Energy for Sustainable Development 41 (2017) 36–48

Contents lists available at ScienceDirect

Energy for Sustainable Development

Sustainable energy and CO_2 reduction policy in Thailand: An input–output approach from production- and consumption-based perspectives

Tharinya Supasa [a], Shu-San Hsiau [a,*], Shih-Mo Lin [b], Wongkot Wongsapai [c], Kuei-Feng Chang [b], Jiunn-Chi Wu [a]

[a] Institute of Energy Engineering, Department of Mechanical Engineering, National Central University, Jhong-Li 32001, Taiwan
[b] Center for Applied Economic Modelling, College of Business, Chung Yuan Christian University, Jhong-Li 32023, Taiwan
[c] Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand

ARTICLE INFO

Article history:
Received 28 March 2017
Revised 9 August 2017
Accepted 11 August 2017
Available online xxxx

Keywords:
Consumption-based analysis
Emissions inventory with trade
Energy and environmental input–output model
Energy shortage effect
Sustainable energy and emission reduction policy

ABSTRACT

Energy shortages and CO_2 emissions reductions are critical contemporary challenges for Thailand. A consumption-based analysis provides crucial information that enables policymakers to more comprehensively understand the hidden contributors of energy demand and CO_2 in the economy. The other manufacturing, construction and food and beverage sectors were amongst the five largest contributors to energy use and emissions in both 2000 and 2010, based on a consumption perspective. However, these sectors have been neglected by energy conservation and climate change mitigation policies in Thailand because they were the least energy-intensive sectors per government energy reports from 1995 to 2015. The CO_2 emissions burden from exports was almost 50% of Thailand's national CO_2 inventory in 2000 and 2010. The embodied CO_2 emissions results revealed that Thailand could reduce its emissions inventory by 12% and 13% if embodied imports replaced exports in 2000 and 2010, respectively. Furthermore, the leading gross domestic product-generating industries in Thailand are seriously vulnerable to natural gas and crude oil shortages despite some sectors using them in small proportions in their production processes. Energy and emissions policies should better reflect consumption characteristics to increase the potential of energy-saving interventions and CO_2 mitigation.

Introduction

Thailand is the second largest economy in Southeast Asia, which is a crucial industrial export region in the world. Its gross domestic product (GDP) placed 27th in the 2015 global ranking (World Bank, 2015). However, Thailand has experienced a more rapid increase in its CO_2 emissions than in its GDP; the country ranked 21st in a global emissions database, which indicates unfavourable emissions control outcomes (Emission Database for Global Atmospheric Research, 2015). The second National Inventory Report submitted by Thailand to the United Nations Framework Convention on Climate Change (UNFCCC) on 24 March 2011 included the nation's most recent greenhouse gas (GHG) inventory data from 2000, when the total net GHG emissions in Thailand, in terms of CO_2 equivalent, was 229 million tonnes. The energy sector was the major source of emissions, accounting for approximately 70% of the total emissions, followed by agriculture (approximately 23%). Amongst the GHGs, CO_2 constituted approximately 69% of the total emissions, followed by CH_4 and N_2O at 26% and 5%, respectively. Hence, CO_2 was clearly the most important GHG (Office of Natural Resources and Environmental Policy and Planning [ONEP], 2011).

In addition to the challenge of mitigating GHG emissions, energy supply security has become a critical challenge for Thailand, particularly in terms of natural gas. Thai power generation has relied heavily on domestic natural gas feedstock, accounting for 67% of the total fuel used in power generation in 2015 (Energy Policy and Planning Office [EPPO], 2015). Rising electricity demand has rapidly increased natural gas extraction from the Gulf of Thailand. According to a BP report (2016), the country reported the lowest reserves to production (R/P) ratio amongst neighbouring countries, such as Malaysia, Indonesia and Vietnam. Moreover, at the current R/P ratio will be able to supply energy to Thailand for only 5.5 years; this represents the lowest level of energy security in Thailand's history.

Aside from natural gas, Thailand has relied significantly on oil imports for decades. Imported crude oil accounted for 68% of its total primary imports in 2014 (EPPO, 2015). Approximately 80% of the nation's oil consumption can be attributed to the transport and manufacturing sectors. Thus, under high dependence on oil imports, the effects of world oil price shocks and political instability in exporting countries induce higher logistics costs for industries in Thailand and the possibility of a crude oil shortage in the future, thereby weakening economic growth.

* Corresponding author.
E-mail address: sshsiau@cc.ncu.edu.tw (S.-S. Hsiau).

http://dx.doi.org/10.1016/j.esd.2017.08.006
0973-0826/

To solve emissions and energy security problems, an integrated policy framework called the *Thailand Climate Change Master Plan (2012–2050)* was launched in 2010; it includes the Energy Efficiency Development Plan, Alternative Energy Development Plan, Power Development Plan (PDP) and Sustainable Transport Plan, which promotes a road-to-rail modal shift for private and freight transport (ONEP, 2015).

Recent energy conservation and climate change policies in Thailand have often focused on energy intensive (EI) industries that exhibit high energy consumption and high levels of GHGs emitted in their production combustion processes, known as the production-based perspective. Therefore, the recent Master Plan prioritises energy-saving actions from the power generation, transport and manufacturing sectors more than that of other sectors because the changes in the energy demand of these sectors are assumed to have a high impact on the nation's overall energy consumption. The key energy and emissions reduction interventions are improving energy efficiency in industries, promoting the use of ethanol and biodiesel and of renewable energy (e.g. biomass and biogas) in power and heating systems in the industrial sector and instigating feed-in tariffs for solar energy installed in industries.

Energy-saving interventions and emissions mitigation based on typical EI industries according to a production-based perspective were considered a crucial factor driving reductions in the nation's energy consumption and emissions. However, some empirical studies have examined the efficacy of Thailand's energy efficiency improvement policy since its introduction in 1995 and reported that improving energy efficiency has not been significant in decreasing the nation's energy consumption (Bhattacharyya and Ussanarassamee, 2004; Chontanawat et al., 2014; Boonkham and Leeprechanon, 2015; Supasa et al., 2016). Importantly, the consumption structure and the level of goods and services demanded by final consumers was the main factor driving growth in energy consumption in Thailand from 1995 to 2010 (Supasa et al., 2016). Several empirical studies on energy and the environment have indicated that although the recent energy conservation policy adopting a production-based approach is practical, it may not be sufficient to enable the implementation of a sustainable energy and climate change policy in the future. Therefore, conducting a simultaneous energy consumption-based analysis can provide the necessary additional information for crucial forecasts of growth in energy use. This would more comprehensively reflect the drivers of the nation's energy consumption to assist in potential energy-saving actions and GHG mitigation (Limmeechokchai and Suksuntornsiri, 2007; Peters and Hertwich, 2008; Peters, 2008; Zhang et al., 2014; Liu et al., 2012).

In the context of Thailand, studies examining energy and emissions inventory accounting from a consumption perspective are rarely found. Therefore, this study attempted to fill the gap by focusing on consumption-based energy and CO_2 inventories. Applying an energy input–output (IO) model using data for Thailand in 2000 and 2010 permits the identification of the nation's embodied energy and CO_2 inventory and an analysis of structural changes over a 10-year period. The EI sectors highlighted by the consumption-based approach were further decomposed to reveal their sources of indirect energy consumption. In addition, the embodied energy consumption during the two studied years was disaggregated into final demand groups to identify the final consumer influence on energy demand growth. Furthermore, the impacts of natural gas and crude oil supply shortages on the Thai economy from a consumption-based perspective were also presented by implementing an IO supply-driven model. Regarding embodied emissions, this study captured emissions by considering the production-based, consumption-based and consumption-based emissions inventory associated with international trade. Our results could enable policymakers to identify elusive factors that increase energy consumption and CO_2 emissions. Key findings and discussion provide an alternate perspective on energy-saving potentials and strategies for mitigating emissions to achieve the goal of sustainable climate change mitigation and enable decision makers to optimise related policies.

Thailand's energy situation

The rapid depletion of energy resources has become a critical challenge for Thailand, particularly in terms of natural gas, the main source for power generation. In 2015, 67% of the fuel used in power generation was natural gas, followed by coal (18%). Renewable energy for electricity production still accounts for a very low proportion, approximately 3% of the total power generation (EPPO, 2015). Prolonged hot weather and higher temperatures—consequences of climate change—as well as urban expansion have considerably increased electricity consumption in household sector. Together with trade promotion policies and industrial growth have also increased the demands for all types of energy, particularly electricity and oil consumption. According to Fig. 1 the electricity demand reached a new peak every year from 2000 to 2015, particularly during summer (March to June). In 2015, the peak demand was 27,346 MW, which was 33% and 83% higher than those in 2005 and 2000, respectively. The annual electricity generation growth rate was approximately 5% from 2000 to 2015 (EPPO, 2016).

The increase in electricity demand has rapidly increased natural extraction from the Gulf of Thailand; at the current reserves to production (R/P) ratio, these reserves will be able to supply energy to Thailand for only 5.5 years, the lowest record in Thailand's history. In 2016,Thailand reported the lowest R/P ratio amongst neighbouring countries, such as Malaysia, Indonesia, and Vietnam, which have natural gas reserves that can last for 17, 38, and 58 years, respectively (BP, 2016). Fig. 2 illustrate that Natural gas production was produced at 113 thousand barrels per day (crude oil equivalent) in 1990 and increased to 732 thousand barrels per day (crude oil equivalent) in 2014, a 5.5-fold production increase, while, the country focuses on importing of crude oil, and coals. Crude oil was the form of energy imported in the highest quantities, accounting for 68% of the total primary energy imports in 2014. Approximately 80% of the nation's oil consumption can be attributed to the transport and manufacturing sectors (EPPO, 2015).

Therefore, to decelerate the depletion of natural gas reserves, the Thai government began importing natural gas and electricity from its neighbours. Natural gas imported from Myanmar through pipeline system accounted for approximately 20% of the total natural gas consumption during 2001–2015, and electricity imported from Laos and Malaysia accounted for roughly 12% of total electricity generation (EPPO, 2016).

However, the investment promotion policy of the ASEAN Economic Community (AEC), implemented in 2015, rapidly increased energy demand in Laos and Malaysia, thereby increasing the possibility of stopping energy sales to Thailand. Shortages in neighbouring energy supplies have strong effects on Thailand's energy system. For example,

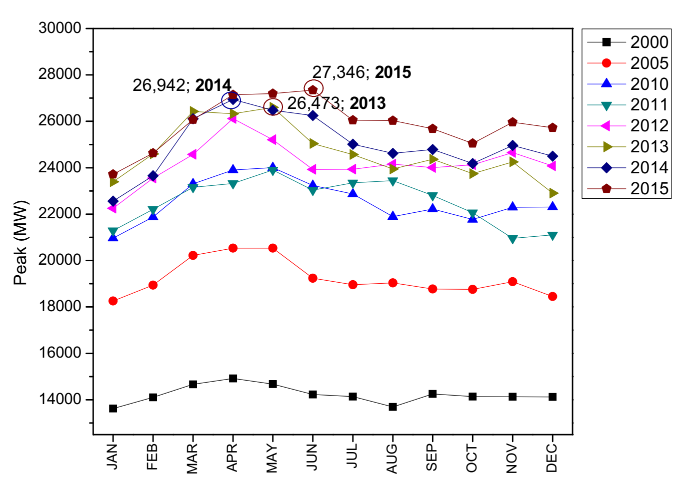

Fig. 1. Dynamic changes in peak demand (MW) (EPPO, 2016).

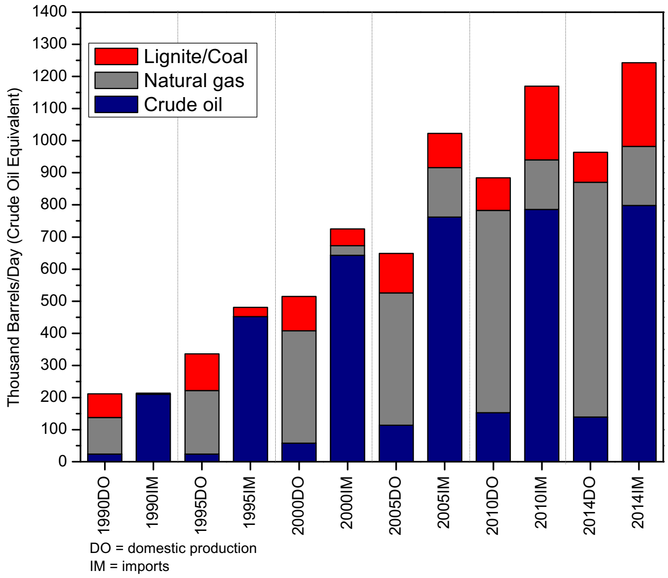

Fig. 2. Dynamic changes in primary commercial energy production and import mix (thousand barrels per day (crude oil equivalent)) (EPPO, 2015).

the temporary pause in natural gas delivery from Myanmar in April 2013 nearly caused brownouts in Thailand. Therefore, if Thailand's energy consumption continues to increase at the existing rate, the country might experience a power shortage dilemma in the near future (EPPO, 2016).

Literature review

An energy consumption-based analysis can identify the major energy-consuming sectors by considering individual sectors' life-cycle energy use and emissions. The production of a unit of products or services involves two types of energy consumption—direct and indirect—as well as emissions (Miller and Blair, 2009; Jain, 2012; Biswas, 2014; Su and Ang, 2015; Lindner and Guan, 2014). Energy is consumed both directly in the production processes (direct energy use) and indirectly through its supply chain, ranging from upstream to downstream industries (indirect energy use); for example, material acquisition, assembly parts manufacturing, and transportation. The accumulated direct and indirect energy and emissions in product or service outputs is called the 'embodied energy and embodied emissions' or 'life-cycle energy and emissions' of goods and services. These embodied values have become crucial indicators of sectoral energy consumption behaviour and environmental responsibility. A sector having high indirect energy consumption could increase direct energy consumption in other related industries, resulting in an increase in the overall energy consumption. Hence, policymakers cannot ignore a consumption-based analysis.

An increasing number of consumption-based energy and emission studies have been conducted actively worldwide. Chang et al. (2010), Zhang et al. (2014), Liu et al. (2012), and Li et al. (2014) have used an input–output (IO) model to analyse embodied energy flows and factors causing energy consumption growth in China to develop a sustainable energy conservation policy. The construction and service sectors were identified as the highest energy consuming sectors from a supply-chain perspective. These sectors are the least EI sectors according to the production-based approach; however, they are the leading sectors in indirect energy consumption because they consume a substantial amount of EI products. The demand for EI products from these typical low EI industries can eventually increase the energy consumption of heavy industries. Cui et al. (2015) claimed that the embodied energy in China's foreign trades had significantly increased faster than direct energy exports during 2001 to 2007. To reduce national energy demand and promote industrial upgrade effectively, the EI industry restrictive export policy must be implemented. Schoer et al. (2007) conducted a hybrid IO to quantify the embodied energy and CO_2 emissions of German exports and compared them with those of German imports. The study reported that Germany had exported more products with high embodied energy intensity and CO_2 emissions than it had imported. Thus, the country's energy demand had increased because of the energy usage in export production. Wang et al. (2016) employed IO analysis to investigate the embodied energy in the subprocess order of supply chains and revealed that the energy-saving actions and green consumption behaviour should be implemented amongst supply chain members to improve a country's energy consumption reduction potential. Furthermore, Tang et al. (2013) described how the United Kingdom had attempted to stabilise the amount of final energy consumption and continue energy security by importing indirect energy through the embodied energy of trade goods, instead of increasing direct energy imports. Limmeechokchai and Suksuntornsiri (2007) applied an IO model to analyse industries in Thailand from 1995 to 2006. The study highlighted that producers of iron and steel, nonmetallic products, concrete, and cement had considerably lower energy consumption and GHG emissions than others, if only the combustion process was considered. However, they became energy- and emission-intensive sectors when entire energy chains were analysed.

Some scholars have argued that a consumption-based approach to emissions provides useful complementary information to assess the efficacy of climate change policies by considering the importance of trade. Under the recent GHG emission inventory framework, the climate change mitigation responsibility was allocated to the place of production and not to the place of consumption. Thus, a country can avoid responsibility for emissions by choosing to import products. Consequently, that global emissions are probably not declining; rather, they are only being shifted from countries with stronger environmental laws to those with weaker ones (Peters and Hertwich, 2008). Therefore, they have criticised the allocation of emission responsibility and carbon leakage from trades (Shui and Harriss, 2006; Li and Hewitt, 2008; Mäenpää and Siikavirta, 2007; Su and Ang, 2014; Wiedmann, 2009). In future, the responsibility for emissions could be shared between the goods' place of consumption and place of production by implementing the consumption-based approach (Peters, 2008; Lin and Sun, 2010). Under the consumption-based approach, the developing countries would have a lower emissions inventory, whereas that of the developed countries would be higher. Thus, a policy using the consumption-based approach could encourage more international cooperation for technology and financial transfers as well as carbon leakage reduction (Wiedmann, 2009).

Although, the consumption-based approach has not been adopted in the UNFCCC. However, the results of the consumption-based approach reveal necessary complementary information for policymakers to understand the drivers of energy consumption, thereby enabling them to manage more wide-reaching sustainable energy-saving and environmental actions.

Methodology

Consumption-based energy and emissions

In 1936, the theoretical tenets of IO analysis were posited by Leontief; this was then extended by Bullard and Herendeen in 1975 to apply to energy studies (Miller and Blair, 2009). Thereafter, the method was further extended to apply to energy–environmental studies and referred to as energy–environmental IO (EIO) analysis. It has become a crucial technique for determining the impacts of energy–environmental interaction amongst the various economic sectors, using sectoral consumption to assess the completed energy supply chain and emissions burden.

Therefore, in this study, the EIO model was employed to capture the embodied energy and CO_2 emissions of each economic sector. The fundamental mathematical equations of the IO model are expressed as follows:

$$X_i = \sum z_{ij} + f_{ik} = \sum a_{ij}X_j + f_{ik} = (I{-}A)^{-1} f = Lf \text{ (demand}-\text{driven)} \tag{1}$$

or

$$X_j = \sum z_{ij} + v_j = \sum {}_{ij}X_j + v_j = \left(I{-}\overset{\tilde{A}}{u}\right)^{-1} v \text{ (supply}-\text{driven)} \tag{2}$$

Eq. (1) is a demand-driven model, whereas Eq. (2) is a supply-driven model. In Eq. (1), X_i is a vector ($n \times 1$) representing the total output of sector i; z_{ij} is the square matrix ($n \times n$) representing the flow of intermediate consumption goods/services from sector i to sector j of n industries within the economy; f_{ik}, is a final ($n \times k$) demand matrix; a_{ij} is a direct coefficient matrix that can be obtained from z_{ij}/X_j; and I is a unity matrix. The Leontief inverse matrix, $L = (I - A)^{-1}$, size $n \times n$. In Eq. (2), X_j is the total output of sector j; v_j is the value-added transpose of sector j; and $\tilde{a}_{ij}$ is a direct coefficient matrix obtained by dividing the z_{ij} transpose by X_j. All the coefficients are expressed in monetary units.

In the extant literature, energy consumption associated with industrial energy consumption includes both direct and embodied energy. Direct energy consumption is the amount of energy used directly by industry, such as in production processes. Embodied energy denotes indirect energy use from consuming energy through using intermediate products and services from other industries.

To analyse direct and embodied energy, an energy hybrid IO model first must be constructed. The amount of energy consumption by energy type was specified in monetary units, replacing physical units, in the z_{ij} matrix for the energy sectors. Then the intermediate sectoral energy consumption is denoted as z_{cj}, where c = number of fuel types. Second, the direct energy intensity by fuel type and by economic sector is derived as per Eq. (3). The direct energy intensity, denoted by η_{cj}, is the direct consumption of fuel c in physical units by industry j to produce a dollar's worth of output value in a monetary unit

$$\eta_{cj} = \frac{\text{amount of fuel } c \text{ consumed by industry } j \text{ (physical unit)}}{\text{Value of industry } j \text{ production in year } t} \tag{3}$$

Next, the embodied energy intensity can be derived by multiplying the direct energy intensity matrix (η_{cj}) with the Leontief inverse matrix (L) as represented in Eq. (4). The embodied energy intensity is a summation of both direct and indirect energy consumption in physical units to produce a dollar's worth of output for industry j. The embodied energy intensity is occasionally referred to as the supply chain intensity coefficient or life-cycle coefficient.

$$\alpha_{cj} = \eta_{cj}(I{-}A + M)^{-1} \tag{4}$$

According to Miller and Blair (2009), the total energy content embodied in commodities and services consumed by industry, referred to as the embodied energy matrices (Q), can be extracted by multiplying the supply chain intensity coefficient (α_{cj}) with the final demand consumption in a monetary unit (f_{ik}), which is expressed in Eq. (5).

$$Q = \eta_{cj}(I{-}A + M)^{-1} \cdot f \tag{5}$$

M is a diagonal matrix of imports that can be obtained from f_{im}/X_j.

Then, the direct emission intensity, Ω_{ij}, is derived as per Eq. (6). To avoid double counting of emissions, only primary energy consumption was considered in deriving CO_2 from domestic energy uses.

$$\Omega_{ij} = C \cdot \eta_{cj} \tag{6}$$

where C is a diagonal matrix of CO_2 emissions factors by fuel type (IPCC, 2014, Table 1). Then, the CO_2 emissions resulting from a completed production chain of commodities and services, referred to as the CO_2 emissions intensity, was quantified. The equation for a completed CO_2 supply chain is expressed in Eq. (7).

$$E_{cj} = \Omega_{ij}(I{-}A + M)^{-1} \tag{7}$$

The sectoral embodied emissions inventory equation (V_{cj}) is derived by multiplying the completed CO_2 supply chain with the final demand consumption in monetary units, which is similar to the embodied energy equation. This is expressed in Eq. (8).

$$V_{cj} = E{\cdot}f \tag{8}$$

Using Eqs. (5) and (8), the embodied energy and embodied emissions were further decomposed into final consumption categories, following those in the IO table. This disaggregation facilitates identifying major consumers within the economy who contribute to the energy consumption and emissions inventory. Further details concerning embodied energy and embodied emissions disaggregation by final demand groups are provided in Appendix A.

Supply driven model

To evaluate the primary energy unit shortage in the output of all other sectors, the supply-driven IO model was employed to address the impact restrictions. Eq. (2) is rewritten its form to Eq. (9) as follows:

$$\Delta X = \left(I{-}\overset{\tilde{A}}{u}\right)^{-1} \Delta v \tag{9}$$

Eq. (10) was used to evaluate the impact of a unit of primary energy shortage. The primary energy sector was treated as an exogenous sector. The value added changes of the exogenous sector were equal to one, whereas no change was observed in the value added changes of all other sectors. This helped in evaluating the impacts of a unit shortage in the individual energy sectors on the outputs of all other sectors.

Data and assumptions

We use the 2000 and 2010 Thailand IO tables in this study; the 2010 IO data were most recently published by the National Economic and Social Development Board (2016). The non-competitive imports assumption was adopted in this paper. Both IO tables were adjusted to constant price tables (2010 prices) using the producer price index, maintained by the Product Group from Thailand's Bureau of Trade and Economic Indices (2015). The physical energy use data were obtained from the 2000 and 2010 Thailand Energy Situation Annual Reports released by the Department of Alternative Energy Development and Efficiency (DEDE) within the Ministry of Energy.

To construct the hybrid-unit IO tables, the original IO data set comprising 179 sectors was aggregated into 23 sectors (18 non-energy and 5 energy sectors) corresponding to energy data from the energy report. Note that the principal for IO sector aggregation in this study

Table 1
Carbon dioxide emission factors by fuel type.

Sector	I/O sector	Fuel type	CO_2 emission factor (tCO_2/TJ)[a]	CO_2 emission (tCO_2/ktoe)[b]
19	30	Coal and lignite	89.5	3781.1
20	31	Crude Oil	73.3	3096.5
21	31, 136	Natural gas	56.1	2366.5

[a] 2006 IPCC Guideline for National Greenhouse Gas Inventories (Default value, Tier 1).
[b] Unit conversion using the net calorific value from DEDE (2010).

follows the sector definitions in these energy data to mitigate against information loss vis-à-vis energy use in the economy. This is the most important concern for operationalising the hybrid-unit IO table. Therefore, note that the uncertainty of numerical energy intensity results in studies using this methodology is a function of sector aggregation.

The energy sectors are coal and lignite, crude oil, natural gas, petroleum products (LPG, diesel, gasoline, etc.), and electricity. Coal and lignite, crude oil, and natural gas are identified as the primary energy sectors. All crude oil is processed to derive petroleum products. Natural gas and coal are the primary sources of fuel for power plants. Natural gas and condensate is used as a petrochemical feedstock and solvent in the chemical industry; it has a final nonenergy use. Because the final energy consumption data of the energy sector was not found in the report by the Ministry of Energy, the results could be misleading. For example, the coal sector had zero final energy consumption in their operations, which is unrealistic because the coal sector requires the use of electricity and petroleum products (diesel, gasoline); moreover, refineries require electricity in their operations. Therefore, we used the proportional manipulation method derived from the IO data sets (monetary units) to estimate the amount of final energy consumption for all energy sectors by extracting the energy amount from the 'other manufacturing' sector in the energy report. Renewable energy and hydropower were not examined in this study because of difficulties in data allocation. The aggregated data set and classification in this study are presented in Table 2. The sector grouping and sector match between the two data sets merit close attention; the IO table and energy data sets could add to the uncertainty of the results, whereas the import assumption might not be a dominant factor (Su et al., 2010; Su and Ang, 2015).

Results and discussions

Production energy uses and embodied energy uses by sector

Under the production-based perspective, the most energy intensive sectors during the two studied years were the road transport, chemical, non-metallic and commercial sectors (Fig. 3a and b). The sectors which exhibited the highest growth in energy consumption from 2000 to 2010 were the metallic, chemical, manufacturing others, commercial and road transport sectors (Fig. 3c). Considering energy type, the transportation and agriculture sectors had the highest petroleum product consumption. The chemical sector consumed all types of energy in their operating processes, and condensate (crude oil) was used as petrochemical feedstock and a solvent. The non-metallic sector was the largest consumer of coal, and the commercial sector had the highest electricity consumption in the two studied years.

The energy consumption-based approach was adopted to estimate 'life-cycle energy' or 'embodied energy', including the amount of energy consumed by the production processes of numerous upstream industries in various sectors, until the final use of goods and services by the final consumer group. The results of the consumption-based approach revealed a different aspect of the drivers of energy consumption: the hidden EI 'consumer' sectors that increase the energy demand of typically EI industries. Note that energy sectors are excluded in this discussion because the energy inflow into energy sectors does not represent final energy uses, particularly in the petroleum and electricity sectors.

A comparison of the production-based and consumption-based approaches to energy consumption of non-energy sectors is presented in Table 3. The embodied energy analysis used national territorial

Table 2
Identified sectors and classification.

Economic sector	Sector	Name	I/O sector	Description	Abbreviation
Agriculture	1	Agriculture	1–29	Crops, agricultural product, livestock, forest products, fishing	AGR
Mining	2	Mining	32–41	Mining and extraction of Iron, Tin, Tungsten, Other non-ferrous metals, mineral	MIN
Manufacturing	3	Food &beverages	42–66	Canning, foods, vegetable & animal oil, beverages, animal feeds, tobacco	FOB
	4	Textiles	67–74	Spinning, weaving, textile goods	TEX
	5	Wood and furniture	78–80	Wooden construction materials, furniture and fixtures	WOF
	6	Paper and paper products	81–83	Pulp, paper products, printing	PAP
	7	Chemical products	84–92	Industrial chemicals, fertilizer and pesticides, Petrochemical products, drugs and medicine, paint, cosmetics	CHE
	8	Non-metallic	95–104	Rubber, plastic wares, glass, ceramics, cement, concrete	NMT
	9	Metallic	105–107	Iron and steel, secondary steel products, non-ferrous metal	MET
	10	Fabricated metals	108–111	Manufacturing of machine tools, metal for building, transport equipment, metal structure components, etc.	FAB
	11	Other manufacturing	75–77, 112–134	Leather products, engines and turbines, agricultural machinery and equipment, special industrial machine, office and household machinery and appliances, electrical appliances, ship & railroad equipment, production and assembly of motor vehicles, repair of motor vehicles, aircraft, manufacturing others.	OTH
Construction	12	Construction	137–144	Construction and repair of building construction, electric plants, irrigation works, construction of communication facilities	CST
Commercial	13	Commercial	145–148, 158–178	Wholesale, retail, restaurants, hotel, hospital, banking, insurance, business service, public administration, education, social welfare services, library, museum, amusement, theatres, radio and television stations, personal service	CMM
Transport	14	Rail	149	Transportation of both passengers and cargo	RAL
	15	Road	150–152, 157	Passenger and freight transport, transportation for tours, includes all land transport support services; parking lots	ROD
	16	Water way	153–155	ocean and water transport	WAT
	17	Air	156	Passengers and freight by air, operation of airport	AIR
Unclassified	18	Unclassified	180	Activities not classified elsewhere	UNC
Energy	19	Coal and lignite	30	Mining coal and lignite	COA
	20	Crude oil	31	Exploration activities for crude petroleum, drilling, carry-out, operation	OIL
	21	Natural gas	31, 136	Exploration activities for natural gas, drilling, carry-out, operation	NGS
	22	Petroleum products	93–94	Oil-processing refineries	PTL
	23	Electricity	135	Generation, transmission and distribution of electricity	ELE

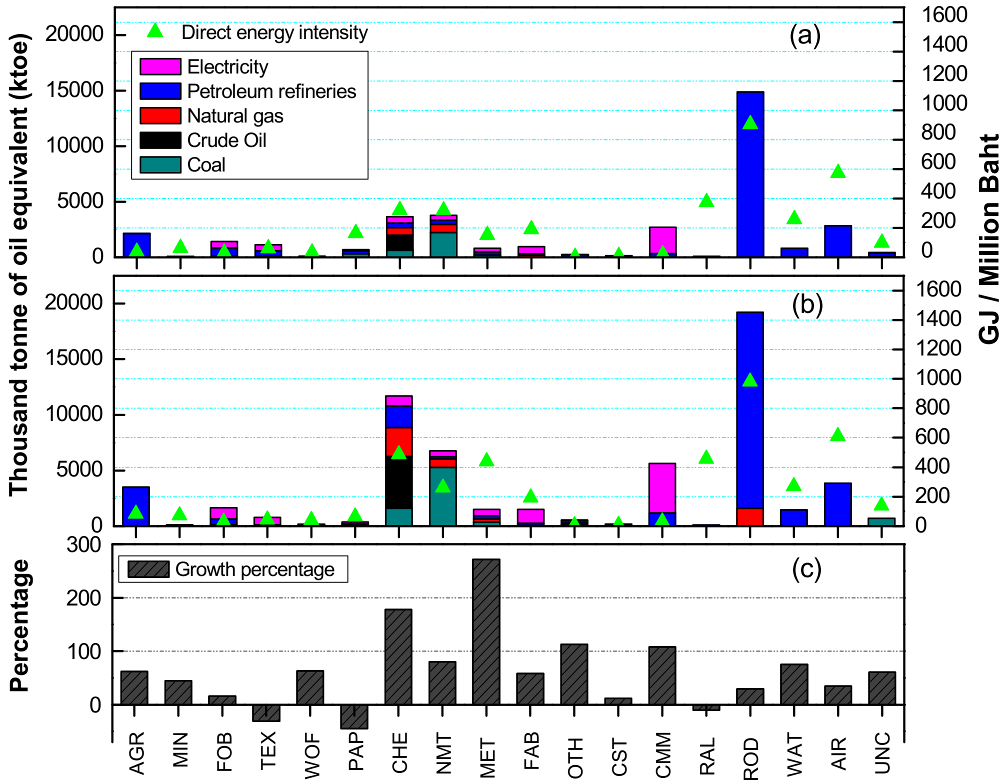

Fig. 3. Energy use and intensity by sector in (a) 2000 and (b) 2010; (c) change in energy consumption from 2000 to 2010 (DEDE, 2000, 2010).

boundaries to exclude embodied imports. Therefore, the summation of total energy use in the production-based approach is equal to that in the consumption-based approach. The five leading embodied energy sectors, called leading EI consuming sectors, in the two studied years were the road transport sector, followed by the commercial, other manufacturing, food and beverages and construction sectors. More specifically, in 2000, the road transport sector had the highest embodied energy consumption (22,722 ktoe), followed by the commercial (15,273 ktoe), food and beverage sectors (8930 ktoe), other manufacturing (7749 ktoe) and construction sectors (6377 ktoe). In 2010, road transport still accounted for the highest level of embodied energy consumption (24,579 ktoe), increasing by 8.2% over that 10-year period. It was followed by the commercial (24,576 ktoe), other manufacturing (19,284 ktoe), food and beverages (13,139 ktoe) and

Table 3
A comparison of production energy use and embodied energy use for 2000 and 2010.

Sector	Abbreviation	Production-based energy consumption (ktoe)					Consumption-based energy consumption (ktoe)				
		2000		2010		Growth (%)	2000		2010		Growth (%)
		ktoe	Rank	ktoe	Rank		ktoe	Rank	ktoe	Rank	
1	AGR	2161	6	3499	6	61.9	1374	12	3779	11	175
2	MIN	85	18	123	17	44.7	−26	18	−456	18	1667
3	FOB	1417	7	1644	7	16.0	8930	3	13,139	4	47
4	TEX	1139	8	783	11	−31.3	5242	6	4526	9	−14
5	WOF	114	16	186	15	63.2	760	15	1227	14	61
6	PAP	701	12	386	14	−44.9	1009	14	793	15	−21
7	CHE	3657	3	11,704	2	220.0	3079	9	5883	8	91
8	NMT	3765	2	6774	3	79.9	3982	8	8345	6	110
9	MET	820	11	1503	8	83.3	665	16	27	17	−96
10	FAB	948	9	1503	9	58.5	2214	10	4525	10	104
11	OTH	260	14	553	13	112.9	7749	4	19,284	3	149
12	CST	149	15	167	16	12.1	6377	5	8931	5	40
13	CMM	2701	5	5620	4	108.1	15,273	2	24,576	2	61
14	RAL	98	17	88	18	−10.2	145	17	118	16	−19
15	ROD	14,875	1	19,211	1	29.1	22,722	1	24,579	1	8
16	WAT	823	10	1443	10	75.3	1461	11	2909	12	99
17	AIR	2856	4	3852	5	34.9	4978	7	6005	7	21
18	UNC	436	13	702	12	61.1	1366	13	1550	13	13
19	COA	10	–	7	–	−33.8	1	–	7	–	559
20	OIL	302	–	331	–	9.6	2	–	19	–	847
21	NGS	3884	–	12,243	–	215.2	29	–	44	–	53
22	PTL	38,474	–	48,170	–	25.2	7734	–	13,734	–	78
23	ELE	21,834	–	33,482	–	53.3	6444	–	10,430	–	62
	Total	**101,509**		**153,974**			**101,509**		**153,974**		

construction sectors (8931 ktoe); this represents growth in embodied energy of 61%, 149%, 47% and 40%, respectively, and it is higher than production-based growth rates, except the commercial sector. A comparison of the two approaches revealed that if the leading EI consuming sectors were neither heavy industries nor high-energy-intensity industries, they received less attention in energy conservation activities. Nevertheless, these EI sectors and their operations consumed a small amount of fossil fuels but a substantial amount of indirect energy, which could imply that they had high levels of embodied energy consumption because of the consumption of intermediate inputs.

The sectors were merged following the classification in Table 2, and their embodied energy was disaggregated for a higher-resolution analysis to investigate the distribution, absorption patterns and consumption characteristics of embodied energy across industries (Fig. 4). First, the results revealed that the agricultural sector consumed the highest amount of indirect energy from intermediate inputs within the sector, followed by the chemical and road transport sectors. Second, the manufacturing sector used considerable indirect energy from intermediate inputs or assembly parts from within the sector, particularly chemical, non-metallic and metallic inputs. Moreover, the manufacturing sector consumed indirect energy by using road transport such as freight services, agricultural feedstock and commercial services. Third, the construction sector consumed one of the lowest amounts of energy according to the production-based approach (2000: 149 ktoe; 2010: 167 ktoe), accounting for <1% of the total final energy consumption. However, the consumption-based approach revealed that the construction sector ranked fifth in total energy consumption according to the consumption-based approach (2000: 6377 ktoe; 2010: 8931 ktoe), which is approximately 50 times higher than the production-based estimate. Fig. 4 illustrates that the metallic (iron, steel and nonferrous metal), chemical (paint), non-metallic (concrete, cement and glass) and road transport sectors accounted for the indirect energy consumption in the construction sector. Embodied energy consumption increased from 2000 to 2010 mainly because of the increased consumption of metallic and chemical products.

Fourth, the commercial sector had the highest electricity consumption, and it was ranked the fourth highest energy consumer in typical production aspects in both 2000 (2701 ktoe) and 2010 (5620 ktoe). Further, its consumption-based values were approximately six and four times higher in 2000 and 2010, respectively, than the production-based alternatives. This result suggests that the commercial sector had high demand for energy in its operations and consumed a substantial amount of indirect energy through intra-sector intermediate inputs (e.g. wholesalers, retail stores, restaurants, banks, business services, public administration, etc.) and inter-sector (chemical products, metallic and road air transport) intermediate inputs. Finally, the transport sector consumed substantial energy from within the sector in addition to a small amount from the manufacturing sector.

The embodied energy of the manufacturing sector was further disaggregated for detailed analyses because it was the largest energy consumption sector in Thailand (Fig. 5). The food and beverages and other manufacturing sectors were also examined because they represent two sectors amongst the five leading EI consumption sectors; however, by contrast, they were the least EI sectors according to the production perspective (Table 3). Fig. 5 illustrates that the food and beverage sector consumed indirect energy from the typical EI sectors, particularly the chemical (drugs and medicines and basic industrial chemicals), agriculture (e.g. poultry, pigs, fish, vegetables and rice), road transport and metallic (nonferrous metal) sectors as well as within the sector itself (canning, preservation of fish and other seafood, sugar and cooking oil). The growth of embodied energy consumption in this sector from 2000 to 2010 stemmed from rapid growth in the consumption of chemical products and freight transport. On the other hand, the other manufacturing sector, which includes many important industries in Thailand, such as the assembly of motor vehicles, radios, televisions, communications equipment, apparatuses and electrical appliances, accounted for only a small portion of the final energy consumption in their production during both studied years (2000; 260 ktoe; 2010; 553 ktoe). However, the embodied energy of this 'other' group was amongst the highest in the manufacturing sector. This sector used numerous inputs from within the sector and from the metallic (secondary

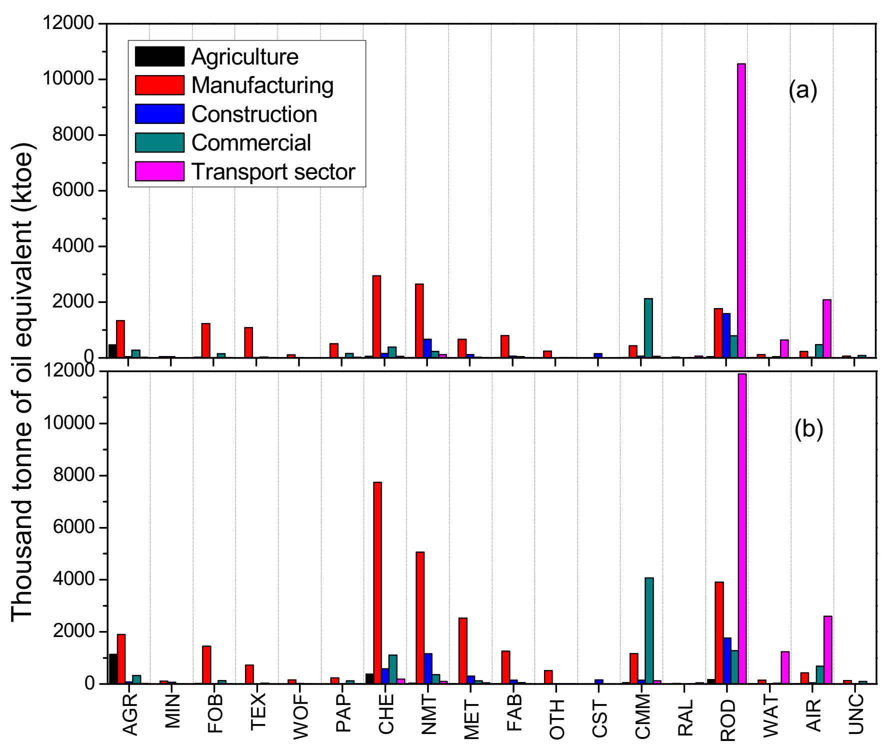

Fig. 4. Distribution of embodied energy consumption in non-energy sectors in (a) 2000 and (b) 2010.

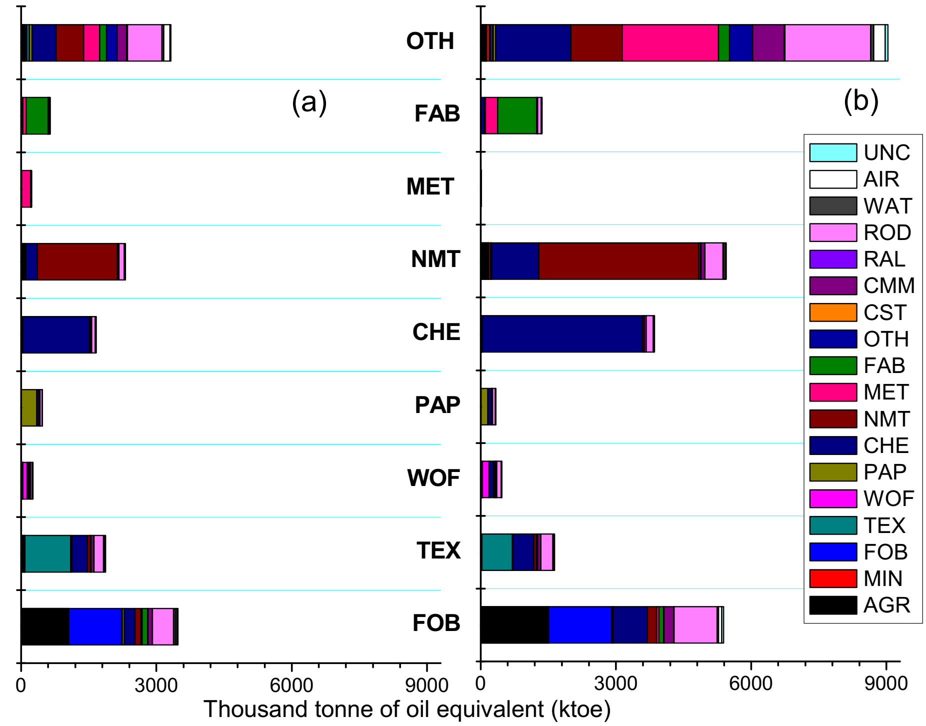

Fig. 5. Distribution of embodied energy consumption for the manufacturing sector in (a) 2000 and (b) 2010.

steel products and nonferrous metal), chemical (petrochemical products, paint and basic industrial chemicals), non-metallic (plastics, rubber and glass) and freight sectors.

Production combustion emissions and embodied CO_2 inventory by sector

This study has presented three CO_2 inventory frameworks for Thailand: production-based, consumption-based and consumption-based with trade (Table 4). The first framework, the production combustion CO_2 inventory, which included non-energy use, is similar to the existing National Emission Inventories report submitted to the UNFCCC. The total CO_2 inventory in 2000 and 2010 was 197.5 and 321.2 Mt CO_2, respectively. Under this framework, the leading sectors contributing to the nation's CO_2 inventory were petroleum and electricity generation, which accounted for 84% and 73% of the CO_2 emissions in 2000 and 2010, respectively. CO_2 emissions from energy sectors increased from 175.6 Mt CO_2 in 2000 to 262.5 Mt CO_2 in 2010, a 49% growth. According to Table 4, because most CO_2 emissions stem from the energy sector, it is held responsible for reducing the nation's CO_2 emissions. Hence, recent emissions mitigation actions have focused on cleaner technology in the energy sector, particularly in electricity (i.e. power plants). However, the production-based framework may be insufficient for developing a sustainable climate change policy for the future because production-based emissions accounting does not reflect the real contributors to emissions; in addition, the energy sector is not a final energy user that causes increases in the nation's energy demand and emissions.

Second, the consumption-based emissions inventory approach, 'Embodied CO_2 emissions', has provided an additional perspective. Therein, emissions associated with domestic consumption and exports were included, but those associated with imports were excluded. This framework allocated emissions according to national territorial boundaries. The total CO_2 inventory for both studied years coincided with the totals in the production-based framework. Table 4 highlights that the energy sector was no longer the leading CO_2 emitter, having been overtaken by the road transport, commercial and manufacturing sectors. CO2 emissions from these sectors were 131.5 Mt CO_2 in 2000 and 210.4 Mt CO_2 in 2010, representing 67% and 66% of the national emissions inventory, respectively.

Because the UNFCCC territorial boundary system was criticised for not distributing mitigation responsibilities between producers and consumers, this study presented an additional CO_2 emissions inventory which is consumption-based and is considered international trade. The inventory associated emissions with domestic consumption by including emissions related to imports and excluding those related to exports. This framework assumes that product consumers, and not producers, should be responsible for emissions. In Table 4, the embodied emissions from exports minus those from imports, termed the embodied emissions balance of trade, had a positive value for both years, implying that Thailand will have a lower CO_2 inventory under this framework. The total CO_2 inventory for 2000, 171.8 Mt CO_2, represents a 25.6 Mt CO_2 reduction compared to the estimate from the two other frameworks. The total CO_2 responsibility in 2010 reduced from 321 Mt CO_2 to 283.9 Mt CO_2 under this framework. The chemical, metallic and fabricated metal sectors had higher responsibilities for CO_2 emissions in both the studied years compared with results under the second framework because imports exceeded exports. In contrast, most of the other sectors had stable, lower responsibilities in the CO_2 inventory, particularly the road transport and food and beverages sectors. Thus, the consumption-based results could improve policymakers' understandings of the key contributors to and the dynamics of the national emissions inventory.

Economy-wide energy and CO_2 balances and structural change

The embodied energy and emissions of individual sectors was disaggregated into final consumer categories. The results reveal energy consumption pathways and identify the leading final consumer group responsible for the increase in energy demand in Thailand over the studied years.

Figs. 6 and 7 present the embodied energy consumed in Thailand during 2000 and 2010. In 2000 (Fig. 6a), the total energy supply was 127,401 ktoe, which was divided into direct energy supply used in production (80%) and additional indirect energy supply from importing

Table 4
A comparison of CO_2 emissions inventories in 2000 and 2010 (Mt CO_2): production-based, consumption-based and consumption-based with trade approaches.

Sector	Abbreviation	2000						2010					
		(1) Production combustion CO_2 inventory	(2) Embodied CO_2 emissions	Domestic consumption	Exports	Imports	(3) Accounting for trade in consumption-based CO_2	(1) Production combustion CO_2 inventory	(2) Embodied CO_2 emissions	Domestic consumption	Exports	Imports	(3) Accounting for trade in consumption-based CO_2
1	AGR	0.0	2.3	1.9	0.5	1.1	3.0	0.0	6.8	4.9	1.9	1.4	6.4
2	MIN	0.0	0.0	−0.1	0.1	0.2	0.1	0.0	−0.9	−1.2	0.3	0.3	−0.8
3	FOB	0.3	15.9	8.7	7.2	2.6	11.3	0.3	24.6	14.6	10.0	3.4	18.0
4	TEX	0.3	9.8	4.9	4.9	2.1	7.0	0.1	9.1	4.0	5.1	2.5	6.5
5	WOF	0.0	1.4	0.6	0.8	0.3	0.9	0.0	2.4	1.6	0.8	0.3	1.9
6	PAP	1.2	2.1	1.2	1.0	1.6	2.7	0.5	1.6	0.9	0.8	1.8	2.7
7	CHE	8.2	7.0	3.5	3.5	9.7	13.2	26.6	14.7	0.0	14.6	23.1	23.1
8	NMT	10.2	9.7	2.9	6.8	4.5	7.4	21.8	22.0	6.2	15.8	7.5	13.7
9	MET	0.8	1.3	0.4	0.9	3.8	4.1	2.0	0.1	−1.2	1.3	12.5	11.3
10	FAB	0.5	4.2	1.9	2.3	3.8	5.6	0.2	8.7	4.1	4.6	6.7	10.8
11	OTH	0.1	15.1	6.1	9.0	9.0	15.1	0.9	39.1	17.7	21.4	16.6	34.2
12	CST	0.0	11.9	11.9	0.0	0.0	11.9	0.0	18.3	18.3	0.0	0.0	18.3
13	CMM	0.0	28.0	23.3	4.7	1.5	24.8	0.0	47.2	38.6	8.6	3.5	42.0
14	RAL	0.0	0.2	0.2	0.1	0.0	0.2	0.0	0.2	0.1	0.1	0.0	0.2
15	ROD	0.0	37.0	23.6	13.4	2.2	25.8	3.8	41.1	25.7	15.4	4.5	30.2
16	WAT	0.0	2.4	0.9	1.4	0.1	1.1	0.0	4.8	2.5	2.3	0.5	3.0
17	AIR	0.0	8.1	3.2	4.9	1.6	4.8	0.0	9.8	5.1	4.7	3.7	8.8
18	UNC	0.2	2.6	2.3	0.3	0.7	3.0	2.7	3.8	3.3	0.5	0.7	4.0
19	COA	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.2	0.2
20	OIL	0.5	0.0	0.0	0.0	1.0	0.9	0.6	0.0	0.0	0.0	1.2	1.2
21	NGS	9.2	0.1	0.0	0.1	1.1	1.1	29.0	0.1	0.0	0.1	11.1	11.1
22	PTL	117.1	23.4	6.5	16.9	4.0	10.6	148.5	42.0	6.7	35.3	0.6	7.2
23	ELE	48.9	15.0	14.9	0.2	2.3	17.1	84.5	25.9	24.7	1.2	5.4	30.1
	Total	197.5	197.5	118.5	78.9	53.3	171.8	321.2	321.2	176.5	144.8	107.4	283.9

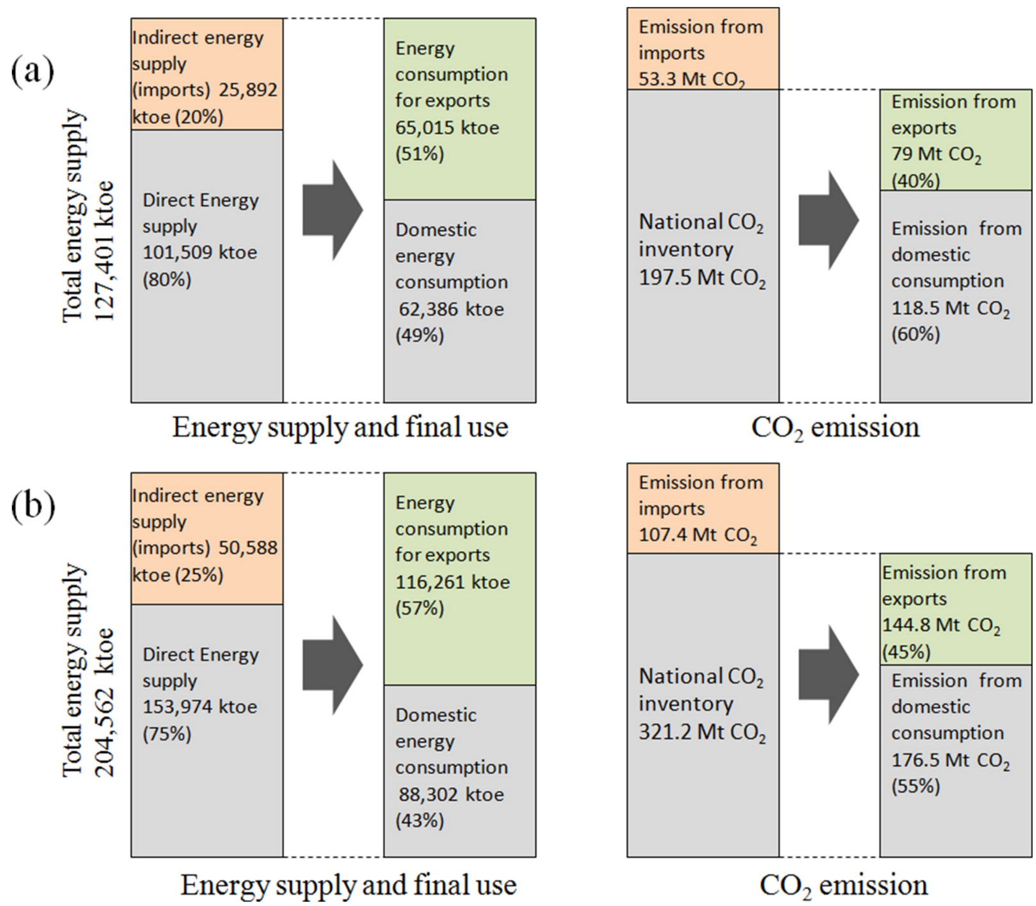

Fig. 6. Economy-wide balance of embodied energy and CO_2 emissions in Thailand during (a) 2000 and (b) 2010.

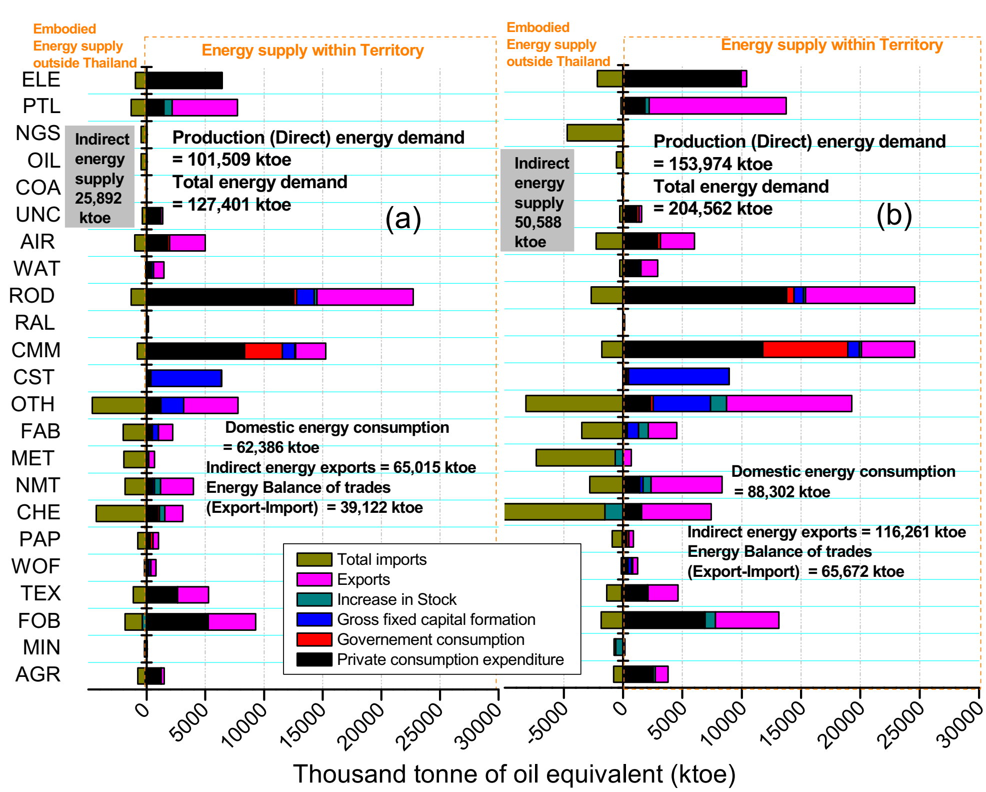

Fig. 7. Embodied energy in goods and services consumed in Thailand during (a) 2000 and (b) 2010 disaggregated by final demand categories.

assembled goods (20%). In the final consumption, the total energy used was both within and outside the country. Within the country, it was directed towards domestic consumption (households, government consumption, infrastructure investments and stock changes), which accounted for 62,386 ktoe or 49% of the total national energy supply. Energy used outside the country amounted to 65,015 ktoe, which came from exporting manufactured goods and road and air transport services to facilitate the exportation of manufactured goods (Fig. 7a). Therefore, in 2000, most of the energy supply was used for producing manufactured exports rather than domestic consumption. In addition, CO_2 emissions from domestic consumption contributed 60% of the national CO_2 inventory, while the other 40% is attributable to emissions related to exports.

Figs. 6b and 7b present Thailand's embodied energy and emissions structure for 2010. The total energy supply amounted to 204,562 ktoe, a 61% increase compared to 2000. Further, direct (indirect) energy supply exhibited a 52% (95%) increase in 2010 compared to 2000. Exports accounted for 116,261 ktoe in 2010 or 57% of the total energy supply; this represents a 79% increase from 2000. Next, domestic consumption amounted to 88,302 ktoe or 43% of the total energy supply, a 42% increase from 2000. In both years, the agricultural, food and beverages, transport and commercial sectors consumed more energy for domestic purposes than trade. Furthermore, the manufacturing sector remained the highest energy consumer because trade was prioritised (Fig. 7).

Therefore, the key factor driving the energy consumption increase in Thailand from 2000 to 2010 was manufacturing exports. The embodied energy consumption from exports was more than that from imports, i.e. 39,122 ktoe in 2000 and 65,672 ktoe in 2010. This could be considered energy leakage because products were manufactured using energy from Thailand that were eventually consumed outside the country. Thus, the country should attempt to reduce its domestic energy demand by restricting the exportation of EI industrial products. However, this policy needs further analysis vis-à-vis economic consequences. In addition, emissions from exports doubled in 2010 compared to 2000 (79 Mt CO_2 in 2000; 144.8 Mt CO_2 in 2010). Emissions related to exports and domestic consumption contributed 45% and 55% to the national CO_2 inventory, respectively. Again, the embodied emissions from exports exceeded those from imports, implying CO_2 emissions leakages from international trade in both studied years.

Economy-wide effects of natural gas and crude oil supply shortages

Thailand faces risks associated with natural gas and crude oil shortages, as mentioned in the introduction. Thus, the impacts of these shortages on the outputs of all other sectors are evaluated using a supply model (Eq. (2)); the results are presented in Table 5. Natural gas and crude oil shortages could influence all sectors of the economy, even though some sectors exhibited zero consumption of either natural gas or oil during both the studied years. This wide influence can be explained in terms of interindustry linkages. The sum of the natural gas shortage effects were 2.3204 in 2000, slightly increasing to 2.4123 in 2010. Because natural gas is the main feedstock for power generation, natural gas shortages could result in electricity shortages. Apart from these two sectors, the next leading sectors that would be affected by a natural gas shortage are other manufacturing and commercial, whereas the five that would be least affected are rail, coal, crude oil, mining and water transport.

Moreover, the effects of a crude oil shortage were much stronger than those of a natural gas shortage during both the studied years; this suggests that Thailand is an economy dominated by oil consumption. The sum of crude oil shortage effects was 19.6025 and 17.1715 for 2000 and 2010, respectively. The sectors most affected by a crude oil shortage were petroleum, other manufacturing, commercial, road transport and food and beverages. The least-affected sectors were rail transport, coal, mining, and wood and furniture. The results are similar for both types of energy and both studied years. Therefore, natural gas and crude oil shortages strongly impact Thailand's key GDP-generating sectors, creating economic insecurity and uncertainty.

Conclusions and policy implication

According to the production-based approach, the road transport, chemical, non-metallic, metallic and commercial sectors were the typical leading EI sectors in Thailand in 2000 and 2010. These sectors had to undertake energy-saving and emissions reduction interventions in collaboration with energy sectors, such as power plants. However, the consumption-based analysis highlighted that the least EI sectors in the production-based approach were the leading EI sectors according to the consumption approach, such as the commercial, other

Table 5
Natural gas and crude oil supply shortage effects: consumption-based analysis for 2000 and 2010.

Sector	Abbreviation	2000					2010				
		GDP value rank	Natural gas supply shortage effect	Rank	Crude oil supply shortage effect	Rank	GDP value rank	Natural gas supply shortage effect	Rank	Crude oil supply shortage effect	Rank
1	AGR	9	0.0255	12	0.7147	8	6	0.0293	10	0.5053	9
2	MIN	20	0.0019	20	0.0515	21	20	0.0027	20	0.0435	21
3	FOB	3	0.0596	8	0.9173	6	3	0.0711	7	0.6226	6
4	TEX	5	0.1051	6	0.5832	10	9	0.0552	8	0.2532	14
5	WOF	11	0.0073	17	0.0609	20	13	0.0076	18	0.0531	20
6	PAP	15	0.0154	14	0.1183	17	18	0.0113	15	0.0780	19
7	CHE	21	0.1275	5	0.7171	7	21	0.0785	5	0.5764	7
8	NMT	7	0.0784	7	0.5274	11	7	0.0774	6	0.5337	8
9	MET	22	0.0222	13	0.1460	16	23	0.0227	12	0.1982	16
10	FAB	17	0.0150	15	0.1102	19	15	0.0205	14	0.1657	17
11	OTH	2	0.2329	3	1.7595	3	2	0.3276	3	2.4623	2
12	CST	4	0.0410	9	0.5938	9	4	0.0469	9	0.4761	10
13	CMM	1	0.1735	4	1.2764	4	1	0.2176	4	1.3170	3
14	RAL	18	0.0003	22	0.0194	22	17	0.0002	23	0.0087	23
15	ROD	6	0.0327	10	2.0605	2	5	0.0221	13	1.2936	4
16	WAT	13	0.0026	19	0.3434	14	10	0.0037	19	0.3424	13
17	AIR	12	0.0068	18	0.4502	13	14	0.0078	17	0.4512	11
18	UNC	14	0.0145	16	0.1171	18	12	0.0109	16	0.0904	18
19	COA	19	0.0002	23	0.0171	23	19	0.0002	22	0.0144	22
20	OIL	23	0.0011	21	1.0000	5	22	0.0025	21	1.0000	5
21	NGS	16	1.0000	1	0.2293	15	16	1.0000	1	0.2338	15
22	PTL	8	0.0257	11	7.2663	1	8	0.0234	11	6.0400	1
23	ELE	10	0.3309	2	0.5229	12	11	0.3731	2	0.4118	12
	Total		**2.3204**		**19.6025**			**2.4123**		**17.1715**	

manufacturing, food and beverages and construction sectors. Most leading EI consumption sectors utilise low amounts of energy in production processes; thus, they were neither EI nor had high energy intensity according to the production-based approach. Thus, they have received less attention in energy conservation policies and actions.

The leading EI consumption sectors were the downstream industries, which mainly produce final rather than intermediate goods for consumption. They consumed a substantial amount of indirect energy by using assembly parts from typical EI sectors, such as those from the metallic, chemical, non-metallic, agricultural and freight transport sectors, for production purposes. Therefore, their indirect energy demand, consumption behaviours and consumption choices vis-a-vis intermediate inputs had an interindustry linkage effect with respect to changes in the energy demand of heavy industries. Consequently, this changed national energy consumption and emissions.

To increase energy-saving potential, policies could be considered which mandate these leading EI consumption sectors to become aware of and reactive to their indirect energy consumption behaviours and choices (e.g. product specifications and consumption patterns). A consumption-based policy employing an economic mechanism, such as an energy or carbon tax evaluated based on industrial consumption (e.g. life-cycle energy and emissions), could be introduced. If the policy extends the responsibility of paying energy or carbon taxes to all supply chain members, it could encourage downstream sectors to obtain materials from manufacturers whose products have lower energy and emissions footprints. Moreover, incentive programmes for downstream industries that have lower-than-average energy and emissions footprints could also be introduced. A carbon trade mechanism could be applied to consumption-based energy and emissions on a domestic scale, i.e. industries that exhibit energy and emissions footprints lower than the limited value can trade their allowances with others. Indeed, this may have better environmental integrity (Su and Ang, 2014; Peters, 2008). These policies will consequently increase the demand for low-embodied energy and emissions inputs and facilitate cooperation in energy efficiency improvements between trade partners, i.e. typical EI production (upstream industries/sellers) and EI consumption (downstream industries/buyers). The EI industries (producers) would strive to reduce their energy consumption intensity to compete with their counterparts in meeting customer demands; in addition, all supply chain members will be more concerned about reducing their energy and emissions footprints. This can be recognised as an energy-saving and low-emissions demand-driven strategy or pull strategy. Nevertheless, the economic impacts of these policies require further analysis using methodologies such as computable general equilibrium modelling to explore their relative advantages and disadvantages in both aggregate and disaggregate terms.

CO_2 inventories were constructed for this study using three analytical frameworks: production-based, consumption-based and consumption-based with international trade. The production-based approach, which is the recent climate change mitigation framework, allocated responsibility for emissions to the petroleum and power generation sectors, whereas the consumption-based approach indicated that the manufacturing, commercial, construction and road transport sectors were the leading CO_2 emitters. These sectors should be held responsible for their emissions instead of the energy sector being held solely responsible for emissions reductions. Moreover, when including embodied emissions from imports and excluding those from exports, Thailand exhibited lower CO_2 emissions in 2000 and 2010 compared to emissions estimated according to the two preceding frameworks.

In terms of the economy-wide balance of embodied energy and emissions consumption, results show that Thailand is a net exporter of embodied energy and emissions. Thus, the energy supply in Thailand has prioritised other countries' needs through exports of manufactured products instead of its own domestic consumption. To increase energy-saving capabilities, the government could more stringently restrict the export of high-EI products or reallocate EI industries to neighbouring energy-resource-rich countries. However, any such policy actions might adversely affect employment, GDP and other pertinent economic performance indicators; thus, further study in terms of economic impact evaluations are required in the first instance. In contrast, the creative and information technology industries, characterised by low-energy intensity but high-value-added, could be intensively promoted by the Thai government.

Because energy supply shortages have become a critical challenge for Thailand, understanding the effects of natural gas and crude oil shortages, as discussed in this study, is important. These shortages even affect sectors that do not consume natural gas and oil in their production processes; a consumption-based supply-driven analysis revealed that the shortage of any primary energy source can affect all sectors in the economy because of interindustry linkages. The effects of a crude oil shortage were markedly stronger than those of a natural gas shortage in both 2000 and 2010. Further, shortages of both these primary energy sources had the greatest effects on the petroleum, other manufacturing, commercial and road transport sectors, which are the highest generators of GDP of Thailand.

In summary, the results of the consumption-based approach, which has been hitherto under-applied for Thailand, provide additional information which could enable policymakers to more comprehensively understand (i) the hidden contributors which drive energy demand in the economy; (ii) energy pathways; and (iii) responsibility for emissions. Since the growth in Thailand's CO_2 emissions has exceeded the country's economic growth, energy shortages have become a critical challenge. Additional energy and emissions policies designed to increase energy savings and emissions reductions potential should be pursued so future economic growth is environmentally sustainable.

Acknowledgement

This research was supported by National Central University, Taiwan. The authors appreciate the reviewers for their valuable comments.

Appendix A. This disaggregation helps identify major consumers within the economy who contribute to the energy consumption and emissions inventory. The disaggregation energy embodied equation is expressed as follows

$$\begin{aligned} Q &= \alpha_{cj} \cdot \left(f_{hh} + f_{gov} + f_{cap} + f_{stk} + (f_{ex} - f_{im})\right) \\ Q &= Q_{hh} + Q_{gov} + Q_{cap} + Q_{stk} + (Q_{ex} - Q_{im}) \end{aligned} \tag{10}$$

The final demand consumption is classified into five categories: households (f_{hh}), government consumption (f_{gov}), capital formation (f_{cap}), stock change (f_{stk}), and trade (exports minus imports, $f_{ex} - f_{im}$). Therefore, Q_{hh} is the energy embodied in consumption; Q_{gov} represents the energy embodied in government consumption; Q_{cap} is the energy embodied in domestic fixed capital formation; Q_{stk} is the energy embodied in stock change; and Q_{ex} and Q_{im} represent the energy embodied in exports and imports, respectively. Moreover, CO_2 emissions can be disaggregated in the same pattern as embodied energy.

References

Bhattacharyya SC, Ussanarassamee A. Decomposition of energy and CO_2 intensities of Thai industry between 1981 and 2000. Energy Econ 2004;26:765–81.

Biswas WK. Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. Int J Sustain Built Environ 2014;3:179–86.

Boonkham P, Leeprechanon N. Decomposition analysis of changes in energy intensity of the Thai manufacturing sector during 1991–2013. Int J Mat Mech Manufact 2015; 3(3):152–6.

Bureau of Trade and Economic Indices. Producer price index by product group classification of products by activity (CPA). http://www.price.moc.go.th/price/ppi/index_new_e.asp, 2015. [accessed 15·06·10].

Chang Y, Ries RJ, Wang Y. The embodied energy and environmental emissions of construction projects in China: an economic input-output LCA model. Energy Policy 2010;38:6597–603.

Chontanawat J, Wiboonchutikula P, Buddhivanich A. Decomposition analysis of the change of energy intensity of manufacturing industries in Thailand. Energy 2014; 77:171–82.

Cui L-B, Peng P, Zhu L. Embodied energy, export policy adjustment and China's sustainable development: a multi-regional input-output analysis. Energy 2015;82:457–67.

DEDE. Thailand Energy Situation Annual Report 2000; 2000.

DEDE. Thailand Energy Situation Annual Report 2010; 2010.

Emission Database for Global Atmospheric Research (EDGAR). CO_2 time series 1990–2013 per capita for world countries. http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts_pc1990-2013&sort=des9. accessed October 2015.

EPPO. Energy Statistics of Thailand 2014. http://www.eppo.go.th/info/cd-2010/index.html, 2015. [accessed 15·04·03].

EPPO. Energy Statistics of Thailand. http://www2.eppo.go.th/info/index-statistics.html, 2016. [accessed 16·09·22].

BP. BP statistical review of world energy June 2016. https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-review-2016/bp-statistical-review-of-world-energy-2016-full-report.pdf, 2016. [accessed 16·12·5].

IPCC. Climate change 2014 impacts, adaptation and vulnerability. http://ipcc-wg2.gov/AR5/images/uploads/WG2AR5_SPM_FINAL.pdf, 2014. [accessed 16·09·12].

Jain S. An input-output analysis to estimate embodied energy of goods. Int J Sci Res 2012; 2:1–12.

Li Y, Hewitt CN. The effect of trade between China and the UK on national and global carbon dioxide emissions. Energy Policy 2008;36:1907–14.

Li F, Song Z, Liu W. China's energy consumption under the global economic crisis: decomposition and sectoral analysis. Energy Policy 2014;64:193–202.

Limmeechokchai B, Suksuntornsiri P. Embedded energy and total greenhouse gas emissions in final consumptions within Thailand. Renew Sustain Energy Rev 2007;11: 259–81.

Lin B, Sun C. Evaluating carbon dioxide emissions in international trade of China. Energy Policy 2010;38:613–21.

Lindner S, Guan D. A hybrid-unit energy input-output model to evaluate embodied energy and life cycle emissions for China's economy. J Ind Ecol 2014;18:201–11.

Liu Z, Geng Y, Lindner S, Zhao H, Fujita T, Guan D. Embodied energy use in China's industrial sectors. Energy Policy 2012;49:751–8.

Mäenpää I, Siikavirta H. Greenhouse gases embodied in the international trade and final consumption of Finland: an input–output analysis. Energy Policy 2007;35:128–43.

Miller RE, Blair PD. Input-Output Analysis: Foundations and Extensions. Cambridge University Press; 2009.

Office of the National Economic and Social Development Board (NESDB). Input-output table of Thailand. http://www.nesdb.go.th, 2016. [accessed 16·05·25].

ONEP. Thailand's Second National Communication under UNFCCC. https://unfccc.int/files/national_reports/non-annex_i_natcom/submitted_natcom/application/pdf/snc_thailand.pdf, 2011. [accessed 15·10·27].

ONEP. Thailand INDC-UNFCCC. http://www4.unfccc.int/ndcregistry/PublishedDocuments/Thailand%20First/Thailand_INDC.pdf, 2015. [accessed 17·01·04].

Peters GP. From production-based to consumption-based national emission inventories. Ecol Econ 2008;65:13–23.

Peters GP, Hertwich EG. Policy analysis CO_2 embodied in international trade with implications for global climate policy. Environ Sci Technol 2008;42:1401–7.

Schoer K, Buyny S, Flachmann C, Klink S, Mayer H. Environmental pressures from German imports and exports — results of environmental-economic accounting on embodied energy, carbon dioxide and transport of goods. 93rd DGINS Conference; 2007.

Shui B, Harriss RC. The role of CO_2 embodiment in US — China trade. Energy Policy 2006; 34:4063–8.

Su B, Ang BW. Input–output analysis of CO_2 emissions embodied in trade: a multi-region model for China. Appl Energy 2014;114:377–84.

Su B, Ang BW. Multiplicative decomposition of aggregate carbon intensity change using input–output analysis. Appl Energy 2015;154:13–20.

Su B, Huang HC, Ang BW, Zhou P. Input–output analysis of CO_2 emissions embodied in trade: the effects of sector aggregation. Energy Econ 2010;32:166–75.

Supasa T, Hsiau S-S, Lin S-M, Wongsapai W, Wu J-C. Has energy conservation been an effective policy for Thailand? An input–output structural decomposition analysis from 1995 to 2010. Energy Policy 2016;98:210–20.

Tang X, Snowden S, Höök M. Analysis of energy embodied in the international trade of UK. Energy Policy 2013;57:418–28.

Wang X, Cai H, Florig HK. Energy-saving implications from supply chain improvement: an exploratory study on China's consumer goods retail system. Energy Policy 2016;95: 411–20.

Wiedmann T. A review of recent multi-region input-output models used for consumption-based emission and resource accounting. Ecol Econ 2009;69:211–22.

World Bank. Data: GDP ranking. http://data.worldbank.org/data-catalog/GDP-ranking-table, 2015. [accessed Febuary 2016].

Zhang L, Hu Q, Zhang F. Input-output modeling for urban energy consumption in Beijing: dynamics and comparison. PLoS One 2014;9(3), e89850.