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An overview of energy consumption of the globalized world economy

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ABSTRACT

For the globalized world economy with intensive international trade, an overview of energy consumption is presented by an embodied energy analysis to track both direct and indirect energy uses based on a systems input–output simulation. In 2004, the total amounts of energy embodied in household consumption, government consumption, and investment are 7749, 874, and 2009 Mtoe (million tons of oil equivalent), respectively. The United States is shown as the world's biggest embodied energy importer (683 Mtoe) and embodied energy surplus receiver (290 Mtoe), in contrast to China as the biggest exporter (662 Mtoe) and deficit receiver (274 Mtoe). Energy embodied in consumption per capita varies from 0.05 (Uganda) to 19.54 toe (Rest of North America). Based on a forecast for 2005–2035, China is to replace the United States as the world's leading embodied energy consumer in 2027, when its per capita energy consumption will be one quarter of that of the United States.

1. Introduction

In the times of globalization, international trade is playing a more and more significant role in shaping the world energy profile by redistributing the energy embodied in industrial products in the economy. Associated with the commonly perceived direct use of energy by country or region (see, e.g., EIA, 2010; IEA, 2010a, b; WB, 2010), between the countries or regions there are network connections as energy flows embodied in the commodity flows as the total energy costs. As traditional analyses are usually focusing on direct energy use, the leakage effects associated with indirect energy use at the global scale are overlooked. Accordingly, a systems analysis of the embodied energy flows to track both direct and indirect energy uses can provide a novel perspective for the global energy issue via taking the overlooked effects into account.

While country-specific analyses have been distinctively made to investigate the energy embodied in final demand for many countries based on different data sources (e.g., Chung et al., 2009; Howdon and Pearson, 1995; Kahrl and Roland-Holst 2008; Liang et al., 2007; Liu et al., 2009; Liu et al., 2010; Machado et al. 2001; Park and Heo, 2007), a global overview of energy use necessitates revealing the energy consumption embodied in all the total output rather than only in final demand of different countries or regions in the globalized world economy based on a consistent basis: firstly, a collective and consistent investigation facilitates the binding commitment of international cooperation for energy conservation as well as related carbon emission mitigation (Chen and Chen, 2011b); secondly, the internationally comparable results also provide a quantitative basis for specific countries to adjust energy use pattern and international trade structure to enhance national energy security (Xia et al., 2011); and the last but not least, equal attention should be paid to energy uses embodied in consumer goods and intermediate products as a significant fraction of the internationally traded commodities are used as intermediate products instead of consumer goods (Chen et al., 2010a).

Embodied energy analysis was originated in systems ecology (Odum, 1953; Odum, 1971) and has been extensively employed to analyze energy transformation in various ecological systems, including economies of different scales (Costanza, 1980; Odum, 1983, 1994). Concrete embodied energy analysis should be constructed on the basis of the thorough understanding of the concerned system's structure. For the macro-scale economy (e.g., the world or some specific nations), the comprehensive embodied analysis can be effectively performed with the aid of economic input–output tables which models the economic network structure of intra- and international trade explicitly. Recently, a systems input–output simulation framework supported by multi-region and multi-scale databases has been constructed to analyze the embodiments of energy and/or other concerned ecological endowments for the global, national, and/or regional economies as well as for the industrial sectors and products (Chen, 2011; Chen and Chen, 2010a, b, c, 2011a, b; Chen and Zhang, 2010; Chen et al., 2009, 2010a, b, 2011; Zhang and Chen, 2010; Zhou, 2008). The present study provides an application as well as extension of the systems input–output simulation framework to the energy consumption of the multi-regional world economy for the first time.

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For the globalized world economy, conducted in this paper is a 112-region (94 nations/districts and 18 supra-national regions), 57-sector coupled systems input–output simulation for energy consumption in 2004. With the obtained direct and embodied energy inventories, the energy consumption by different economic activities, e.g., household consumption, investment, and interregional trades, is investigated. The equality issue is studied by analyzing per capita consumptions of embodied energy by different population groups. And finally, the results are extended for the period of 2005–2035 to reveal the general trend of embodied energy consumption for ten highlighted regions.

2. Method and data

The systems ecological method, i.e., systems input–output simulation, followed in this study processes the calculation based on the physical input–output balance to reveal embodied ecological endowment in all the economic flows including but not limited to final demand (Chen et al., 2010a; Costanza, 1980; Odum, 1983; Zhou, 2008).

The preliminary task of the systems input–output simulation is to compile an input–output table integrating concerned economic and ecological flows, which illustrates the economic network structure and the resources/emission endowment of the target system. Presented in Table 1 is a schematic integrated input–output table for energy analysis, in which each entry stands for an individual sector from the world economy, n the total entry number, $t_{i,j}$ the monetary value of goods sold by Entry i as intermediate input to Entry j, d_i the monetary value of goods from Entry i used as final demand, o_i the monetary value of total output of Entry i, f_i the amount of primary energy input to Entry i, f_d the amount of primary energy input to household, and f_o the total amount of primary energy input.

The input–output balance in terms of embodied energy flows for Entry i can be formulated as

$$f_i+\sum_{j=1}^{n}\varepsilon_j t_{j,i}=\varepsilon_i o_i, \tag{1}$$

where ε_i and ε_j denote the embodied energy intensities of goods from Entries i and j, which imply the average amounts of direct plus indirect energy uses in the supply chains to produce one unit of goods by corresponding entries. Then for all the n entries a compact matrix equation is obtained as

$$F+ET=EP, \tag{2}$$

in which $F=[f_i]_{1\times n}$, $E=[\varepsilon_i]_{1\times n}$, $T=[t_{i,j}]_{n\times n}$, and $P=[p_{i,j}]_{n\times n}$ where $i,j\in(1,2,\ldots,n)$, $p_{i,j}=o_i$ $(i=j)$, and $p_{i,j}=0$ $(i\neq j)$. With properly given direct energy inventory (F), trade flow between entries (T), and total sectoral output (P), the embodied energy intensity can be obtained as

$$E=F(P-T)^{-1}. \tag{3}$$

Table 1
A schematic input–output table integrating monetary flow and primary energy input.

From\to		Entry purchase			Final demand	Total
		1	…	n		
Entry sale	1	$t_{1,1}$		$t_{1,n}$	d_1	o_1
	…					
	n	$t_{n,1}$		$t_{n,n}$	d_n	o_n
Direct energy input		f_1		f_n	f_d	f_o

Introduce the direct energy intensity $f=FP^{-1}$ and technology coefficients matrix $A=TP^{-1}$, with the identity matrix I we have the Leontief Inverse Matrix expression of embodied intensity as

$$E=f(I-A)^{-1}. \tag{4}$$

Finally, energy embodied in any particular process can be calculated as

$$X=EY+Z, \tag{5}$$

where Y is a vector showing commodity input and Z the energy input during the concerned process.

Different to the direct energy input (DEI) into the local economic sectors, energy embodied in consumption (EEC) is considered as the energy footprint (Ferng, 2003) by the consumption of residents, enterprises, and the government. As an indicator to measure the difference between EEC and DEI, the concerned energy embodied in trade balance (EEB) can also be determined according to the traded embodied energy fluxes of energy embodied in import (EEI) and export (EEE): an economy receives positive EEB (embodied energy surplus) when its EEI exceeds EEE, and receives negative EEB (embodied energy deficit) vice versa. The indicators of EEB, EEI, and EEE quantitatively reflect the separation between production and consumption. In order to describe the imbalance between DEI and EEC, we define energy imbalance ratio (EIR) as the ratio of EEB over DEI, which is of significance to the energy trading structure of a concerned region: larger EIR implies larger net import of embodied energy and thus the region can share larger energy welfare with less domestic energy input.

The Global Trade Analysis Project (GTAP) dataset (Version 7 Interim Release 2) is applied as the basis for the global economic input–output table for 2004 (Narayanan and Walmsley, 2008). The interregional trade flows from the GTAP dataset are disaggregated (Davis and Caldeira, 2010; Miller and Blair, 2009) to obtain the inter-sectoral input–output details (T and P in formula (3) and Y in formula (5)). With each sector in each region taken into account as an independent entry in the globalized world economy, the simulated network for this study has 6384×6384 trading flows. The accounted energy sources (F in Formula (3) and Z in Formula (5)) include coal, crude oil, natural gas, hydropower, and nuclear power, which sum up to 10 632 Mtoe (million tons of oil equivalent), corresponding to about 90% of the global primary energy consumption in 2004 (IEA, 2006; EIA, 2007; WB, 2010). The fossil energy data are also obtained from the GTAP dataset (Narayanan and Walmsley, 2008) while the hydropower and nuclear power data are estimated according to the electricity production data extracted from the World Bank (WB) dataset (WB, 2010). Hydroelectricity and nuclear electricity production efficiencies are assumed to be 90% and 33%, respectively, according to Zhou (2008). Besides, the primary energy consumption estimations for the world and for ten highlighted regions from 2005 to 2035 are adopted from the United States Energy Information Administration (EIA) statistics (EIA, 2010). Finally, the population data applied in this study are obtained from the GTAP dataset item "Population", which are compiled from the WB dataset to provide populations for the 112 regions in 2004 (Narayanan and Walmsley, 2008; WB, 2010).

Several issues regarding the GTAP dataset were broadly discussed in previous studies. Though the economic statistics are not always the latest available owing to the voluntary nature of data contribution and the contributed data are usually manipulated to satisfy the requirement for general computable equilibrium modeling (Hertwich and Peters, 2009; Peters, 2007), the GTAP dataset has attracted extensive concerns because of its broad coverage of both regions and sectors. Even if the uncertainty induced by the application of the GTAP dataset "is impossible to quantify" (Davis and Caldeira, 2010), this unique dataset has been widely adopted for global economic as well as environmental analyses (Chen et al., 2010a; Chen and Chen, 2011b; Davis and Caldeira, 2010; Hertwich and Peters, 2009; Peters and Hertwich, 2008), and the data treatment process in the present study is consistent with those in the latest studies (Chen et al., 2010a; Chen and Chen, 2011b; Davis and Caldeira, 2010).

3. Results and discussion

According to the input–output formulae and data sources provided in Section 2, the energy consumption of the 112 regions is calculated and corresponding results and discussion are presented in this section.

3.1. Regional energy inventory and interregional trade

According to the results (see Appendix A), there are 77 regions with positive EEBs and other 35 with negative ones. Meanwhile, the absolute value of regional EEB exceeds 10% of its DEI for 94 regions, exceeds 50% for 41 regions, and exceeds 100% for 24 regions. The picture of real energy consumption in terms of EEC is shown strikingly different from that of nominal energy use in terms of DEI.

For the global economy as a whole, the amounts of energy embodied in (the products used for) household consumption of non-fuel goods, household consumption of fuels, government consumption, and investment are 6658, and 2009 Mtoe, respectively. Conventional analyses on household energy consumption usually focused on the direct energy use by residents (Zhang et al., 2009). However, the present results indicate that the direct energy use is less than one-sixth of the household embodied energy consumption at the global scale. The final demand category of investment also attracts special attention because a considerable fraction of investment is used for production (Peters and Hertwich, 2008). It is interesting to find that several regions in Asia, especially those covered in the "East Asia Culture Sphere" (China, Japan, Korea, Vietnam, etc.), have notably higher fractions of energy embodied in investment (normalized by EEC), which implies a significant influence of their higher saving preference.

The United States (683 Mtoe), Germany (290 Mtoe), and Japan (265 Mtoe) have the world's largest EEIs in 2004, while China (mainland) (534 Mtoe), the United States (394 Mtoe), and Russia (268 Mtoe) have the largest EEEs. Accordingly, the United States is the world's largest net embodied energy importer (with EEB of 290 Mtoe) and China (mainland) turns out to be the largest net embodied energy exporter (with EEB of −271 Mtoe). Besides, the global energy embodied in trade (EEI or EEE) is 4395 Mtoe, but less than 30% of this amount is used to satisfy final demand directly while more than 70% is for production. Evidently, a partial account of energy embodied in final demand cannot give a complete picture of the global embodied energy balance.

Shown in Fig. 1 are the major interregional embodied energy fluxes. The United States, the European Union, and China (Macau is excluded due to data limitation) are shown as the world's dominant trading centers in terms of embodied energy. However, EEEs from China to the United States (149 Mtoe) and to the European Union (139 Mtoe) are about five times in magnitude of those EEIs in opposite directions as counterparts (31 and 30 Mtoe). As the economic trade imbalances in terms of currency between China and the two regions are relatively much smaller (exports from China to the United States and the European Union are $228 billion and $224 billion while corresponding imports are $128 billion and $84 billion according to the GTAP dataset), the higher nominal embodied energy intensity (ratio of energy

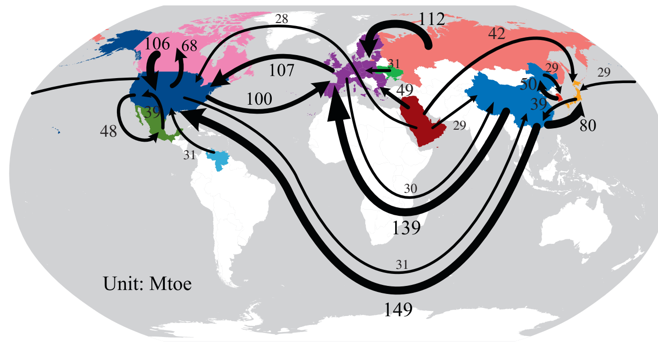

Fig. 1. Major energy flows embodied in interregional trade, in which the China region includes the mainland, Hong Kong, and Taiwan, but excludes Macau because of data limitation, and the 27 members of the European Union are aggregated into one region (calculated by the authors according to the GTAP and WB datasets, Narayanan and Walmsley, 2008; WB, 2010).

embodiment to nominal price) for the product made in China is one of the major reasons for the energy trade imbalance.

3.2. Energy consumption distribution between populations

In contrast to the financial wealth in terms of money which implies a proxy of utility, the embodied energy represents a real physical wealth since the reception of utility of energy can be considered as a physical dimension of welfare (Sen, 1985). With the concrete effect to redistribute energy welfare via commodity exchange, international trade can have an essential role in shaping the equality status, resulting in equality as an important topic in international negotiation on both energy and climate problems. The basis of the equality rule was illustrated by Michael Grubb, one of the experts on international climate negotiation, as "every human being has an equal right to use the atmospheric (as well as other) resource" (Grubb, 1989). In fact, an expected future status towards equality of per capita emission right has been explicitly mentioned in an early draft of the Climate Convention (Beckerman and Pasek, 1995; Böhringer and Welsch, 2004).

According to the simulated results (see Appendix A), global distribution of energy welfare in terms of per capita EEC is extremely unbalanced and the general trend is for resident in richer region to share higher welfare. The world's average per capita EEC in 2004 is 1.66 toe, but merely one quarter of the population (1.68 of 6.40 billion) from 51 regions share energy welfare above the average. Rest of North America (19.54 toe), Luxembourg (14.91 toe), and the United States (9.11 toe) have the highest per capita EEC, while Uganda (0.05 toe), Ethiopia (0.05 toe), and Madagascar (0.06 toe) have the lowest, among the 112 regions. That is, one person in the most energy-consuming region has almost 400 times of energy consumption to that in the least energy-consuming region. However, the difference is smaller than that between per capita DEI (over 500 times) since the least energy-consuming regions generally have high EIRs (see Appendix).

3.3. Energy consumption estimation 2005–2035

To prevent the lagging effect of policy implementation, a reasonable projection on the energy consumption situation plays a significant role in policy making. In this section, we estimate the total and per capita EECs of ten highlighted regions (the United States, Canada, Mexico, Japan, Korea, Australia/New Zealand, Russia, China, India, and Brazil) during 2005–2035 according to the statistics and projection (reference scenario) provided in International Energy Outlook 2010 (EIA, 2010). The referred scenario, which was generated from EIA's World Energy Projections Plus

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modeling system with the latest economic recession taken into account, is consistent with the latest IEA projection (released on 9 November, 2010) in the Current Policies Scenario in general with the same annual growth rate of 1.4% in energy demand to 2035 (IEA, 2010b).

The estimation is made by assuming the regional EIR for total primary energy is the same as that for the five accounted categories, and its value keeps constant during the focused period. Meanwhile, because the original data is only for 2005, 2006, 2007, 2015, 2020, 2025, and 2035, data for the other years are estimated by assuming constant annual percent change during the year intervals.

Different categories of energy are considered to have good substitutability and this property is to be enhanced in the future because of technology innovation (e.g., when all automobiles combust petroleum in the past, nowadays you can also choose vehicles using mixed fuel, gas, or even electricity, which means you have more choices, in terms of energy type, to arrive at your destination). Meanwhile, included in the simulation are primary energy accounting for about 90% of the total primary energy consumption during the period 2005–2035 (EIA, 2010). As a result, the representativeness of the accounted primary energy categories supports the assumption of "regional EIR for total primary energy is the same as that for the five accounted categories".

Changes of international trading pattern and energy efficiency are two important factors for the variation of EIR. Take the Chinese mainland for example, its dependency on foreign trade (ratio of total value of imports and exports to gross domestic product) increases from 59.9% to 64.3% from 2004 to 2007. During the same period, the national direct energy intensity decreases from 85.7 to 80.3 toe/million RMB (in 2005 price). In this case, when the expansion of international trade is to result in a rise (7.4%) of EIR, the improvement in energy efficiency tends to lower (6.7%) the indicator on the contrary and the combined effect is less than 1%, which is relatively small comparing to the simulation error (Peters, 2007). This is also the case for other regions since globalization and energy efficiency improvement seem to be the general trends for the world economy in the near future. As such, it is reasonable to take a constant EIR in the projection.

The regional and per capita EECs for the ten regions during 2005–2035 are given in Figs. 2 and 3 (numerical results are provided in Appendix). According to Fig. 2, EEC of India is to exceed that of Russia in 2012 and that of Japan in 2021. On the other side, China is to replace the United States to be the world's largest direct energy consumer in 2016 (EIA, 2010), but it will not become the world's largest embodied energy consumer until 2027. However, it is worth mentioning that even when the regional EEC of China exceeds that of the United States, its per capita value is just one quarter of that of the United States.

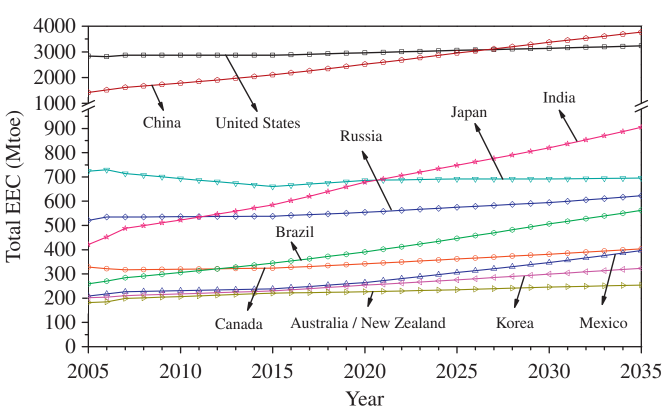

Fig. 2. Total EECs for ten regions during 2005–2035.

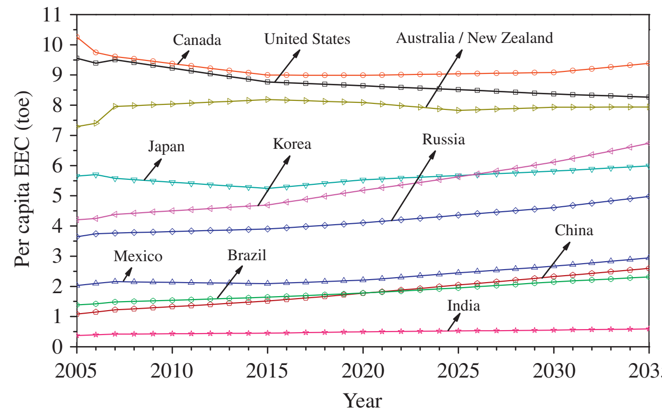

Fig. 3. Per capita EECs for ten regions during 2005–2035.

The ten regions can be classified into four groups in terms of per capita energy welfare: per capita EEC of the highest group (the United States, Canada, and Australia/New Zealand) is over three times of that of the world; per capita EEC of the second highest group (Japan, Korea, and Russia) is generally between two and three times of that of the world; per capita EEC of the lower group (Mexico, China, and Brazil) is around that of the world; and per capita EEC of the lowest group (India) is less than one third of that of the world (see Table A3 and Appendix A).

4. Concluding remarks

Taking the previously overlooked embodied energy flows into account, this study presents an overview of the global energy profile and provides a preliminary foundation for reflecting energy issues at the scale of the world. The present study analyzes the energy embodiment for 112 regions in 2004 via applying a systems input–output simulation to track both direct and indirect energy inputs. In addition to the regional energy inventories, the equality of energy welfare distribution is also discussed. And the regional and per capita energy consumption in terms of embodiment for ten key regions during 2005–2035 is estimated according to the simulated results.

As a result of the interregional trade, embodied energy surpluses are obtained by 77 regions when deficits are obtained by the other 35 regions, with the United States as the biggest embodied energy importer (683 Mtoe) and surplus receiver (290 Mtoe), in contrast to China as biggest exporter (534 Mtoe when only the mainland is included, 662 Mtoe when Hong Kong and Taiwan are also included) and deficit receiver (271 Mtoe when only the mainland is included, 274 Mtoe when Hong Kong and Taiwan are also included). Regional distribution of energy welfare is far from equal as characterized by the per capita EECs of different population groups. Under the prevailing conditions, China is to replace the United States as the world's leading embodied energy consumer in 2027, when per capita EEC in China becomes one quarter of that in the States.

This study presents an overview of embodied energy consumption for the world economy with implications for international as well as national energy policy making. Regarding international cooperation, the collective simulation with a consistent basis may motivate technology transfer from high efficiency to low efficiency countries and economic subsidy by net embodied energy importer to net embodied energy exporter. Meanwhile, the comparative advantage determined by embodied energy cost can be applied to make more appropriate allocation of the limited energy resources. Regarding specific country, the

Table A1
Direct and embodied energy inventories for 112 regions and the world for 2004 (calculated by the authors according to the GTAP and WB datasets, Narayanan and Walmsley, 2008; WB, 2010).

Region	Item										
	DEI (Mtoe)	EEC (Mtoe)	Per capita EEC (toe)	EEI (Mtoe)	EEE (Mtoe)	EEB (Mtoe)	EIR (%)	Investment[a] (%)	Government[a] (%)	Household non-fuel[a] (%)	Household fuel[a] (%)
Albania	1	3	1.08	3	1	2	161	17	2	70	10
Argentina	67	49	1.27	12	30	−18	−27	18	6	66	9
Armenia	2	3	0.84	1	1	1	28	9	10	77	5
Australia	116	125	6.28	52	43	9	8	20	10	61	9
Austria	26	44	5.34	44	26	18	70	18	9	63	10
Azerbaijan	13	13	1.50	5	5	0	−1	22	5	69	4
Bangladesh	13	21	0.15	12	4	8	63	18	2	70	10
Belarus	37	23	2.36	16	30	−14	−38	14	12	62	13
Belgium	73	79	7.59	103	97	6	8	15	10	62	13
Bolivia	5	5	0.56	1	1	0	3	8	8	68	16
Botswana	1	3	1.54	3	1	2	226	20	20	50	10
Brazil	172	158	0.86	49	63	−14	−8	14	7	66	13
Bulgaria	21	15	1.99	9	14	−5	−25	13	10	71	6
Cambodia	1	2	0.11	2	2	0	33	31	7	54	8
Canada	269	237	7.42	113	145	−32	−12	17	11	59	13
Caribbean	64	67	1.75	33	30	3	5	16	3	71	10
Chile	29	25	1.54	14	18	−4	−14	19	4	63	14
China, Hong Kong	9	35	5.03	51	25	26	296	23	6	68	2
China, mainland	1436	1165	0.89	263	534	−271	−19	41	8	44	8
China, Taiwan	103	74	3.25	75	103	−29	−28	19	5	67	9
Colombia	31	30	0.67	8	9	−1	−2	14	6	68	12
Costa Rica	2	4	0.97	5	2	2	146	13	3	70	13
Croatia	10	12	2.58	7	5	2	23	15	9	66	9
Cyprus	1	4	4.70	5	2	3	512	19	8	65	8
Czech Republic	44	40	3.92	25	29	−4	−9	15	16	58	11
Denmark	18	29	5.44	29	18	11	59	19	12	61	8
Ecuador	11	14	1.06	6	4	2	22	12	3	69	15
Egypt	67	56	0.78	13	24	−11	−16	12	8	66	14
Estonia	4	5	4.08	5	4	1	25	16	10	67	7
Ethiopia	1	4	0.05	4	1	3	333	14	8	61	17
Finland	33	36	6.93	29	26	3	9	17	12	64	7
France	285	325	5.40	172	132	40	14	11	9	66	13
Georgia	2	3	0.74	2	1	2	87	15	4	66	15
Germany	358	450	5.44	290	198	91	26	15	10	62	14
Greece	36	51	4.56	34	20	15	41	15	5	68	12
Guatemala	1	7	0.56	7	1	5	373	18	1	67	14
Hungary	24	28	2.79	23	19	4	16	15	10	66	10
India	400	382	0.35	67	85	−18	−4	21	5	63	12
Indonesia	129	133	0.61	52	47	5	4	16	5	65	15
Iran Islamic Republic of	152	151	2.19	31	33	−2	−1	24	5	55	15
Ireland	11	24	5.77	31	19	12	106	21	8	57	15
Italy	189	250	4.31	157	96	61	32	16	7	65	12
Japan	520	646	5.05	265	139	126	24	22	11	59	9
Kazakhstan	57	50	3.36	15	22	−7	−12	16	17	64	3
Korea	234	202	4.23	120	153	−32	−14	26	8	57	10
Kyrgyztan	3	3	0.63	2	1	0	14	9	14	71	6
Lao People’s Democratic Republic	1	1	0.14	1	0	0	44	24	13	54	8
Latvia	2	6	2.73	7	2	4	201	19	11	62	8
Lithuania	15	10	2.96	7	12	−5	−34	16	12	67	6
Luxembourg	2	7	14.91	12	7	5	205	19	7	57	17
Madagascar	0	1	0.06	1	0	1	405	14	3	71	13
Malawi	0	1	0.06	1	0	1	725	10	11	72	8
Malaysia	61	40	1.62	47	67	−20	−34	15	7	62	16
Malta[b]	0	1	3.35	2	1	1	1299	13	10	69	7
Mauritius	0	2	1.55	3	1	2	549	23	6	61	10
Mexico	164	191	1.81	79	52	27	17	18	3	66	13
Moldova	3	5	1.18	4	2	2	76	14	11	60	15
Morocco	11	17	0.55	11	5	6	58	18	18	55	10
Mozambique	1	2	0.10	2	2	1	44	19	8	64	9

Table A1 (*continued*)

Region	Item										
	DEI (Mtoe)	EEC (Mtoe)	Per capita EEC (toe)	EEI (Mtoe)	EEE (Mtoe)	EEB (Mtoe)	EIR (%)	Investment[a] (%)	Government[a] (%)	Household non-fuel[a] (%)	Household fuel[a] (%)
Netherlands	104	84	5.18	98	118	−20	−19	16	12	67	5
New Zealand	15	18	4.58	12	8	4	26	20	8	62	11
Nicaragua	1	2	0.38	2	1	1	90	18	5	67	10
Nigeria	19	29	0.22	17	7	10	53	20	10	52	18
Norway	37	32	7.04	27	31	−4	−12	20	12	63	5
Pakistan	42	55	0.35	22	9	13	30	18	4	73	6
Panama	1	4	1.32	5	2	3	465	9	7	75	9
Paraguay	5	3	0.53	3	5	−2	−42	10	1	75	13
Peru	13	17	0.60	7	3	3	25	11	4	74	11
Philippines	22	32	0.39	24	14	10	44	14	5	70	12
Poland	91	91	2.35	36	36	−1	−1	10	7	71	12
Portugal	23	32	3.09	23	14	9	38	17	8	64	10
Rest of Central Africa	5	7	0.20	4	2	2	47	22	7	58	14
Rest of Central America	2	8	0.59	8	3	6	252	13	4	72	11
Rest of East Asia	22	18	0.73	6	9	−3	−15	37	21	39	3
Rest of Eastern Africa	9	17	0.17	12	3	8	93	17	9	64	9
Rest of European Free Trade Association	25	28	1.94	12	9	3	11	17	7	68	8
Rest of Europe	2	3	8.91	3	2	1	73	17	8	67	8
Rest of Former Soviet Union	62	47	1.25	9	24	−16	−25	14	18	55	13
Rest of North Africa	78	58	1.52	13	34	−20	−26	18	2	65	14
Rest of North America	1	3	19.54	2	0	2	202	15	11	66	8
Rest of Oceania	3	7	0.85	7	3	4	118	19	13	58	9
Rest of South African Customs	1	3	0.62	5	2	2	424	22	9	58	12
Rest of South America	0	1	0.81	1	1	1	205	13	10	65	12
Rest of South Asia	2	7	0.12	6	1	5	255	18	9	62	11
Rest of South Central Africa	4	8	0.11	5	2	4	84	18	21	52	9
Rest of Southeast Asia	6	7	0.13	4	3	1	10	17	8	64	11
Rest of Western Africa	10	18	0.16	14	5	9	90	15	5	68	12
Rest of Western Asia	475	325	2.74	115	265	−150	−32	13	13	62	11
Romania	36	34	1.57	15	17	−2	−6	15	9	71	6
Russian Federation	680	474	3.29	62	268	−207	−30	14	10	70	6
Senegal	2	3	0.25	2	1	1	91	13	5	72	11
Singapore	49	25	5.92	65	88	−24	−48	27	11	58	3
Slovakia	21	17	3.13	12	16	−4	−19	14	10	64	11
Slovenia	5	8	4.10	9	6	3	53	16	9	60	15
South Africa	129	90	1.90	21	61	−39	−30	13	7	69	10
Spain	141	176	4.13	105	70	35	25	24	9	56	11
Sri Lanka	3	8	0.38	7	3	4	129	17	4	68	10
Sweden	53	56	6.26	39	36	3	6	11	16	66	7
Switzerland	24	48	6.60	52	28	24	99	23	5	59	14
Tanzania	1	3	0.09	3	1	3	321	18	5	63	13
Thailand	94	72	1.13	44	66	−22	−24	21	6	62	11
Tunisia	6	10	0.98	9	5	4	64	17	7	65	11
Turkey	74	94	1.30	55	35	20	27	19	4	67	11
Uganda	0	1	0.05	1	0	1	311	22	11	51	16
Ukraine	144	83	1.77	26	87	−62	−43	12	9	67	12
United Kingdom	222	313	5.26	198	108	91	41	16	11	66	7
United States of America	2401	2691	9.11	683	394	290	12	14	7	69	10
Uruguay	3	4	1.17	3	2	1	34	12	9	69	10
Venezuela	96	51	1.93	7	53	−46	−47	17	8	60	15
Viet Nam	18	32	0.39	34	19	14	81	30	3	54	12
Zambia	2	2	0.15	1	1	0	6	18	9	65	8
Zimbabwe	3	3	0.24	2	2	0	7	11	9	73	7
World	10632	10632	1.66	4395	4395	0	0	19	8	63	10

[a] Share of EEC.
[b] Malta is corresponding to Rest of the Europe of the GTAP database.

presented results with economic network taken into account provide substantial basis for domestic energy use regulation as well as international trading structure adjustment. For example, if a country tries to develop its automobile industry with given energy constraint, what the policy makers concern is how much energy use will be induced for the whole economy instead of for this single industry.

Besides, the present study also provide essential basis for the policy regarding energy-induced greenhouse gas emission mitigation. While the effect of current mitigation policy associated with the production responsibility principle has been questioned due to the separation between energy input and energy consumption (e.g., regarding the Kyoto Protocol, Annex B countries can transfer energy-intensive industry to and import energy-intensive products from non-Annex B countries), the embodiment analysis seems to be a promising approach to overcome such problem.

The resulted database, including embodied energy intensities of all 6384 entries and related energy inventories for all 112 regions, can also be applied for further research on specific industry in the context of globalized economy. For example, the evaluation of low-energy as well as low-carbon buildings necessitates a systems metrics framework based on a consistent embodied intensity database (Chen et al., 2011).

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Appendix A

See Tables A1–A3.

Table A2
Estimated total EEC for ten regions and the world during 2005–2035.

Year	Region										
	US	Canada	Mexico	Japan	Korea	Australia/New Zealand	Russia	China	India	Brazil	World[a]
2005	2837	328	209	723	202	182	521	1418	421	259	11907
2006	2817	322	218	730	204	185	535	1514	452	271	12170
2007	2871	317	227	714	211	199	535	1617	488	285	12474
2008	2871	318	228	707	213	202	535	1671	500	292	12628
2009	2870	319	229	700	215	204	536	1727	511	299	12353
2010	2870	320	231	694	218	207	536	1785	523	306	12598
2011	2869	320	232	687	220	210	537	1844	534	313	12836
2012	2869	321	234	680	223	212	537	1906	547	321	13072
2013	2869	322	235	674	225	215	537	1969	559	329	13279
2014	2868	323	237	667	228	218	538	2035	572	337	13492
2015	2868	324	238	661	230	221	538	2103	585	345	13690
2016	2887	327	243	666	235	222	541	2180	602	354	13994
2017	2906	331	249	671	239	223	545	2260	621	363	14214
2018	2925	334	254	676	244	224	548	2342	639	372	14431
2019	2945	338	259	681	249	225	551	2428	659	381	14650
2020	2964	342	265	686	254	227	554	2517	679	391	14874
2021	2982	345	273	687	258	228	558	2599	692	402	15107
2022	3001	349	281	688	262	230	562	2683	706	412	15346
2023	3020	353	289	690	267	231	567	2770	720	424	15592
2024	3038	357	297	691	271	233	571	2860	734	435	15849
2025	3057	362	306	692	276	235	575	2953	748	447	16089
2026	3073	365	314	692	280	237	579	3033	762	458	16340
2027	3090	369	322	692	285	239	583	3114	776	470	16584
2028	3106	373	330	692	290	241	587	3199	791	482	16822
2029	3123	377	338	692	295	244	590	3285	806	494	17056
2030	3139	381	347	692	300	246	594	3374	821	507	17293
2031	3157	386	357	693	304	247	600	3450	837	517	17539
2032	3176	390	366	693	309	249	605	3528	853	528	17799
2033	3195	395	376	694	314	251	611	3607	870	539	18063
2034	3213	399	387	695	318	252	617	3689	887	551	18334
2035	3232	404	397	695	323	254	622	3772	905	562	18608

[a] Equal to global DEI in EIA (2010).

Table A3
Estimated per capita EEC for ten regions and the world during 2005–2035.

Year	Region										
	US	Canada	Mexico	Japan	Korea	Australia/New Zealand	Russia	China	India	Brazil	World[a]
2005	9.55	10.26	2.03	5.65	4.21	7.29	3.64	1.08	0.37	1.39	1.83
2006	9.39	9.75	2.09	5.70	4.25	7.40	3.74	1.15	0.39	1.43	1.85
2007	9.51	9.61	2.16	5.58	4.39	7.96	3.77	1.22	0.42	1.48	1.88

Table A3 (*continued*)

Year	Region										
	US	Canada	Mexico	Japan	Korea	Australia/New Zealand	Russia	China	India	Brazil	World[a]
2008	9.41	9.53	2.15	5.54	4.42	7.98	3.78	1.26	0.42	1.50	1.88
2009	9.32	9.45	2.14	5.49	4.46	8.01	3.80	1.29	0.43	1.52	1.82
2010	9.22	9.38	2.13	5.45	4.50	8.04	3.82	1.33	0.43	1.54	1.83
2011	9.13	9.30	2.12	5.41	4.54	8.07	3.83	1.36	0.44	1.56	1.85
2012	9.04	9.22	2.11	5.37	4.58	8.10	3.85	1.40	0.44	1.58	1.86
2013	8.95	9.15	2.11	5.33	4.62	8.13	3.87	1.44	0.44	1.60	1.87
2014	8.86	9.07	2.10	5.28	4.66	8.16	3.88	1.48	0.45	1.62	1.88
2015	8.77	9.00	2.09	5.24	4.70	8.18	3.90	1.52	0.45	1.64	1.89
2016	8.74	8.99	2.11	5.30	4.79	8.17	3.94	1.56	0.46	1.67	1.91
2017	8.72	8.99	2.14	5.36	4.88	8.15	3.98	1.61	0.47	1.70	1.92
2018	8.69	8.99	2.16	5.41	4.98	8.13	4.02	1.66	0.48	1.72	1.93
2019	8.67	8.99	2.18	5.47	5.08	8.11	4.06	1.72	0.49	1.75	1.94
2020	8.64	8.99	2.21	5.53	5.18	8.09	4.10	1.77	0.50	1.78	1.95
2021	8.62	9.00	2.25	5.56	5.27	8.04	4.15	1.82	0.50	1.81	1.97
2022	8.59	9.01	2.30	5.59	5.36	7.98	4.20	1.88	0.51	1.84	1.98
2023	8.57	9.02	2.35	5.62	5.44	7.93	4.25	1.93	0.51	1.88	2.00
2024	8.54	9.03	2.40	5.64	5.53	7.88	4.31	1.99	0.52	1.91	2.01
2025	8.52	9.04	2.45	5.67	5.63	7.83	4.36	2.05	0.52	1.95	2.03
2026	8.49	9.05	2.49	5.70	5.72	7.85	4.41	2.10	0.53	1.99	2.05
2027	8.46	9.06	2.53	5.73	5.82	7.87	4.46	2.15	0.53	2.03	2.06
2028	8.43	9.07	2.58	5.76	5.91	7.89	4.51	2.21	0.54	2.07	2.08
2029	8.40	9.07	2.62	5.79	6.01	7.91	4.56	2.27	0.55	2.11	2.09
2030	8.37	9.08	2.67	5.82	6.11	7.93	4.61	2.32	0.55	2.15	2.10
2031	8.35	9.14	2.72	5.85	6.23	7.93	4.68	2.38	0.56	2.18	2.12
2032	8.33	9.20	2.78	5.89	6.36	7.94	4.75	2.43	0.57	2.21	2.14
2033	8.31	9.26	2.83	5.92	6.48	7.94	4.83	2.48	0.58	2.25	2.16
2034	8.29	9.33	2.89	5.96	6.61	7.94	4.90	2.54	0.58	2.28	2.18
2035	8.27	9.39	2.94	5.99	6.74	7.94	4.98	2.60	0.59	2.31	2.20

[a] Equal to global DEI in EIA (2010).

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