table 5. As to fishery, Japan has much higher CO_2 emission per unit volume of production than Canada. Japanese deep sea fishery consumes more fuel oil for shipments than Canadian coastal fishery.

Japan's CO_2 emissions in minings are relatively lower than those of Canada. It is not easy to understand how this is happen. But minings in Japan are classified to the same sector no. 29. Japan's CO_2 emission in copper minings are averaged out into the other minings.

In food manufacturing sectors, Japan's beef and poke have higher CO_2 emissions per unit volume of production than Canada's beef and poke. These sectors belong to the same classification in both of the countries. Beer is an independent sector for both of the countries, and Japan's beer emits a little less CO_2 than Canada's beer per unit volume of production.

Lumber and timber in Canada has smaller CO_2 emission per unit volume of production than in Japan, as well as wood pulp. This reflects that newsprint paper and paperboard in Canada has also smaller CO_2 emission per unit volume of production than in Japan, because papers induce pulp production and its CO_2 emission.

CO_2 emission from unit volume of production of caustic soda in Canada is less than that in Japan. This is consistent with that salt in Canada has lower CO_2 emission than in Japan.

As to ethylene, both of the countries has almost the same CO_2 emission per unit volume of production. While styrene in Japan has higher CO_2 emission per unit volume of production, but almost the same CO_2 emission in terms of one dollar worth of production.

Though Japan classifies petroleum products, such as gasoline, LPG, naphtha, into one sector, gasoline and LPG in Japan have lower CO_2 emission, but naphtha in Japan has higher CO_2 emission than in Canada.

Steel in Japan is separated into at least three sectors, i.e. pig iron (blast furnaces), crude steel (converter furnaces) and crude steel (electric furnaces). Steel in Canada is aggregated into commodities, such as ferro alloys, iron and steel ingot. Thus, the comparison is very difficult, but Canada's CO_2 emission from steel production is within the range of the Japan's CO_2 emissions of the steel sectors.

As to the metal industry, except for copper and silver, Canada's CO_2 emissions from unit volume of metal production are less than those of Japan. Especially, Canada's CO_2 emission from per unit volume of aluminum production is much lower than that of Japan, because of lower CO_2 emission of the electric power in Canada.

There are only a few comparable data for the machinery production. Canada's CO_2 emission from unit automobile production is larger than Japan's CO_2 emission, whereas Japan's CO_2 emission from unit truck production is larger than Canada's.

Public utility, such as electric power and gas distribution, Canada's CO_2 emissions are lower than those of Japan.

It is very difficult to say in general what is clear from these comparisons of CO_2 emissions in terms of unit volume production. The results of 1990 input-output tables increase difficulty of

Table 5: CO_2 emissions per unit output: Canada and Japan, 1995[a,b,c]

Canada				Japan		
IO No	Commodity (output unit)	CO_2 (1,000t) per volume	CO_2 (1,000t) per mil.USD	IO No	CO_2 per volume	CO_2 (1,000t) per mil.USD
5	Wheat(1,000t)	0.140	1.322	2	0.342	0.2068
6	Barley(1,000t)	0.054	1.324	2	0.316	0.2068
15	Soybeans(1,000t)		1.325	4	0.341	0.1337
15	Canola	0.319	1.325			
6	Oats(1,000t)	0.091	1.324	9	0.104	0.1462
15	Corn(1,000t)	0.388	1.324	9	0.301	0.1462
6	Rye(1,000t)		1.324	10	0.006	0.1363
16	Raw tobacco(1,000t)	4.618	1.322	13		
102	Unmanufactured tobacco(1,000t)	1.977	0.531	13	2.833	0.1370
8	Eggs(1,000t)	0.930	1.322	15	0.351	0.1991
19	Logs (1000m^3)	0.022	0.813	24	0.038	0.1557
23	Fish seafood (1000t)	1.366	0.990	26	2.148	0.8028
23	Marine culture (1000t)			27	3.682	0.5151
23	Inland water fishery and culture (1000t)			28	3.711	0.3207
25	Gold( )	0.011	0.752	29	0.005	0.5129
27	Iron ores(1,000t)	0.107	2.544	29	0.763	0.5129
29	Copper minings(1,000t)	1.586	0.617	29	1.072	0.5129
190	Lead minings(1,000t)	0.598	0.852	29	0.130	0.5129
191	Zinc minings(1,000t)	0.616	0.850	29	0.289	0.5129
287	Lime(1,000t)	0.006	3.140	30	0.004	0.4557
30	Coal(1,000t)	0.041	1.208	34	0.097	0.6748
31	Crude oil(1,000t)	0.297	2.384	35	0.044	0.2144
32	Natural gas(10^{15}J)	0.177	2.384	35	0.180	0.2144
44	Beef(1,000t)	0.225	0.979	36	1.927	0.1637
44	Pork(1,000t)	0.129	0.979	36	0.715	0.1637
54	Poultry(1,000t)	0.952	0.875	36	0.380	0.1637
7	Milk(1,000kl)	0.528	1.322	40	0.455	0.2365
58	Cheese(1,000t)	5.729	0.995	40	2.794	0.2365
76	Wheat flour(1,000t)	0.406	0.531	48	0.215	0.1641
48	Margarine(1,000t)	0.745	0.842	57	0.997	0.2681
100	Beer (1000kl)	0.697	0.326	66	0.581	0.1286

[a] Canadian quantities used in this table were collected from the following sources: Statistics Canada Website; Statics Bureau, Ministry of Japan *World Statistics*. The Japanese I-O tables include data on physical output for most I-O commodity sectors. They do not necessarily provide quantities for all sub-categories of commodities which constitute I-O sectors. Additional output data were collected from the following sources: Japanese Statics Bureau, Ministry of Public Management, Home Affairs, Posts and Telecommunications *Japan Statistical Yearbook*.

[b] Numbers for CO_2 / volume are estimated amounts of emission per unit volume of production, using CO_2 / USD million, commodity production value in USD million, and commodity production volume.

[c] Numbers for CO_2 / USD million are estimated amounts of emissions of CO_2 in kilo tonnes generated by one million U.S. dollars worth of production. Exchange rates used are 94.06 yen per U.S. dollar and 1.3724 Canadian dollar per U.S. dollar.

Table 5: CO_2 emissions per unit output: Canada and Japan, 1995 (continued)[a,b,c]

Canada				Japan		
IO No	Commodity (output unit)	CO_2 (1,000t) per volume	CO_2 (1,000t) per mil.USD	IO No	CO_2 per volume	CO_2 (1,000t) per mil.USD
143	Lumber and timber (1,000m^3)	0.106	0.701	92	0.096	0.1349
154	Wood pulp(1,000t)	0.409	1.250	99	1.178	1.5567
155	Newsprint paper(1,000t)	0.771	1.241	100	1.924	1.4056
159	Paperboard(1,000t)	0.235	1.239	101	0.962	1.3462
	Nitrogen fertilizer(1,000t)			112	0.432	0.7484
311	Fertilizer	0.052	1.464			
329	Caustic soda(1,000t)	0.545	2.243	113	1.037	1.9421
36	Salt(1,000t)	0.017	0.859	116	0.900	2.2556
326	Sulphuric acid(1,000t)	0.055	1.648	117	0.065	0.7719
335	Ethylene(1,000t)	0.579	1.963	118	0.580	0.9246
340	Propylene(1,000t)	0.485	0.885	118	0.413	0.9246
314	Ethylene glycol(1,000t)		0.850	120	2.228	1.1823
338	Styrene(1,000t)	0.343	0.850	121	0.966	0.8446
351	Synthetic rubber(1,000t)	2.512	0.849	122	4.091	1.0401
340	Polyethylene(1,000t)		0.885	129	1.377	0.8275
303	Motor gasoline(1,000t)	0.642	3.287	143	0.340	0.3100
307	LPG(1,000t)	0.404	2.308	143	0.166	0.3100
308	Naphtha(1,000t)	0.015	1.130	143	0.060	0.3100
106	Tire(1,000)	0.019	0.574	147	0.029	0.4546
286	Cement(1,000t)	0.949	13.758	157	0.837	10.1580
35	Gypsum(1,000t)	0.012	1.421	165	0.348	1.7490
	Pig iron(1,000t)			166	1.070	6.2306
179	Crude steel(1,000t)	0.864	2.455	168	1.259	3.3898
	Crude steel(1,000t) (electric furnaces)			169	0.707	1.6492
190	Lead in primary forms(1,000t)	0.448	0.852	180	1.091	1.1803
191	Zinc in primary forms(1,000t)	0.952	0.850	180	1.665	1.1803
192	Aluminum(1,000t)	1.733	1.013	181	2.541	0.5088
193	Silver in primary forms(t)	0.174	0.904	182	0.048	0.2747
251	Automobiles(1,000)	6.542	0.211	247	3.529	0.2338
252	Trucks(1,000)	9.558	0.850	248	10.748	0.850
409	Electric power (mill kWh)	0.165	4.881	290	0.379	2.19214
410	Gas distribution(10^{15}J)	0.023	0.740	292	0.075	0.0318

[a] Canadian quantities used in this table were collected from the following sources: Statistics Canada Website; Statics Bureau, Ministry of Japan *World Statistics*. The Japanese I-O tables include data on physical output for most I-O commodity sectors. They do not necessarily provide quantities for all sub-categories of commodities which constitute I-O sectors. Additional output data were collected from the following sources: Japanese Statics Bureau, Ministry of Public Management, Home Affairs, Posts and Telecommunications *Japan Statistical Yearbook*.

[b] Numbers for CO_2 / volume are estimated amounts of emission per unit volume of production, using CO_2 / USD million, commodity production value in USD million, and commodity production volume.

[c] Numbers for CO_2 / USD million are estimated amounts of emissions of CO_2 in kilo tonnes generated by one million U.S. dollars worth of production. Exchange rates used are 94.06 yen per U.S. dollar and 1.3724 Canadian dollar per U.S. dollar.

Table 6: CO_2 emissions per unit output: Canada and Japan, 1990[a,b]

Canada				Japan		
No	Sector (output unit)	CO_2/volume	CO_2/USD mill.	No	CO_2/volume	CO_2/USD mill.
031	Coal (1000 t)	0.02624	1.32641	038	0.09734	0.95706
033	Natural gas (million m^3)	0.09916	2.20927	040	0.10189	0.39375
322	Gasoline (1000 kl)	0.54723	2.79369	153	0.28792	0.46348
005	Wheat unmilled (1000 t)	0.12198	1.27639	002	0.29303	0.28303
008	Eggs in the shell (1000 t)	1.62231	1.27639	017	0.45099	0.28902
002	Hogs (1000 head)	0.20715	1.27639	019	0.09239	0.25052
001	Cattle and calves (1000 head)	0.36075	1.27639	020	0.24479	0.18436
020	Logs, poles, pilings (1000 m^3)	0.02684	0.75395	026	0.03397	0.20050
024	Fish and seafood, fr.,chi, (1000 t)	0.14116	1.08819	028	1.70162	1.20206
086	Sugar (1000 t)	0.85796	1.56606	059	0.69237	0.64306
037	Salt (1000t)	0.02080	1.1697	063	0.71479	4.15599
101	Beer, incl. coolers (100 kl)	0.04554	0.44291	070	0.04726	0.20213
163	Pulp (1000 t)	0.44407	1.7222	106	0.75499	1.30795
164	Newsprint paper (1000 t)	0.81938	1.71636	107	1.98989	2.19081
305	Cement (1000 t)	1.31749	11.5343	167	0.76586	12.2864
187	Ferro-alloys (1000 t)	1.19672	3.27569	177	5.25009	4.10248
195	Oil&gas casing&drill pipe 1000t	1.23780	1.38754	181	1.39212	1.71929
204	Aluminum,primary forms, 1000t	1.99672	1.33313	192	1.31781	0.82257
430	Electric power generation (gwh)	0.19601	5.43939	300	0.42540	3.4689

[a] The Canadian I-O tables do not include data on physical output for commodities. Canadian quantities used in this table were collected from the following sources: UN *Energy Statistics Yearbook*, UN *Industrial Commodity Statistics*; UN *Statistical Yearbook*, UN/FAO *Yearbook Production*, APEC *Energy Database*. The Japanese I-O tables include data on physical output for most I-O commodity sectors. They do not necessarily provide quantities for all sub-categories of commodities which constitute I-O sectors. Additional output data were collected from the following sources: UN/FAO *Yearbook Production*, Japanese Ministry of Agriculture *Japan International Statistics on Agriculture, Statistics and Fisheries*, APEC *Energy Database*; Japanese Management and Coordination Agency *Japan Statistical Yearbook*, and Japanese Ministry of Transport *Foreign Transport Statistics*.

[b] Numbers for CO_2 / USD million are estimated amounts of emissions of CO_2 in kilo tonnes generated by one million U.S. dollars worth of production. Exchange rates used are 144.79 yen per U.S. dollar and 1.1668 Canadian dollar per U.S. dollar. Numbers for CO_2 / volume are estimated amounts of emission per unit volume of production.

interpretation on the differences, not only because of changes of the CO_2 volume but also because of changes of the sectoral classifications.

Comparing the results of 1990 with those of 1995, there can be found some stable tendencies of CO_2 emission between the two countries. For example, CO_2 emissions from unit production of gasoline, eggs and cement in Japan are lower than in Canada, while CO_2 emissions from unit production of wheat, fish, salt, pulp, paper, and electric power in Canada are lower than in Japan.

If there are differences in CO_2 emission from unit volume production, we can find rooms to reduce overall CO_2 emission through re-locating production between the countries. Before we investigate it, we should evaluate that the CO_2 emissions from the international trade and the transportation are not so dominant that they cancel the CO_2 reduction achieved by re-location of production sites.

4 CO_2 emission through trade between Canada and Japan

The result of this section has already presented in Hayami, Nakamura, Asakura, and Yoshioka [1999], therefore we will show only the main results. The calculation formula employed are based on the competitive import model. And using the OECD's trade statistics, we separated the import vectors from the partner country (B) and the vectors from the rest of the world. The import vector from the country B is converted into the country B's export vector to the country A. In the country B, the export vector to the country A induces the domestic production and therefore the import from the country A. These international trade linkages are to be continued until its convergence. We have calculated the sequence of trade interactions as a trade linkage inverse matrix.[4]

This process can be described formally as follows. The countries A and B have their own sectoral classification, and we have calculated the bridge matrices $Z^{A,B}$ and $Z^{B,A}$. $Z^{A,B}$ converts the country A's export vector $ex^{A,B}$ to the country B's import vector $im^{A,B}$, and $Z^{B,A}$ converts the country B's export vector $ex^{B,A}$ to the country A's import vector $im^{B,A}$:

$$im^{A,B} = Z^{A,B} ex^{A,B}, \quad im^{B,A} = Z^{B,A} ex^{B,A}.$$

The balance system of the two countries and the rest of the world is express as follows:

$$\begin{aligned} x^A + im^{B,A} + im^{R,A} &= A^A x^A + ex^{A,B} + ex^{A,R} + fd^A \\ x^B + im^{A,B} + im^{R,B} &= A^B x^B + ex^{B,A} + ex^{B,R} + fd^B. \end{aligned}$$

Introducing the competitive import assumption, and assuming that the import demand is proportional to the domestic demand, the following equations define the import coefficient matrices.

$$\begin{aligned} im^{B,A} &= \hat{M}^{B,A}(A^A x^A + fd^A) \\ im^{R,A} &= \hat{M}^{R,A}(A^A x^A + fd^A) \\ im^{A,B} &= \hat{M}^{A,B}(A^B x^B + fd^B) \\ im^{R,B} &= \hat{M}^{R,B}(A^B x^B + fd^B). \end{aligned}$$

And the bridge matrices $Z^{A,B}$ and $Z^{B,A}$ are applied to the export vectors $ex^{A,B}$ and $ex^{B,A}$, which reduce to the following system of the equations:

$$\begin{pmatrix} I - (I - \hat{M}^A)A^A & -Z^{A,B}\hat{M}^{A,B}A^B \\ -Z^{B,A}\hat{M}^{B,A}A^A & I - (I - \hat{M}^B)A^B \end{pmatrix} \begin{pmatrix} x^A \\ x^B \end{pmatrix} = \begin{pmatrix} (I - \hat{M}^A)fd^A + Z^{A,B}\hat{M}^{A,B}fd^B + ex^{A,R} \\ (I - \hat{M}^B)fd^B + Z^{B,A}\hat{M}^{B,A}fd^A + ex^{B,R} \end{pmatrix}.$$

This system calculates how much one unit of a domestic final demand induces each countries production x^A and x^B, and the CO_2 emission matrices for each country provide the corresponding CO_2 emissions.

Table 7 shows Canada's CO_2 emissions due to Canada's exports to Japan in 1990.[5] The calculation is derived from the following equation:

$$\begin{pmatrix} x^C \\ x^J \end{pmatrix} = \begin{pmatrix} I - (I - \hat{M}^C)A^C & -Z^{C,J}\hat{M}^{C,J}A^J \\ -Z^{J,C}\hat{M}^{J,C}A^C & I - (I - \hat{M}^J)A^J \end{pmatrix}^{-1} \begin{pmatrix} ex^{C,J} \\ 0 \end{pmatrix},$$

where ^{C} denotes Canada, and ^{J} denotes Japan. CO_2 emission is calculated by $E^C x^C$.

Electric power in Canada does not export to Japan, but its CO_2 emission generated by Japanese demand for Canadian goods is relatively large in the total CO_2 emission from the Canadian export to

[4] The model is a class of the competitive import model by Chenery and Moses.

[5] We have not yet compiling the bridge matrices for 1995.

Table 7: CO_2 emissions generated by bilateral trade in Canada: Canada's exports to Japan, 1990[a]

No	Sector	Exports (USD million)	Induced output (USD million)	CO_2 (kilo tonnes)
031	Coal	693.163	697.728	599.02
163	Pulp	531.567	577.067	495.39
015	Canola and other oil seeds	444.349	461.466	256.13
305	Cement	0.000	1.411	15.350
030	Other metal ores and concentrates	805.170	899.378	204.87
204	Aluminum in primary forms	255.885	263.226	161.37
191	Flat iron&steel, incl. galv. tinplate	0.027	17.363	38.865
430	Electric power	0.000	193.575	994.22
188	Iron and steel ingots, billets, etc.	4.116	7.667	17.2
028	Iron ores and concentrates	25.959	28.238	59.259
313	Natural stone building products	1.033	1.1124	2.043
330	Fertilizers, excl. nitrogenous	43.348	72.995	88.072
150	Lumber and treated wood	750.408	787.112	90.258
360	Methyl alcohol	43.685	44.098	55.810
035	Asbestos, crude and milled	27.950	27.976	27.823
223	Flat iron and steel, alloy, other coated	0.476	3.218	7.179
372	Antifreezing preparations	0.004	1.070	1.630
032	Crude mineral oils	11.786	97.562	191.21
306	Lime	0.000	5.018	9.123
	Total	5599.331	10560.259	5439.6

[a] CO_2 emissions reported here arise from production of each sector commodity resulting from Canadian exports to Japan. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

Japan. Coal and pulp are major export commodities to Japan generate CO_2 emission, while lumber and treated wood are also major export goods with much less CO_2 emission than coal and pulp. The total CO_2 in Canada generated by Canadian exports to Japan is 5.44 million tonnes (in CO_2 equivalent). As the Canada's total CO_2 emission from the industry sectors is 353.4 million tonnes in 1990, the CO_2 emission from the exports to Japan consists of 1.5%.

On the contrary, Table 8 shows Japan's CO_2 emission due to Japan's exports to Canada. The sector with the most CO_2 emission is electric power, which generates 700 kilo tonnes of CO_2 in Japan. The calculation is derived from the following equation:

$$\begin{pmatrix} x^C \\ x^J \end{pmatrix} = \begin{pmatrix} I - (I - \hat{M}^C)A^C & -Z^{C,J}\hat{M}^{C,J}A^J \\ -Z^{J,C}\hat{M}^{J,C}A^C & I - (I - \hat{M}^J)A^J \end{pmatrix}^{-1} \begin{pmatrix} 0 \\ ex^{J,C} \end{pmatrix}.$$

CO_2 emission is calculated by $E^J x^J$.

Japanese electric power does not export to Canada at all. It is the same as the Canadian electric power. Besides electric power, coal products, ferro alloy, and self-freight transport do not export to Canada, but they generate CO_2 emission larger than from passenger car. Passenger cars export consists about 35% of the total export value to Canada from Japan, but its CO_2 emission is less than 1% of the total CO_2 emission due to Japan's exports to Canada. The total CO_2 emission in Japan due to Japan's exports to Canada is 2.83 million tonnes (CO_2 equivalent), and it is negligible comparing with the Japan's total CO_2 emission 1.08 billion tonnes of CO_2.

Findings here can be summarized as follows: The tradables do not always generate large amount of CO_2 compared to electric power and the other non traded commodities. Electric power generates relatively large amount of CO_2 due to exporting the other commodities. The total CO_2 emissions

Table 8: CO_2 emissions generated by bilateral trade in Japan: Japan's exports to Canada, 1990[a]

No	Sector	Exports (USD million)	Induced output (USD million)	CO_2 (kilo tonnes)
063	Salt	0.001	0.539	1.642
167	Cement	0.742	1.278	14.479
176	Pig iron	0.015	80.434	314.655
301	Self power generation	0.000	15.100	176.549
121	Industrial soda chemicals	1.856	17.200	19.161
175	Miscellaneous ceramics	2.512	18.016	51.043
154	Coal products	0.000	54.973	254.188
325	Ocean transport	0.000	0.050	0.068
133	Oil and fat industrial chemicals	0.000	2.926	0.927
177	Ferro alloy	0.000	8.582	23.200
324	Self-freight transport by private	0.000	20.530	29.297
153	Petroleum refinery production	0.305	99.170	39.215
326	Coastal and inland water transport	0.000	18.074	29.063
172	Other structural clay products	0.013	0.287	0.183
307	Other sanitary service (public)	0.000	0.596	1.721
300	Electric power	0.000	211.760	700.745
191	Zinc incl. regenerated zinc	0.000	9.603	9.816
107	Western and Japanese type paper	4.880	43.476	52.459
157	Tires and inner tubes	109.460	154.448	22.089
257	Passenger cars	2227.676	2222.676	21.215
	Total	6398.270	16564.405	2832.382

[a] CO_2 emissions reported here arise from production of each sector commodity resulting from Canadian exports to Japan. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

generated by the bilateral trade between Canada and Japan are small amounts compared to the total CO_2 emissions from the industry sectors.

Tables 9 and 10 show how much unit of the Japanese automobile exports generates CO_2 in Japan and in Canada. Japan produces 1,000 US dollar worth of automobile production that is about 1/10 of an average single passenger car production. It requires ocean transport to export to Canada. In Table 9, the value of ocean transport is calculated from the ocean transport output value and the export value, that is, we use the average ocean export margin. The direct effect shows CO_2 emission from the production process of passenger car and the ocean transport without considering further input-output linkage. Formally, the final demand vector of $\mathbf{f}$ is defined as follows:

$$\mathbf{f}^{J,C} = \begin{pmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0.04691 \\ \vdots \\ 0 \end{pmatrix} \begin{matrix} \\ \\ (automobile) \\ \\ (ocean\ transport) \\ \\ . \end{matrix}$$

And the direct CO_2 emissions is obtained from $\hat{\mathbf{E}}^J \, \mathbf{f}^{J,C}$. The total output value induced by domestic

Table 9: Japanese production and CO_2 emissions resulting from Canadian imports of USD 1,000 worth of Japanese automobile, 1990

Direct effect			Direct effect		
No	Sector	Output US$1,000	No	Sector	CO_2-kg
257	Passenger car	1.0000	325	Ocean transport	62.92722
325	Ocean transport	0.04691	257	Passenger car	9.52356
Total output value induced by domestic demand and trade			Total CO_2 emission induced by domestic demand and trade		
No	Sector	Output US$1,000	No	Sector	CO_2-kg
257	Passenger cars	1.00000	300	Electric power	106.17770
262	Motor vehicle parts and access	0.53466	325	Ocean transport	83.93054
261	Internal combustion engine for	0.22152	176	Pig iron	31.65077
309	Wholesale trade	0.11748	154	Coal products	29.35207
255	Electrical equipment for inter	0.08209	301	Self-Power generation	19.63334
358	Research and development(priva	0.06740	186	Cast and forged materials(iron	15.14578
260	Motor vehicle bodies	0.06725	262	Motor vehicle parts and access	11.57419
325	Ocean transport	0.06257	321	Road freight transport	10.28545
156	Plastic products	0.06100	257	Passenger cars	9.52356
311	Financial service	0.04054	153	Petroleum refinery products(in	7.01917
300	Electric power	0.03209	323	Self-Passenger transport by pr	6.47464
180	Hot rolled steel	0.02638	164	Sheet glass and safety glass	5.64517
374	Goods renting and leasing(exce	0.02409	326	Coastal and inland water trans	5.58544
382	Other business services	0.02405	180	Hot rolled steel	5.48003
377	Machine repairing	0.02356	178	Crude steel(converters)	5.31962
160	Other rubber products	0.02321	175	Miscellaneous ceramic,stone an	5.24723
186	Cast and forged materials(iron	0.02088	107	Foreign paper and Japanese pap	5.01293
321	Road freight transport	0.02062	261	Internal combustion engine for	4.91431
182	Cold-finished steel	0.02016	358	Research and development(priva	4.52891
153	Petroleum refinery products(in	0.01775	138	Thermoplastics resin	4.50226
315	Real estate rent	0.01763	126	Petrochemical basic products	4.31515
327	Transport service in harbor	0.01614	182	Cold-finished steel	4.30387
197	Non-ferrous metal castings and	0.01608	324	Self-freight transport by priv	4.22287
164	Sheet glass and safety glass	0.01507	130	Synthetic rubber	2.99657
116	Printing,engraving and book bi	0.01469	179	Crude steel(electric furnaces)	2.90390
157	Tires and inner tubes	0.01448	328	Air transport	2.49041
371	Advertising agencies	0.01408	405	Activities not elsewhere class	2.37526
231	Electric audio equipment	0.01384	308	Other sanitary services(indust	2.35077
372	Information service	0.01325	177	Ferro alloy	2.31446
252	Batteries	0.01251	128	Aliphatic intermediates	2.26295
408	Others	0.44208	408	Others	50.44436
406	Total	3.07715	406	Total	457.98368

[a] CO_2 emissions reported here arise from production activities in Japan, which is induced by Japan's passenger car production to meet Canada's demand for automobile. Total output value and CO_2 emission induced by domestic demand and trade include Japan's production activates caused by Japan's car production, to meet demand for domestic intermediate commodities and export throughout all transactions with Canada. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

Table 10: Canadian production and CO_2 emissions resulting from Canadian imports of USD 1,000 worth of Japanese automobile, 1990

Total output value through trade		Total CO_2 emission through trade	
No Sector	Output US$1,000	No Sector	CO_2-kg
278 Other motor vehicle parts	0.00018	430 Electric power	0.14937
204 Aluminum in primary forms	0.00013	163 Pulp	0.08964
163 Pulp	0.00010	204 Aluminum in primary forms	0.07978
030 Other metal ores and concentrates	0.00008	031 Coal	0.03698
026 Gold and alloys in primary forms	0.00006	191 Flat iron and steel,incl galv,tinplate	0.03356
031 Coal	0.00004	360 Methyl alcohol	0.02333
150 Lumber and treated wood	0.00004	032 Crude mineral oils	0.02066
434 Wholesaling margins	0.00004	417 Water transportation	0.01937
464 Spare parts and maint.suppl.mach ad equip	0.00004	030 Other metal ores and concentrates	0.01891
020 Logs, poles, pilings, bolts, etc	0.00003	330 Fertilizers, excl nitrogenous	0.01406
430 Electric power	0.00003	323 Diesel and fuel oil, aviation fuel	0.01381
149 Wood chips	0.00002	278 Other motor vehicle parts	0.01330
203 Zinc in primary forms	0.00002	420 Truck transportation	0.01174
357 Styrene	0.00002	359 Other hydrocarbons and derivatives	0.01094
360 Methyl alcohol	0.00002	026 Gold and alloys in primary forms	0.01067
420 Truck transportation	0.00002	164 Newsprint paper	0.01063
467 Transportation margins	0.00002	033 Natural gas	0.00984
021 Pulpwood	0.00001	188 Iron and steel ingots, billets, etc	0.00893
023 Custom forestry	0.00001	020 Logs, poles, pilings, bolts, etc	0.00862
032 Crude mineral oils	0.00001	424 Pipeline transportation	0.00802
033 Natural gas	0.00001	419 Railway transportation	0.00752
044 Services incidental to mining	0.00001	434 Wholesaling margins	0.00739
164 Newsprint paper	0.00001	190 Steel bars and rods	0.00543
191 Flat iron and steel,incl galv,tinplate	0.00001	198 Other cast iron products	0.00535
198 Other cast iron products	0.00001	326 Other liquid petroleum gases	0.00481
202 Lead in primary forms	0.00001	375 Explosives and non-military ammo.	0.00471
209 Metal scrap	0.00001	322 Gasoline	0.00461
242 Custom metal working	0.00001	150 Lumber and treated wood	0.00453
276 Motor vehicle engines and parts	0.00001	354 Ethylene	0.00447
323 Diesel and fuel oil, aviation fuel	0.00001	187 Ferro-alloys	0.00434
482 Others	0.00037	482 Others	0.13040
480 Total	0.00139	480 Total	0.77572

[a] CO_2 emissions reported here arise from production activities in Canada, which is induced by Japan's passenger car production to meet Canada's demand for automobile. Total output value and CO_2 emission through trade include Canada's exports to Japan caused by Japan's car production and Canada's production activities induced throughout all transactions between the two countries. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

demand and trade is calculated by the following formula:

$$\begin{pmatrix} x^C_{auto} \\ x^J_{auto} \end{pmatrix} = \begin{pmatrix} I-(I-\hat{M}^C)A^C & -Z^{C,J}\hat{M}^{C,J}A^J \\ -Z^{J,C}\hat{M}^{J,C}A^C & I-(I-\hat{M}^J)A^J \end{pmatrix}^{-1} \begin{pmatrix} 0 \\ f^{J,C} \end{pmatrix}.$$

The left column of Table 9 shows values of x^J_{auto} and the right column is $\hat{E}^J x^J_{auto}$.

Similarly, the left column of Table 10 shows values x^C_{auto} and the right column is $\hat{E}^C x^C_{auto}$.

Table 9 covers over 85% of the output value induced by unit automobile production and ocean transportation, and about 89% of the CO_2 emission generated by the same. Electric power consists of 23.2 % of the CO_2 emission, which is the dominant sector that generates CO_2 emission by automobile export. As the average producer price of automobile is about 10,000 US dollar, one automobile export generates about 4.58 tonnes of CO_2 in Japan.

And CO_2 emissions in Canada are presented in Table 10, which are relatively small, but again electric power is the dominant sector that generates CO_2. The total CO_2 emission in Canada due to Japan's 1,000 US dollar worth of automobile export to Canada is 0.7757 kg (CO_2 equivalent). In other words, one Japanese automobile export to Canada generates about 7.8kg of CO_2 in Canada. It is small, but it is not negligible.

Next we calculated CO_2 emission related to Canada's pulp export to Japan. Canada's pulp export to Japan generates CO_2 emission in Japan as well as in Canada. Canada's ocean transport is included in water transport, then we have to use the average value of the transportation activities required to export. As a result, the final demand vector $f^{C,J}$ is defined as follows:

$$f^{C,J} = \begin{pmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0.01359 \\ \vdots \\ 0 \end{pmatrix} \begin{matrix} \\ \\ (pulp) \\ \\ (water\ transport) \\ \\ . \end{matrix}$$

And the total output value induced by Canada's unit pulp export to Japan is calculated by the following formula:

$$\begin{pmatrix} x^C_{pulp} \\ x^J_{pulp} \end{pmatrix} = \begin{pmatrix} I-(I-\hat{M}^C)A^C & -Z^{C,J}\hat{M}^{C,J}A^J \\ -Z^{J,C}\hat{M}^{J,C}A^C & I-(I-\hat{M}^J)A^J \end{pmatrix}^{-1} \begin{pmatrix} 0 \\ f^{C,J} \end{pmatrix}.$$

The left column of Table 11 shows output values of x^C_{pulp} and the right column is $\hat{E}^C x^C_{pulp}$. Similarly, the left column of Table 12 shows values of x^J_{pulp} and the right column is $\hat{E}^J x^J_{pulp}$.

Table 11 covers 89% of the total output value in Canada induced by Canadian pulp production, and 96% of the total CO_2 emission in Canada generated by the same. CO_2 emission generated by pulp export is mostly from own pulp sector 920 kg, which is 53.4% of the total CO_2 emission. And CO_2 emission from electric power is 388 kg, which is the second most contributor. The total CO_2 emission generated by 10,000 US dollar worth of pulp production, which is nominally the same value as one automobile producer's price in Japan, is 17.2 tonnes of CO_2. Pulp export with the same output value as an automobile induces CO_2 at 3.67 times as much as an automobile.

On the other hand, pulp export to Japan stimulates Japan's export to Canada, and generates CO_2 emission in Japan. Table 12 shows how much it is. It is 0.771 kg (CO_2 equivalent), and it is about the same amount as the case of an automobile export (0.775 kg).

Table 11: Canadian production and CO_2 emissions resulting from Japanese imports of USD 1,000 worth of Canadian pulp, 1990

Direct effect			Direct effect		
No	Sector	Output US$1,000	No	Sector	CO_2-kg
163	Pulp	1.00000	163	Pulp	858.47333
417	Water transportation	0.01359	417	Water transportation	18.77791

Total output value induced by domestic demand and trade			Total CO_2 emission induced by domestic demand and trade		
No	Sector	Output US$1,000	No	Sector	CO_2-kg
163	Pulp	1.07209	163	Pulp	920.36371
149	Wood chips	0.09446	430	Electric power	388.16776
021	Pulpwood	0.08865	420	Truck transportation	31.58195
464	Spare parts and maint.suppl.mach and equip	0.08840	417	Water transportation	30.09386
430	Electric power	0.07558	032	Crude mineral oils	29.33568
434	Wholesaling margins	0.05563	021	Pulpwood	29.18842
467	Transportation margins	0.05070	323	Diesel and fuel oil, aviation fuel	26.89690
420	Truck transportation	0.04606	033	Natural gas	21.03574
020	Logs, poles, pilings, bolts, etc	0.03762	419	Railway transportation	17.04658
023	Custom forestry	0.03709	424	Pipeline transportation	15.66706
435	Repair service for mach and equip	0.02216	348	Caustic soda	13.52631
417	Water transportation	0.02177	020	Logs, poles, pilings, bolts, etc	12.94343
323	Diesel and fuel oil, aviation fuel	0.02069	023	Custom forestry	12.25323
444	Govt. royalties on nat. resources	0.01785	434	Wholesaling margins	11.71371
439	Other finance and real estate serv	0.01780	149	Wood chips	11.69195
406	Repair construction	0.01763	349	Sodium chlorate	11.07504
032	Crude mineral oils	0.01497	433	Water, waste disp. and other utilities	10.03095
419	Railway transportation	0.01357	418	Serv incidental to water transport	6.90354
443	Other rent	0.01193	341	Chlorine	5.86235
450	Professional serv to bus. management	0.01108	339	Other industrial chemical prep.	5.76928
033	Natural gas	0.01074	414	Air transportation	4.91669
348	Caustic soda	0.01069	353	Other inorganic chemicals	4.85746
469	Traveling and entertainment	0.01035	326	Other liquid petroleum gases	4.14150
470	Advertising and promotion	0.01034	435	Repair service for mach and equip	3.98385
126	Felt	0.00911	469	Traveling and entertainment	3.86320
349	Sodium chlorate	0.00875	322	Gasoline	3.77340
463	Rental, oth mach and equip incl const.	0.00875	329	Petrochemical feed stock	3.49398
428	Telephone and other telecommunications	0.00794	463	Rental, oth mach and equip incl const.	3.45924
460	Other services to business and persons	0.00765	352	Other metallic salts and peroxysalts	3.16642
437	Retailing margins	0.00753	354	Ethylene	3.05921
482	Others	0.22919	482	Others	71.13803
480	Total	2.13677	480	Total	1721.00043

[a] CO_2 emissions reported here arise from production activities in Canada, which is induced by Canada's pulp production to meet Japanese pulp demand. Total output value and CO_2 emission induced by domestic demand and trade include Canada's production activates caused by Canada's pulp production, to meet demand for domestic intermediate commodities and export throughout all transactions with Japan. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

Table 12: Japanese production and CO_2 emissions resulting from Japanese imports of USD 1,000 worth of Canadian pulp, 1990

Total output value through trade			Total CO_2 emission through trade		
No	Sector	Output US$1,000	No	Sector	CO_2-kg
157	Tires and inner tubes	0.00010	300	Electric power	0.13395
094	Other fabricated textile produ	0.00008	176	Pig iron	0.08897
180	Hot rolled steel	0.00008	325	Ocean transport	0.08095
309	Wholesale trade	0.00008	154	Coal products	0.06660
262	Motor vehicle parts and access	0.00007	301	Self-Power generation	0.05662
261	Internal combustion engine for	0.00006	125	Other industrial inorganic che	0.03277
325	Ocean transport	0.00006	121	Industrial soda chemicals	0.01944
156	Plastic products	0.00005	180	Hot rolled steel	0.01675
206	Other metal products	0.00005	178	Crude steel(converters)	0.01611
125	Other industrial inorganic che	0.00004	107	Foreign paper and Japanese pap	0.01434
216	Mining,civil engineering and c	0.00004	130	Synthetic rubber	0.01378
219	Metal machine tools	0.00004	157	Tires and inner tubes	0.01371
300	Electric power	0.00004	175	Miscellaneous ceramic,stone an	0.01131
311	Financial service	0.00004	153	Petroleum refinery products(in	0.01082
358	Research and development(priva	0.00004	126	Petrochemical basic products	0.00945
152	Other final chemical products	0.00003	321	Road freight transport	0.00867
153	Petroleum refinery products(in	0.00003	179	Crude steel(electric furnaces)	0.00848
160	Other rubber products	0.00003	186	Cast and forged materials(iron	0.00783
178	Crude steel(converters)	0.00003	323	Self-Passenger transport by pr	0.00729
182	Cold-finished steel	0.00003	177	Ferro alloy	0.00663
224	Other special industrial machi	0.00003	182	Cold-finished steel	0.00545
226	Bearings	0.00003	094	Other fabricated textile produ	0.00534
090	Yarn and fabric dyeing and fin	0.00002	090	Yarn and fabric dyeing and fin	0.00519
116	Printing,engraving and book bi	0.00002	128	Aliphatic intermediates	0.00514
121	Industrial soda chemicals	0.00002	326	Coastal and inland water trans	0.00511
126	Petrochemical basic products	0.00002	140	Other resin	0.00492
130	Synthetic rubber	0.00002	138	Thermoplastics resin	0.00470
148	Photographic sensitive materia	0.00002	127	Petrochemical aromatic product	0.00458
176	Pig iron	0.00002	324	Self-freight transport by priv	0.00457
179	Crude steel(electric furnaces)	0.00002	129	Cyclic intermediates	0.00403
408	Others	0.00102	408	Others	0.09727
406	Total	0.00226	406	Total	0.77077

[a] CO_2 emissions reported here arise from production activities in Japan, which is induced by Canada's pulp production to meet Japanese pulp demand. Total output value and CO_2 emission through trade include Japan's exports to Canada caused by Canada's pulp production and Japan's production activities induced throughout all transactions between the two countries. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

Table 13: Additional CO_2 emissions arising from no imports, 1990*

Japanese emission without imports from Canada			Canadian emission without imports from Japan		
No	Sector	CO_2 1,000t	No	Sector	CO_2 1,000t
2	wheat and barley	21.084	28	iron ores and concentrates	84.444
26	logs	36.420	32	crude mineral oils	132.522
28	coastal, off-shore, distant fishing	372.348	33	natural gas	59.393
38	coal mining	69.377	187	ferro-alloys	58.516
106	pulp	410.937	188	iron and steel ingots, billets, etc.	132.230
107	western and Japanese type paper	173.469	190	steel bars and rods	224.406
121	industrial soda chemicals	76.157	191	flat iron and steel,incl. galv.tin plate	846.813
125	other industrial inorganic chemicals	115.928	192	iron and steel railway const. mater	68.832
153	petroleum refinery products	145.871	198	other cast iron products	83.482
154	coal products	207.814	223	flat iron and steel, alloy, other coated	248.309
167	cement	66.355	259	industry specific machinery	82.438
176	pig iron	100.173	269	automobiles, incl. vans	86.899
191	zinc (inc. regenerated zinc)	45.271	276	motor vehicle engines and parts	53.690
192	aluminum (inc. regenerated alum.)	122.489	278	other motor vehicle parts	153.917
193	other non-ferrous metals	154.800	414	air transportation	70.084
300	electric power	1280.417	419	railway transportation	77.674
301	self power generation	1547.094	420	truck transportation	100.365
321	road freight transport	131.684	424	pipeline transportation	57.954
323	self-passenger transport by privat	117.774	430	electric power	903.949
324	self-freight transport by provate	360.320	434	wholesaling margins	89.953
326	coastal and inland water transport	46.846	469	traveling and entertainment	54.512
	Total	6,552.504		Total	5,341.698

[a] Numbers are estimated amounts of emissions of CO_2 in kilo tonnes generated if domestic production substitutes for imported commodities. Exchange rates used in our calculations are 144.79 yen per U.S. dollar and 1.1668 Canadian dollar per U.S. dollar. Calculations here are based on Canada's and Japan's 1990 input-output tables, and trade statistics of 1990.

It is indeed that the international trade generates CO_2 emission as described above. But if the bilateral trade has been stopped, whether CO_2 emissions over all increase or decrease? Table 13 shows the answer. We assume that Japan produces the same amount of goods domestically as the imports from Canada, and calculate additional CO_2 emission in Japan. Table 7 shows Canada's CO_2 emissions due to Japan's export. Comparing these figures, 6,553 kilo tonnes of CO_2 required in Japan, whereas Canada generates 5,440 kilo tonnes. The international trade gains 1,113 kilo tonnes of CO_2, when the productions take place in Canada rather than in Japan. The same argument can be applicable to the Japan's export to Canada. Canada generates 5,342 kilo tonnes of CO_2 replacing the imports from Japan to the domestic production. From Table 8, Japan generates 2,832 kilo tonnes of CO_2 in order to export to Canada. Again, the international trade reduces 2,510 kilo tonnes of CO_2.

The bilateral trade between the two countries implicitly reduces CO_2 emission about 3.6 million tonnes.

5 Comparison of CO_2 from photovoltaic production: an implication of investment location to joint implementation

This section investigates CO_2 emissions from production of a photovoltaic module. Photovoltaic (PV) technology is one of the most promising alternative technologies that reduce CO_2 emission for sustainable development. Our approach is a simple application of the input-output technique, comparing locations of PV production. Using the Canada's 1995 input-output tables and the Japan's 1995 input-output tables, we calculated CO_2 emission generated by production of one unit of a PV module.

Several types of PV technologies are produced at the moment, monocrystalline silicon, polycrystalline silicon, amorphous silicon, ribbon silicon, cadmium-tellurium (CdTe), $CuInSe_2$ (CIS), their thin-film types, and the hybrid types.[6] According to Photovoltaic Power Generation Technology (PVTEC), production of polycrystalline silicon cells is the most dominant in the world solar cell market. It is about 128 MW in 2000 in the world. The second most produced solar cell is monocrystalline type, which is about 90 MW. The other types of solar cells are about 60 MW, therefore polycrystalline and monocrystalline solar cells are still prevailing technology.

The data we have obtained are of polycrystalline solar cells, which are largely divided into three production processes: (1) Solar-grade Silicon (SOG-Si) production (including wafer production), (2) cell processing, and (3) module processing.[7] Table 14–16 show required materials and energy for each production processes.

We first classified these materials into the commodity classifications of the input-output tables, multiplied the commodity prices to the volumes in the tables, and obtained energy-materials vectors for the three PV processes.[8]

The figures of Table 14–16 do not include delivery costs. Then we estimated transportation margins, wholesaling margins, retailing margins and storage fee, using input-output tables. For Japanese data, the 1995 input-output tables report all these margins for each commodity by sector. For Canadian data, we use the average margin rates for each commodity.

[6] Alsema and Nieuwlaar [2000], Photovoltaic Power Generation Technology Research Association (PVTEC) [2000], and PVTEC's website http:/www.pvtec.or.jp.

[7] PVTEC [2000], and additional information from Mitsubishi electric corporation.

[8] We owe compiling the price for each materials and classifying them into the input-output tables to Mr Satoshi Nakano, Graduate school, Keio University. The price data in Japan are obtained mainly from the Japan's 1995 input-output tables. Some of the price data in Canada are from OECD International Trade by Commodities Statistics HS Rev.1 Edition 1998, and from the municipal water pricing 1991-1999. The other price data are from the price of Japanese commodity and the PPP index.

Table 14: Required materials and energy in Photovoltaic production (1): SOG-Si production

SOG-Si production(10MW)			
Silica production			
No	Item	Volume	Unit
1.1.1	Raw material		
	Silica sand for glass	462.00	t
1.1.2	Melting		
	Sodium carbonate	273.00	t
	Crude oil	172.80	kl
1.1.3	Extraction/Purification		
	Mineral acid	1050.00	t
	Limestone	960.00	t
	Electric power	439.86	MWh
	Water supply	23100.00	kl
Carbon pellet production			
No	Item	Volume	Unit
	Acetylene black	161.00	t
	Resorcinol	97.00	t
	Electric power	3370.95	MWh
	Chlorine	36.60	t
	Sodium hydroxide	21.90	t
SOG-Si production			
No	Item	Volume	Unit
1.3.1	SiO_2 Reduction		
	Argon	16.38	$1000m^3$
	Graphite nozzle	1.82	t
	Graphite electrode	9.10	t
	Electric power	2132.37	MWh
1.3.2	Carbon Removal		
	Electric power	258.93	MWh
1.3.3	Directional Solidification		
	Brick	4830.00	kg
	Electric power	441.87	MWh
Wafer production			
No	Item	Volume	Unit
	SiC grindstone	210.00	t
	Piano wire for cutting	34.00	t
	Electric power	2766.22	MWh

Table 15: Required materials and energy in Photovoltaic production (2): Cell processing

Cell processing(10MW)			
No	Item	Volume	Unit
2.1.1	Texture formation		
	Potassium hydroxide(KOH)	11.10	t
	Isopropyl alcohol(IPA)	27.30	t
	DI water	3690.00	t
	Teflon jig	0.38	t
	Electric power	80.00	MWh
2.2.1	Pn-junction formation		
	POCl3	0.59	t
	N2/O2	1.40	t
	Quartz tube	0.25	g
	Quartz holder	0.05	g
	DI water	3670.00	t
	Teflon jig	0.38	t
	Electric power	450.00	MWh
2.3.1	AR-coating		
	TPT	0.73	t
	Electric power	280.00	MWh
2.4.1	Back surface etching		
	Potassium hydroxide(KOH)	10.80	t
	Isopropyl alcohol(IPA)	26.70	t
	DI water	3610.00	t
	Teflon jig	0.38	t
	Electric power	80.00	MWh
2.5.1	Electrode formation(Back surface)		
	Screen	715.00	Unit
	Ag-Al paste	1.25	t
	N2/O2	216.07	t
	Electric power	420.00	MWh
2.6.1	Electrode formation		
	Screen	710.00	Unit
	Ag-Al paste	0.64	t
	N2/O2	384.52	t
	Electric power	420.00	MWh
2.7.1	Performance evaluation		
	Xenon lamp	6.00	Unit
	Case	70100.00	Unit
	Electric power	15.00	MWh

Table 16: Required materials and energy in Photovoltaic production (3): Module processing

Module processing(10MW)			
No	Item	Volume	Unit
3.1	Cover glass	84.5	$1000m^2$
	Aluminum frame	154	t
	Copper wire	7.72	t
	EVA	92.2	t
	PVF	12.7	t
	Aluminum Sheet	6.6	t
	Back Surface Seal	19.3	t
	Butyl rubber	9.3	t
	Electric power	188.2	MWh

Table 17: Polycrystalline silicon solar cell production (10MW) in Canada 1995

				Canadian dollar
No	Sector	SOG-Si	Cell	Module
031	Crude mineral oils	19,503		
042	Stone and silica sand for ind. use	11,071		
113	Other plastic products		507	1,757,543
182	Carbon and graphite products	55,429		
192	Aluminum, other primary forms		1,423,761	
195	Other inorg. bases and metal. oxides		2,185	
197	Aluminum and alum.alloy fabricated mat.		268,723	786,769
213	Other metal end products		3,305	
214	Iron and steel wire and cable	641,164		
282	Wire and cable insulated excl. alum.			45,276
285	Electric light bulbs and tubes		554	
293	Refractory products	4,944		
299	Glass and other glass products		172,832	4,024,336
302	Abrasive products	1,782,058		
312	Ethylene polymers			869,343
322	Chlorine	7,189		
323	Oxygen		96,494	
325	Other chemical elements	21,005		
326	Sulphuric acid	58,590		
329	Caustic soda	7,295		
332	Sodium carbonate	54,484		
334	Other inorganic chemicals		154,973	
342	Other alcohols and derivatives		38,824	
344	Other phenols	132,617		
347	Other organic chemicals		43,184	
349	Carbon	179,130		
351	Synthetic rubber			87,689
399	Truck transportation	10,187	7,099	23,676
409	Electric power	274,515	50,905	5,490
412	Water and other utilities	10,890	15,273	
413	Wholesaling margins	168,551	117,448	391,737
416	Retailing margins and service	926	645	2,152
422	Other rent	20,374	14,197	47,353
444	Transportation margins	29,635	20,650	68,877
	Subtotal	3,488,872	2,431,040	8,108,606
	Total			14,028,518

The polycrystalline silicon solar cell production vectors used are presented in Tables 17–18. In SOG-Si production, abrasive products are the most significant cost share of inputs, in Cell processing, aluminum, and in Module processing, glass, in Canada. In Japan, aluminum and glass are the most significant cost share of the inputs for Cell and Module, but electric power rather than abrasive products is the heaviest cost in SOG-Si production.

From Tables 17–18, we can calculate unit capacity cost of PV production. Table 19 shows the unit capacity cost of PV production in both of the countries. Our estimation shows that the overall material and energy costs of PV per Watt are 1.19 US dollar/W. This unit cost is calculated from estimation for the Japanese PV production cost, and we adjusted the exchange rate of the Canadian material and energy prices that are not directly available, to obtain the same PPP cost between the two countries. If we use the actual exchange rate of 1995, the nominal values of Canadian input vectors are higher than expected.

We should compare the estimated 1.19 US dollar cost of production per Watt with overall mate-

Table 18: Polycrystalline silicon solar cell production (10MW) in Japan 1995

Million yen

No	Sector	SOG-Si	Cell	Module
030	Materials for ceramics limest	2.942		
035	Crude petroleum Natural gas	2.068		
113	Industrial soda chemicals	13.448		
114	Inorganic pigment	19.036		
115	Compressed gas and liquidised gas	2.233		
115	Compressed gas and liquidised gas		10.114	
117	Other industrial inorganic chemical	8.360	19.336	
120	Aliphatic intermediates		6.555	
121	Cyclic intermediates	14.103		
122	Synthetic rubber			9.300
127	Other industrial organic chemical		4.580	
129	Thermoplastics resin			92.200
146	Plastic products		54.600	186.700
154	Sheet glass and safety glass			426.817
156	Other glass and glass products		18.330	
161	Clay refractories	1.057		
163	Carbon and graphite products	5.880		
164	Abrasive	189.000		
181	Aluminum(inc.regenerated)		151.000	
183	Electric wires and cables			4.799
186	Rolled aluminum products		28.500	103.092
196	Other metal products	68.000	0.351	
243	Electric bulbs		0.059	
290	Electric power	197.615	36.642	3.952
294	Water supply		10.970	
295	Industrial water supply	1.155		
299	Wholesale trade	71.755	38.010	135.809
300	Retail trade	0.705	2.414	2.813
308	Railway freight transport	0.322	0.126	0.168
311	Road freight transport	17.709	6.627	25.173
315	Coastal and inland water trans	5.541	0.675	1.849
316	Transport service in harbor	0.692	0.301	1.421
317	Air transport	0.001	0.007	
318	Railway forward	1.547	0.316	1.206
319	Storage facility service	8.127	1.628	3.677
	Subtotal	631.296	391.244	998,977
	Total			2,021.517

Table 19: Comparing material and energy costs of PV production (10MW) in 1995

Unit material cost of PV : per watt at peak (/Wp)

	Canada			Japan		
	Canadian dollar	US dollar		yen	US dollar	
		Exchange rate	PPP		Exchange rate	PPP
	CA$/Wp	$/Wp	$/Wp	¥/Wp	$/Wp	$/Wp
SOG-Si	0.35	0.25	0.30	63.1	0.67	0.37
Cell	0.24	0.18	0.21	39.1	0.42	0.23
Module	0.81	0.59	0.69	99.9	1.06	0.59
Total	1.40	1.02	1.19	202.1	2.15	1.19

The exchange rates used are 1.3724 Canadian dollar per US dollar, 94.06 yen per US dollar.
PPPs for GDP used are 1.18 Canadian dollar per US dollar, and 170 yen per US dollar.
PPP for GDP is from OECD *National accounts of OECD countries: main aggregate*, vol. 1, 2001.

Table 20: Average price and cost of PV systems in Japan

	Residential use (3kW standard)[a]		
	Manufacturing cost	Module price	System installed price
1995	¥189/W[b]	¥800/W	¥1,433/W
2000	¥140/W	¥590/W	¥ 873/W
	System installed price[a]		Solar cell price[a]
	Public facility use (10kW standard)	Industry use (Standard system)	from sales value divided by volume
1995	¥280/W		¥860/W
1999	¥150/W	¥108/W	¥650/W
	poly-Si[c]	Hybrid of mono-Si and a-Si[c]	
1999	¥458/W	¥476	

Sources:

[a]: PVTEC website http//www.pvtec.or.jp/data.html.htm

[b]: Estimated using the module price and the overall material cost of 2000.

[c]: NEDO [2000].

rial and energy costs of the other PV systems. Our estimate of the overall material and energy cost of a PV system is ¥202/W in Japan. Table 20 shows that the average manufacturing cost of residential PV systems was ¥189/W in 1995. For the other PV systems such as public facility use, and industry use, the manufacturing cost is not available, but it should be not so different from the cost of the residential system. The manufacturing cost accounts 16% of the system installed price. The manufacturing cost includes direct labour cost, depreciation, and taxes, which are not included in our material and energy costs. Therefore, our estimated system is more expensive than the average unit cost of PV production described in Table 20.

Payne, Duke, and Williams [2001] estimated production costs of PV systems, and obtained that the sum of the material costs, energy and utilities costs is 0.28 US dollar/Watt at peak (Wp) for a rigid module (using glass).[9] Their estimation of the module sales price is 1.55 US dollar per Wp, which is about 1/4 of the prevailing price in 2002. The prevailing sales price was US$ 6.1 per Wp in June 2002 (from www.solarbuzz.com). Using the proportion of their material and energy costs over the sales price, we can show that the sales price estimated is about 6.59 US dollar per Wp, when the material, energy and utility costs are US$ 1.19 as in this case.[10] PV sales price per Wp in 1995 was about US$ 6/Wp, and cheaper than US$ 6.59/Wp.

Because the unit price of the evaluated PV system is higher than the average price in both of the countries, CO_2 emissions from the system should be higher than the average. Tables 21 and 22 present direct and indirect CO_2 emissions of PV module production. The tables are sorted by the total volume of CO_2 generated by the three processes. CO_2 from electric power is the most dominant sector in both Canada and Japan. Especially for Japan CO_2 from electric power and self-power generation is over half of the CO_2 emission from PV production. The second largest contributor of CO_2 is glass sector. In Canada, 87.3% of the total CO_2 emission from PV production are generated by the above listed 40 sectors, and in Japan 97.7% of the total CO_2 emission are from the 40 sectors. Japan's CO_2 emissions are more concentrated to smaller numbers of sectors.

The total CO_2 emissions in Japan is 13,574 CO_2-tonnes, which is 37.8% larger than 9,847 CO_2-tonnes in Canada. Difference of CO_2 per kWh production of electric power between Canada and

[9]See Payne, Duke, and Williams [2001] Table 1 at page 791, or Table 2 at page 792.

[10]Our calculation is based on the 10MW PV plant, and we assume that total solar cells produced have the same capacity Watt at peak as the plant capacity, but see notes of Table 24.

Table 21: CO_2 emission from PV production, Canada, 1995

Unit: CO_2 kg per 10MW

No.	Sector	SOG	Cell	Module	Total
409	Electric power	1,188,214	392,163	561,067	2,141,444
299	Glass and other glass products	2,688	46,746	1,047,006	1,096,440
192	Aluminum in primary forms	3,480	482,475	8,987	494,942
302	Abrasive products	462,681	115	372	463,168
179	Flat iron and steel	92,381	64,904	230,885	388,170
113	Other plastic prod. and rubber end prod.	1,406	1,211	341,688	344,305
31	Crude mineral oils	99,473	48,155	165,220	312,848
399	Truck transportation	66,101	47,783	155,474	269,358
312	Polymers	5,428	3,626	259,641	268,695
197	Aluminum and aluminum alloy fabricated materials	4,163	60,745	179,053	243,961
286	Cement	52,770	40,002	134,230	227,002
349	Carbon	205,187	984	3,235	209,406
32	Natural gas	42,270	32,261	104,690	179,221
413	Wholesaling margins	42,207	29,353	99,808	171,368
214	Iron and steel wire and cable	161,534	1,189	4,000	166,723
403	Pipeline transportation	39,343	26,870	84,797	151,010
304	Diesel and fuel oil	37,143	27,557	85,907	150,607
303	Motor gasoline	28,704	22,288	73,261	124,253
335	Ethylene	29,578	16,528	76,566	122,672
323	Oxygen	1,956	111,409	5,052	118,417
398	Railway transportation	20,132	14,561	47,331	82,024
178	Reinforcing bars and rods	20,070	13,906	47,518	81,494
29	Other metal ores and concentrates	14,114	31,425	34,933	80,472
307	Liquid petroleum gases	16,310	12,906	42,083	71,299
446	Traveling and entertainment	16,557	10,983	40,039	67,579
7	Fluid milk	15,741	9,922	39,123	64,786
393	Air transportation	15,091	10,143	36,184	61,418
310	Petrochemical feed stock	14,090	9,081	25,697	48,868
334	Deuterium oxide	498	42,496	1,287	44,281
309	Asphalt compound and other asphalt products	9,584	7,584	24,706	41,874
27	Iron ores and concentrates	8,448	6,647	21,779	36,874
344	Other phenol	34,632	77	255	34,964
305	Lubricating oils and greases	7,934	6,242	20,350	34,526
412	Water and other utilities	8,419	7,950	15,287	31,656
15	Canola	7,233	5,713	18,667	31,613
156	Other paper	7,231	5,389	18,402	31,022
422	Other rent	7,308	5,018	17,423	29,749
329	Caustic soda	12,584	3,373	10,977	26,934
159	Paperboard	6,066	4,244	15,931	26,241
351	Synthetic rubber	693	545	24,389	25,627
	Subtotal	2,809,442	1,664,569	4,123,300	8,597,311
	Total	3,141,114	1,891,306	4,814,916	9,847,336

Using the PV production vectors $\mathbf{f}_{PV}=\mathbf{f}_{SOG}$, $\mathbf{f}_{cell}$, and $\mathbf{f}_{module}$ in Table 17, we calculated $\mathbf{x}_{PV}=(\mathbf{I}-(\mathbf{I}-\hat{\mathbf{M}})\mathbf{A})^{-1}\mathbf{f}_{PV}$, and $\hat{\mathbf{E}}\mathbf{x}_{PV}$ for CO_2 emission. The calculation is based on the 1995 Canadian input-output tables.

Subtotal denotes total of the above 40 sectors.

Table 22: CO_2 emission from PV production, Japan, 1995

Unit: CO_2 kg per 10MW

No.	Sector	SOG	Cell	Module	Total
290	Electric power	4,705,751	1,190,138	869,623	6,765,512
154	Sheet glass and safety glass	501	301	1,359,291	1,360,093
291	Self-Power generation	288,570	302,714	543,166	1,134,450
144	Coal products	323,906	140,873	160,196	624,975
181	Aluminum(inc.regenerated)	3,872	336,184	40,830	380,886
129	Thermoplastics resin	1,690	19,685	303,813	325,188
311	Road freight transport	81,152	44,301	135,449	260,902
113	Industrial soda chemicals	102,162	26,499	79,121	207,782
120	Aliphatic intermediates	9,655	46,709	99,515	155,879
143	Petroleum refinery products(in	36,403	21,911	84,862	143,176
315	Coastal and inland water trans	68,757	20,214	51,319	140,290
312	Self-Passenger transport by pr	41,870	25,464	66,988	134,322
165	Miscellaneous ceramic+stone	79,608	16,923	37,629	134,160
164	Abrasive	132,432	28	99	132,559
117	Other industrial inorganic che	33,788	67,861	10,608	112,257
118	Petrochemical basic products	7,682	10,387	89,474	107,543
313	Self-freight transport by priv	28,791	15,231	55,507	99,529
166	Pig iron	60,088	7,847	23,180	91,115
121	Cyclic intermediates	38,497	5,525	44,736	88,758
156	Other glass and glass products	988	76,364	4,705	82,057
186	Rolled aluminum products	965	17,136	61,937	80,038
146	Plastic products	1,115	16,047	56,428	73,590
298	Other sanitary services(indust	25,773	9,504	27,723	63,000
114	Inorganic pigment	57,772	778	3,984	62,534
127	Other industrial organic chemi	8,927	15,571	24,705	49,203
100	Foreign paper and Japanese pap	19,584	6,918	22,333	48,835
111	Ammonia	15,576	13,147	18,651	47,374
122	Synthetic rubber	2,991	1,141	42,057	46,189
119	Petrochemical aromatic product	18,623	3,658	23,284	45,565
317	Air transport	11,934	7,695	21,478	41,107
299	Wholesale trade	9,237	6,818	17,923	33,978
157	Cement	13,767	4,191	9,014	26,972
131	Other resin	745	4,831	17,074	22,650
163	Carbon and graphite products	12,320	6,971	1,046	20,337
101	Paperboard	5,980	4,051	10,038	20,069
99	Pulp	7,182	3,088	9,308	19,578
116	Salt	10,325	2,401	6,384	19,110
30	Materials for ceramics limest	5,168	618	12,936	18,722
196	Other metal products	16,352	272	1,488	18,112
310	Hired car and taxi transport	4,823	2,915	8,816	16,554
	Subtotal	6,295,322	2,502,910	4,456,718	13,254,950
	Total	6,415,646	2,566,109	4,592,172	13,573,927

Using the PV production vectors $\mathbf{f}_{PV}$=$\mathbf{f}_{SOG}$, $\mathbf{f}_{cell}$, and $\mathbf{f}_{module}$ in Table 17, we calculated $\mathbf{x}_{PV}=(\mathbf{I}-(\mathbf{I}-\hat{\mathbf{M}})\mathbf{A})^{-1}\mathbf{f}_{PV}$, and $\hat{\mathbf{E}}\mathbf{x}_{PV}$ for CO_2 emission.The calculation is based on the 1995 Japanese input-output tables.

Subtotal denotes total of the above 40 sectors.

Table 23: CO_2 evaluation of the other PV systems

	Rooftop residential use PV system (irradiation 1427kWh/m^2/yr)[a]					
	poly-Si 10MW		a-Si 10MW		CdS/CdTe 10MW	
SOG-Si	664	g-CO_2/W		g-CO_2/W		g-CO_2/W
Cell	411	g-CO_2/W	554	g-CO_2/W	429	g-CO_2/W
Module	359	g-CO_2/W	488	g-CO_2/W	521	g-CO_2/W
Total	1,434	g-CO_2/W	1,042	g-CO_2/W	950	g-CO_2/W
CO_2	71.5	g-CO_2/kWh	59.0	g-CO_2/kWh	51.3	g-CO_2/kWh
EPT	2.4	year	2.2	year	1.7	year
	Rooftop residential use PV system (irradiation 1700kWh/m^2/yr)[b]					
	mc-Si, IEA		mc-Si, 1999		Thin film, 1999	
CO_2	87	g-CO_2/kWh	60	g-CO_2/kWh	50	g-CO_2/kWh
EPT			3.3	year	2.7	year

Source:

[a]: Photovoltaic Power Generation Technology Research Association [2000]. The CO_2 estimations are based on the 1990 input-output tables. Duration of the system is assumed 20 years, system output coefficient (system performance ratio) is 0.81, and module efficiency is 11.9% for poly-Si, 8.0% for a-Si, 10.3% for CdS/CdTe. System capacity is 3,502 W for poly-Si, 2,385 W for a-Si, and 3,066 W for CdS/CuTe. Array area is 29.4 m^2 for poly-Si, 29.8 for a-Si, and 29.8 for CdS/CuTe.

[b]: Alsema and Nieuwlaar [2000]. Duration of the system is assumed to be 30 years, module efficiency is 13% for multicrystalline silicon, 7% for thin film, system performance ratio is 0.75.

EPT: Energy payback time.

Japan is the main reason of CO_2 emission from PV production. CO_2 emission from Japan's electric power (including self-power generation) is 7,900 CO_2-tonnes, and CO_2 from Canada's electric power is 2,141 CO_2-tonnes. The difference is 5,759 CO_2-tonnes, and this overtakes the total CO_2 difference of 3,727 CO_2-tonnes.

Comparisons with the other existing researches show that our CO_2 evaluation of PV system is within the range of the existing studies. Table 23 is from Photovoltaic Power Generation Technology Research Association (PVTEC) [2000] and Alsema and Nieuwlaar [2000]. Poly-Si system studie by PVTEC is comparable to the evaluation for our Japanese PV production in Table 24. Poly-Si system of PVTEC is 1,434 g-CO_2/W, compared to 1,357 g-CO_2/W in our estimation.

If we assume the same capacity, efficiency and duration as the PVTEC's poly-Si, the resulting CO_2 per power generation kWh is 68.1 g-CO_2/kWh for the PV system produced in Japan, and 51.9 g-CO_2/kWh for the PV system produced in Canada. Several reasons exist for the difference between our estimation and PVTEC's poly-Si; the difference of CO_2 emission factor (PVTEC uses the 1990 input-output tables for CO_2 emission), and the difference of volume and prices adopted (we have modified volumes and prices from the inforamtion of Mitsubishi electric corportaion). But the difference is relatively small, when we compare it with CO_2 emission from PV production in Canada. CO_2 generated by poly-Si produced in Canada (51.9 g-CO_2/kWh) is almost the same as CO_2 by CdS/CuTe (51.3 g-CO_2/kWh).

6 Concluding remarks

This paper examined three facts related to CO_2 emission between Canada and Japan, using the input-output tables of the same year and similiarily detailed classifications. Firstly, we have identified differences and simiralities of CO_2 emission generatated by unit producition. Canada's electric

Table 24: Comparison of CO_2 evaluation of PV system between the two countries

	Canada poly-Si 10MW		Japan poly-Si 10MW	
SOG-Si	314	g-CO_2/W	642	g-CO_2/W
Cell	189	g-CO_2/W	257	g-CO_2/W
Module	481	g-CO_2/W	459	g-CO_2/W
Total	985	g-CO_2/W	1,357	g-CO_2/W
CO_2 [a]	42.6	g-CO_2/kWh	58.8	g-CO_2/kWh
CO_2 from BOS[b]	9.3 g-CO_2/kWh			

Calculated from Tables 17 and 18.

[a]: The assumptions are the same as for poly-Si in Table 23. Duration of the system is assumed 20 years, system output coefficient is 0.81, and module efficiency is 11.9%, system capacity is 3,502 W, array area is 29.4 m^2.

Irradiation, array area, system output coefficient, module efficiency, and duration provide the lifetime power generation for the system. $1{,}427 \times 0.81 \times 0.119 \times 29.4 = 4{,}044$ kWh/yr $\times$ 20 yr.

System capacity required and unit CO_2 emission per W provides the lifetime CO_2 emission.

[b]: CO_2 from BOS is from PVTEC [2000] Table 1.1.23 at page 33.

power generation has directly and indirectly lower CO_2 emission than Japan's. It was Canadian 165 (CO_2-g/kWh) vs Japanese 379 (CO_2-g/kWh) in 1995, and Canadian 196 (CO_2-g/kWh) vs Japan 425 (CO_2-g/kWh) in 1990. But it is electric generation for both of the countries that emits the second most CO_2 per one dollar worth of production, i.e. the largest contributor of CO_2 emission per unit production except cement. The ranking order of sectors on CO_2 emission per one dollar worth of prodcution is quite alike between the two countries.

Secondly, we have calculated CO_2 through the bilateral trade between the countries. If trade generates excessive CO_2 emission, the most easiest way to reduce the global CO_2 emisson is to reduce the interantional trade. But according to our calculation for the bilateral trade, the result is contrary. The interantional trade between the two countries implicitly reduces CO_2 emission, comparing to no-trade between the two. This result suggests that relocating production still has room to improve the global CO_2 emission using the joint-implimentation mechanism.

Finally, our forcus is on location for photovoltaic cell, which will reduce the global CO_2 considerably. There are many industry relocations through direct investments even under the floating exchange rate, though it is politically difficult to relocate existing industry. But it is quite possible to choose plant location internationally, if the technology is not matuared or not exists at all.

In advance of the actual mass production of photovoltaic cells, the production location should be carefully chosen on account of reducing the global CO_2 emission. Our estimate suggests that Canadian photovoltaic production can reduce CO_2 emission more effectively than Japanese production. Because CO_2 emission from electric power in Japan is considerably higher than in Canada. At the first stage, Canadia produces photovoltaic cells and exports to Japan. As a result, at the second stage, Japan's electric power can reduce CO_2 emission using Canadian photovoltaic. After reducing Japan's CO_2 from electric power, Japan can produce photovoltaic cells efficiently in terms of CO_2, because Japan's other industry sectors have less CO_2 emission as our estimation suggests.

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