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Global Embodied Energy Flow and Stock Analysis with Endogeneous Fixed Capital

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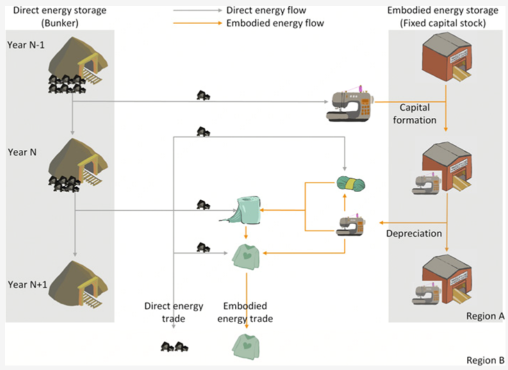
ABSTRACT: Fixed capital stock functions as an embodied energy storage system that connects economic activities which do not happen simultaneously. This paper constructs a dynamic energy input–output model to analyze embodied energy flows and stocks along both temporal and spatial dimensions from 2000 to 2014. The results show that 2043 exajoule of embodied energy was stored in the global fixed capital stock in 2014, which was about three times the world's direct energy use. Compared with those in developed countries, the gaps between the dynamic energy footprints and the traditional ones were larger in fast-developing countries. Net embodied energy usually flowed from high-intensity economies to lower-intensity economies, and around 10% of the energy embodied in trade came from depreciation. The dynamic embodied energy indicators provide information for improving energy efficiency and mitigating corresponding problems from the perspective of consumption.



KEYWORDS: *capital, energy input–output model, energy footprint, energy storage, investment, embodied energy*

INTRODUCTION

Energy is an essential resource that provides utility to people.[1] For instance, energy can be used directly to warm a house or indirectly to produce heavy jackets that warm the body. Therefore, global energy use increases constantly to meet the expanding consumption demand.[2,3] However, using energy has negative effects as well. It is widely understood that emissions from fossil energy sources lead to climate change[4] and health risks.[5] However, nonfossil energy also leads to problems.[6] Large hydropower plants have ecosystem impacts,[7] nuclear power plants pose risks from radiation,[8] and a life cycle perspective implies that even wind and solar power plants create environmental and social problems during their construction and disposal.[9,10]

Energy efficiency improvement is needed to reduce energy costs. From a production perspective, improving energy efficiency means reducing direct energy use per unit of output. From a consumption perspective, improving energy efficiency means reducing embodied energy per unit of final consumption. Energy embodied in goods and services stands for the total (direct plus indirect) energy used to produce them.[11,12] For example, the energy embodied in a pen includes the energy used directly in the plant to assemble it plus all the energy used indirectly to produce each input, including the penholder, the pen point, as well as the plant itself.

This paper analyzes embodied energy flows and stocks along both spatial (trade) and temporal (storage) dimensions and provides relevant insights to help improve energy efficiency. In particular, a dynamic energy input–output model is adopted by endogenizing international trade and capital stock change to calculate the dynamic energy footprints of 43 economies from 2000 to 2014. The term "dynamic energy footprint" is used to define both current energy (household and sector direct energy use) and previous energy (energy embodied in depreciation) embodied in final consumption of one year. This paper analyzes dynamic footprints because energy embodied in trade, fixed capital, and final consumption is interconnected. In terms of spatial dimension, energy embodied in imports affects national energy footprint. In terms of temporal dimension, the construction of fixed capital and the occurrence of capital depreciation make the energy embodied in fixed capital stock (FCS) this year affect the future national energy footprint.

It needs to be clarified that embodied energy trade and storage is different from direct energy trade and storage. Direct energy trade refers to the direct trade of coal, crude oil, and other energy sources. While embodied energy trade occurs when all goods and services are traded. In 2013, the direct energy trade of crude oil, natural gas, and coal summed up to 167 Exajoules (10^{18} Joules, EJ hereafter).[13] However, embodied energy trade accounts for much more: 519 EJ.[14] Like energy trade, there are direct and embodied energy

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storages. Direct storage saves energy in the physical form for future use. For example, underground gas storage is often used to meet the peak gas demand in the heating season.[15] By contrast, embodied energy storage redistributes energy service across time by storing embodied energy (not physical energy) in FCS. Owing to the lengthy life cycle of fixed capital, the effect of embodied energy storage becomes more observable in the long term. For example, a new aircraft stores embodied energy during its building period when the aircraft becomes the gross fixed capital formation (GFCF) and provides transport services that embody energy during its service period through aircraft depreciation.

■ MATERIALS AND METHODS

Dynamic Energy Input−Output Model. To build a comprehensive understanding of a country's energy use and the associated cost, information about territorial direct energy use from the production perspective and embodied energy from the consumption perspective are useful. While territorial direct energy use data are periodically compiled by governments and major institutions, embodied energy accounting has attracted increasing attention in recent years. Embodied energy and carbon emissions of products,[16,17] industries,[18] countries,[19−21] regions,[22] and inter-regional trades[23−25] have been reported.

The Input−Output Analysis (IOA) is the most frequently applied method for macro-level embodied energy accounting, and this method is still being improved in various aspects. One of the most important improvements in modeling is closing the system to obtain a more comprehensive reflection on life-cycle energy uses and emissions.[26] For example, international trade and foreign production technology are closed to reflect the impact of international feedback in national energy footprint accounting.[24,27,28]

In an extended production function, we can write $Y = F(K, L, N)$, where Y, K, L, and N indicate output, capital input, labor input, and energy input, respectively. If substitution exists (which is true in most cases), using more K or L will save N to get the same Y. At the same time, the production of K and L also needs N. Therefore, besides trade internalization, labor and capital internalizations are another two important ways to improve the IOA and energy footprint accounting. As this paper focuses on the role of capital in global energy footprint accounting, this paper constructs a capital endogeneous model.

Capital endogenization considers that not only intermediate inputs (such as steel used by pen manufacturers) but also fixed capital used in production (such as machines owned by pen manufacturers) contributes to the embodied energy of the final output.[29] Capital endogeneous methods are mainly divided into two categories: the augmentation method and the flow matrix method.

The augmentation method treats all types of capital as a homogeneous commodity and adds the capital sector to the intermediate input matrix. Calculated by this approach instead of the traditional input−output model, Australia's CO_2 intensity of different sectors increased by about 10−15% on average[30] and China's export-related CO_2 emissions were 43% higher.[31]

The flow matrix method disaggregates capital input and capital expenditure to create a capital flow matrix. Bullard III and Herendeen[32] extended the 82-sector table of interindustry capital flows compiled by the BEA to 92 sectors to match the input−output table they used. Lenzen and Treloar[30] used the semi-survey method to construct a capital flow matrix. Similar to the results of the augmentation method, the embodied energy intensity calculated by the flow matrix method is also higher than that of the traditional energy input−output model.

In early studies, a constant FCS assumption (investment and depreciation are equal in a year) lay in both methods. The total FCS of most developed countries is relatively stable; thus, the bias introduced by the assumption is acceptable. However, for fast-developing countries with high capital investment compared to capital depreciation, the traditional model significantly overestimates the energy footprints.

Containing the difference between capital formation and capital consumption in the model can avoid such bias. Adopting the augmentation method, Chen et al.[33] added depreciation, inventory, and time to the traditional model and constructed a dynamic capital endogeneous model to calculate the CO_2 intensity with the World Input−Output Database (WIOD). Constructing a capital flow matrix for 49 economies with the EXIOBASE data and consumption of fixed capital in KLEMS and national accounts, Södersten et al.[26] calculated global carbon footprint. This model has been used and improved for global and regional embodied materials, energy, and other environmental pressure accounting.[34−36] Similarly, Miller et al.[37] constructed a capital flow matrix of America using consumption of fixed capital rather than capital formation, and environmental impacts on capital consumption were analyzed based on this matrix.[38]

After weighting the data quality (especially for the fast-developing countries which contribute significantly to the capital stock change but have poor sector-specific capital stock data) and the research target (the impact of fixed capital as a whole on global energy footprint), this paper chooses the augmented matrix method and regards fixed capital to be a homogeneous good. To be specific, we make improvements to the model presented in Chen et al.[33] by modifying the depreciation calculation and including price changes. A detailed methodology can be found in the following text as well as the Supporting Information, Supporting Text. The discussion on different asset types will be the direction of the follow-up research. The definitions of all abbreviations in eqs 123 are shown in Table 1.

Equation 1 is the energy balance equation for sector i in the traditional energy input−output model. By setting up n equations, the embodied energy intensity ε of each sector can be calculated.

$$g_i + \sum_{j=1}^{n} x_{j,i}\varepsilon_j = x_i\varepsilon_i,\ \ i = 1, 2, ..., n \tag{1}$$

The basic idea of the energy input−output model is conservation of embodied energy, that is, the energy embodied in the total input (sum of direct energy use and energy embodied in the intermediate input) of sector i equals the energy embodied in the total output of this sector.

The traditional model defines the energy footprint as direct and indirect energy consumption in the final demand, so the energy embodied in GFCF is included in a country's footprint. However, energy footprint should be considered energy service to meet final consumption in the current period, but energy embodied in GFCF is stored in FCS temporarily to provide future energy service. Therefore, energy embodied in depreciation rather than in GFCF should be included in the energy footprint.

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Table 1. Abbreviations and Definitions in This Paper

abbreviation	definition
g_i	the direct energy use in sector i
$x_{j,i}$	the transaction from sector j to sector i
ε_i	the embodied energy intensity in sectors i: direct and indirect energy use when producing one unit output in sectors i
x_i	the total output in sector i
d_i	the capital depreciation in sector i
$\bar{\varepsilon}_k$	the embodied energy intensity of the FCS in region k
c_i	the changes in inventories and valuables in sector i
ca_i	the use of inventories and valuables in sector i
cb_i	the formation of inventories and valuables in sector i
s_k	the FCS in region k
$f_{j,k}$	the output of sector j which becomes the GFCF in region k
subscript i, j	sector i or j among n sectors
subscript k	region k among m regions, each region has n/m sectors
subscript t	period t
superscript c	the variable is denominated in current years' prices
superscript p	the variable is denominated in previous years' prices. for example, $x^p_{i,2001}$ stands for the total output in sector i in year 2001 and is denominated in 2000 USD.

This paper adds time and capital to the traditional energy input−output model to make it dynamic. Four additional assumptions are made when compared with the traditional model.[33] (a) Depreciation is the loss of FCS, so this paper assumes that the embodied energy intensity of fixed capital depreciated in period t is the same as that of FCS in period $t-1$. (b) This paper assumes that the embodied energy intensities in sector i are the same in the first two periods ($\varepsilon_{i,t_0+1} = \varepsilon_{i,t_0}$), as are the embodied energy intensities of FCS in region k ($\bar{\varepsilon}_{k,t_0+1} = \bar{\varepsilon}_{k,t_0}$). The discussion based on different initial conditions ($\bar{\varepsilon}_{k,t_0+1} = 1.05 \times \bar{\varepsilon}_{k,t_0}$ and $\bar{\varepsilon}_{k,t_0+1} = 0.95 \times \bar{\varepsilon}_{k,t_0}$) can be found in the Supplementary Information of Chen et al.[33] (c) Because of our lack of data on inventories and valuables usage and formation, this paper assumes that if $c_{i,t} > 0$, then $ca_{i,t} = 0$, $cb_{i,t} = c_{i,t}$; if $c_{i,t} < 0$, then $ca_{i,t} = -c_{i,t}$, $cb_{i,t} = 0$. Note that inventories are current assets, not fixed capital. (d) There are no data on which sector uses the inventories and valuables of sector i. Compared with total output and GFCF, changes in inventories and valuables are smaller, so this paper assumes that the inventories and valuables in sector i are all used as the intermediate input of this sector for the sake of simple calculation.

Then, we can enrich eq 1 into eq 2. The embodied energy in input for sector i includes direct energy use and embodied energy of intermediate input, inventories and valuable usage, and fixed capital depreciation.

$$g_{i,t} + \sum_{j=1}^{i-1} x^p_{j,i,t}\varepsilon^p_{j,t} + (x^p_{i,i,t} - ca^p_{i,t})\varepsilon^p_{i,t} + ca^p_{i,t}\varepsilon^c_{i,t-1} + \sum_{j=i+1}^{n} x^p_{j,i,t}\varepsilon^p_{j,t} + d^p_{i,t}\bar{\varepsilon}^c_{k,t-1} = x^p_{i,t}\varepsilon^p_{i,t},\quad i = 1, 2, ..., n;\ k = 1, 2, ..., m \qquad (2)$$

Equation 3 is the energy balance equation of FCS in region k. The embodied energy of FCS in period $t-1$, minus the embodied energy of depreciation in period t, plus the embodied energy of GFCF in period t, equals the embodied energy of FCS in period t.

$$s^c_{k,t-1}\bar{\varepsilon}^c_{k,t-1} - \bar{\varepsilon}^c_{k,t-1}d^p_{k,t} + \sum_{j=1}^{n} f^p_{j,k,t}\varepsilon^p_{j,t} = s^p_{k,t}\bar{\varepsilon}^p_{k,t},\quad k = 1, 2, ..., m;\ j = 1, 2, ..., n \qquad (3)$$

Because we assume that $\varepsilon_{i,t_0+1} = \varepsilon_{i,t_0}$ and $\bar{\varepsilon}_{k,t_0+1} = \bar{\varepsilon}_{k,t_0}$, by solving eqs 2 and 3 synchronously, we can get the embodied energy intensities of each sector and FCS in 2000 and 2001. Then, by solving these two equations sequentially, we can get the intensities in each period from 2002.

Data Source and Manipulations. The multiregional input−output tables, GFCF, and exchange rates are derived from WIOD (2016 release).[39] The world is divided into 44 economies, with each economy divided into 56 sectors. The

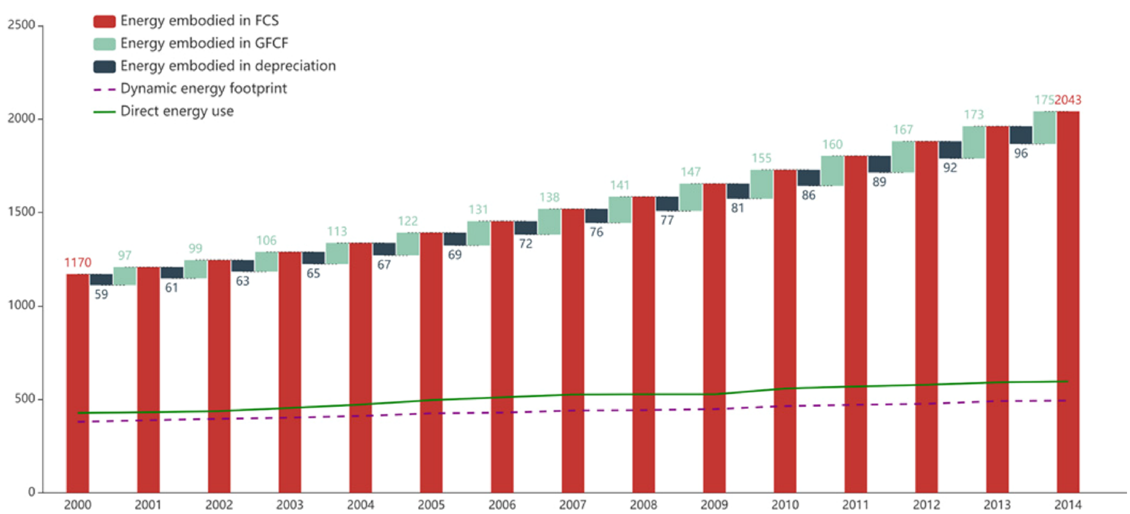

Figure 1. Global direct and embodied energy of 2000−2014 (EJ). FCS stands for fixed capital stock. GFCF stands for gross fixed capital formation. Direct energy use includes household and sector physical energy use of one year. Dynamic energy footprint includes both current energy (household and sector direct energy use) and previous energy (energy embodied in depreciation) embodied in the final consumption of one year. The gap between the dynamic energy footprint and direct energy use equals the difference between energy embodied in capital depreciation and GFCF.

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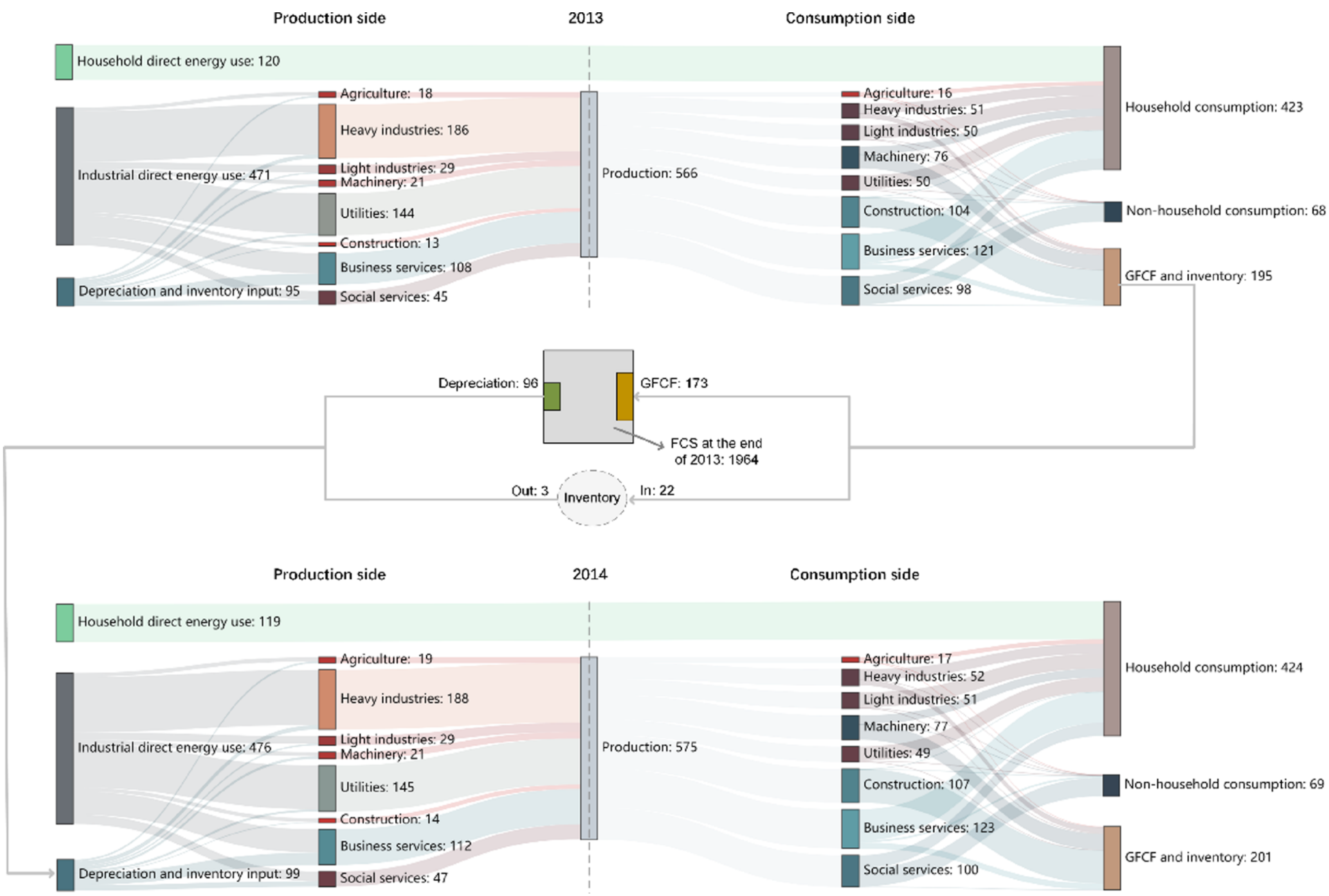

Figure 2. Intertemporal energy flows connecting 2013 and 2014 (EJ). FCS stands for fixed capital stock. GFCF stands for gross fixed capital formation. Because the change in energy embodied in inventories and valuables is small, we combine inventories and valuables and fixed capital in this figure as "Depreciation and inventory input" and "GFCF and inventory". The area of the ellipse does not represent the amount of energy embodied in inventories and valuables. Household direct energy use includes all primary and secondary energy (household direct fuel use, personal transport fuels, etc.) consumed by households. Detailed sector classification is provided in Supporting Information, Table S1.

names of the sectors and economies are shown in Supporting Information, Tables S1 and S2.

The gross output price index is provided by the Socio-Economic Accounts (SEA) of WIOD (2016 release).[40] The FCS price index, FCS, and depreciation are estimated based on data from the EU KLEMS database (2019 release),[41] the SEA,[40] and the BEA.[42]

Sector and household direct energy use are derived from the EU Science Hub,[43] and the energy accounting standard is the physical energy content. According to the global energy assessment, there are two other major energy accounting standards, namely, the partial substitution method and the direct equivalent method.[44] Considering that the choice of accounting standard may affect the results, we conducted sensitivity analyses by changing the energy accounting standards, and the results are consistent with those presented in the main text. Because the direct energy use provided by the EU Science Hub[43] includes both primary and secondary energy, there is a problem of double counting.[45] In this paper, the elimination of double counting is carried out according to the energy balance data of the International Energy Agency.[13]

Detailed methods, data sources, and sensitivity analyses can be found in the Supporting Information, Supporting Text.

■ RESULTS

Global Embodied Energy. Along with the increasing energy use to sustain economic development, global FCS functions as a large, embodied energy storage system to redistribute embodied energy across time. During 2000−2014, a growing amount of energy was embodied in GFCF, capital depreciation, and FCS (Figure 1). With more energy embodied in GFCF than in depreciation, the world's direct energy use exceeded its dynamic energy footprint by around 17% (60 EJ per year), leading to net storage of embodied energy in FCS. On average, the energy embodied in the global FCS (1552 EJ) equaled 3.0 times the annual direct energy use (513 EJ) and 3.6 times the annual dynamic energy footprint (437 EJ). Moreover, both ratios continued to grow, implying that capital plays a more and more important role in economic development and energy footprint.

The intertemporal energy flows of the world are illustrated in Figure 2. Energy can be consumed by households directly or it can be used to produce, and thus embodied in, an output to meet final consumption. During the latter process, FCS serves as an embodied energy storage system that connects different economic activities which do not happen simultaneously. First, energy is embodied in GFCF during production (for example, when producing a plane, energy used directly and indirectly is embodied in the plane). Second, GFCF becomes part of FCS (the plane is bought by an airline). Third, the embodied

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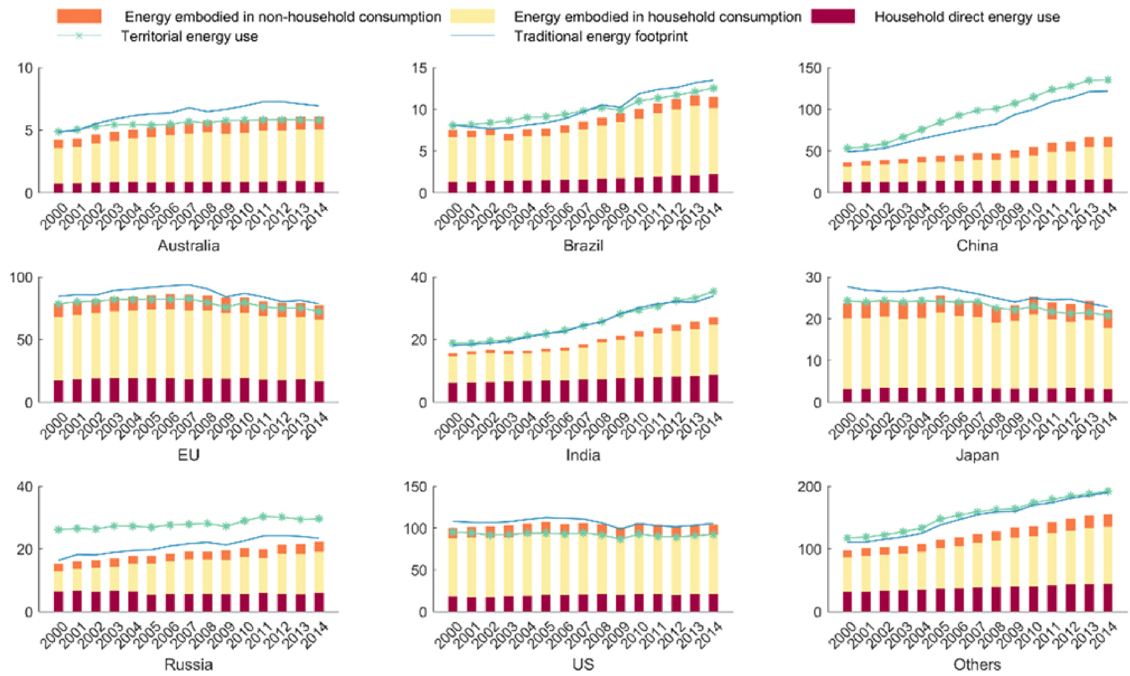

Figure 3. Direct and embodied energy indicators of 2000−2014 (EJ). Territorial energy use is the sum of household direct energy use and sector direct energy use. Traditional energy footprint is calculated by the traditional model (without capital endogenization) as the sum of household direct energy use and energy embodied in final demand (the sum of final consumption, gross fixed capital formation, and changes in inventories and valuables).[46] Dynamic energy footprint is calculated by the dynamic model (with capital endogenization) as the sum of household direct energy use, energy embodied in household, and nonhousehold consumption. The value of dynamic energy footprint is indicated by the total height of the stacked bars. "Others" stands for the rest of the world except for the listed eight economies.

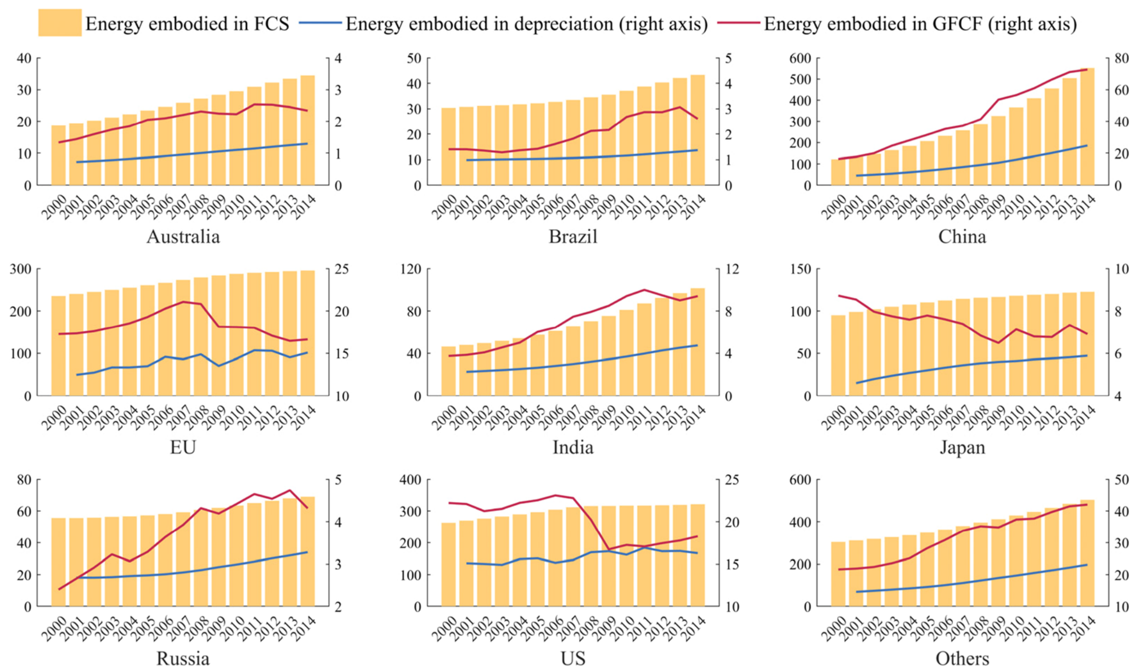

Figure 4. Energy embodied in fixed capital (EJ) of 2000−2014. FCS stands for fixed capital stock. GFCF stands for gross fixed capital formation.

energy of FCS enters the production process through depreciation to meet future consumption (as the aircraft depreciates, energy embodied in the plane is gradually converted to business services, then to household consumption).

In 2014, the energy embodied in production reached 575 EJ, while industrial direct energy use and energy embodied in depreciation were 476 EJ and 99 EJ, respectively. The heavy industries sector contributed the largest portion (188 EJ, or 33%) to the energy embodied in production, followed by the utilities sector (145 EJ, or 25%) and the business services sector (112 EJ, or 19%). Large portions of embodied energy came from industrial direct energy use for the heavy industries sector, the utilities sector, the light industries sector, the construction sector, and the agriculture sector. Meanwhile, energy embodied in depreciation was important for the

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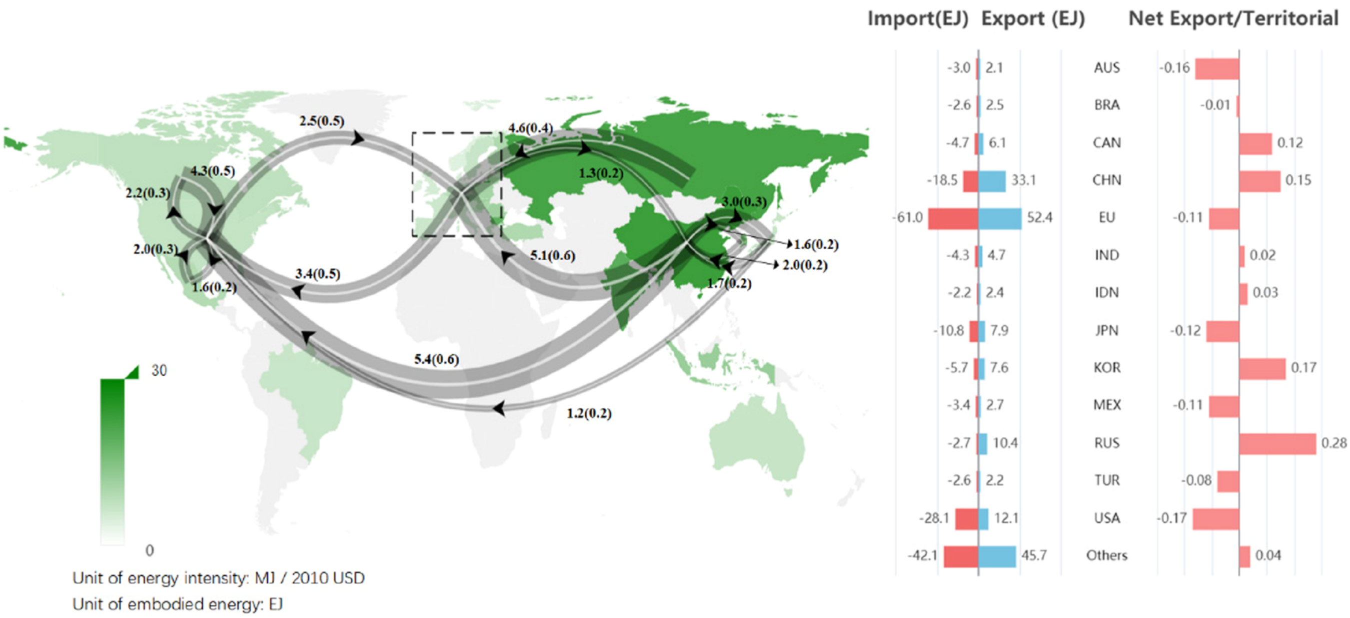

Figure 5. Major international embodied energy trade on average in 2000−2014. The region in the dotted box represents the EU. The color of the territory indicates energy intensity. The curve with an arrow illustrates the energy embodied in trade flow. The numbers beside the curves are total embodied energy and historical embodied energy (energy embodied in depreciation, inside parentheses) in bilateral trade. On the right side, "Import" and "Export" represent energy embodied in import and export, respectively, and "Net Export/Territorial" stands for the ratio of energy embodied in net export to territorial direct energy use.

business services sector, the social services sector, and the machinery sector.

The energy embodied in global final demand summed up to 694 EJ in 2014, where household consumption, nonhousehold consumption, and GFCF accounted for 424 EJ, 69 EJ, and 201 EJ, respectively. The business services sector (123 EJ, or 18%), construction sector (107 EJ, or 15%), and social services sector (100 EJ, or 14%) embodied larger proportions of energy. The embodied energy intensities in the utilities sector, heavy industries sector, and construction sector were higher than those in other sectors, reaching 41.8, 20.3, and 11.8 MJ/2010 USD, respectively, in 2014 (Table S13). Households consume most of the final outputs, and the associated embodied energy in goods and services mainly came from the business services sector, the light industries sector, the utilities sector, the heavy industries sector, and the agriculture sector. Almost all energy embodied in construction and around two-thirds of energy embodied in machinery outputs was stored in GFCF for future use. The energy embodied in goods and services paid by nonhousehold institutions was mainly from social services sectors.

National Embodied Energy. While the world's dynamic energy footprint rose during 2000−2014, the national embodied energy varied (Figure 3). The EU, Japan, and the US have passed their dynamic energy footprint peaks. On the other hand, the dynamic energy footprints of the BRICs countries (Brazil, Russia, India, and China) and Australia maintained steady growth.

Figure 3 contrasts the traditional and dynamic energy footprints to show how capital endogenization affects footprint accounting. A large fraction of energy stored in capital stock to meet future final consumption (in domestic and foreign countries) is included in domestic energy footprint of the building year based on the traditional model. This is an approximation based on the assumption of constant FCS, that is, investment and depreciation are balanced.[31,47] By releasing this assumption and acknowledging the contribution of capital stock change, the dynamic energy footprint includes energy embodied in depreciation but excludes energy embodied in GFCF and provides a more close-to-reality accounting of the embodied energy. The difference is significant for fast-developing countries. For example, traditional footprints were on average 38 and 20% larger than the dynamic ones for China and India, respectively, during 2000−2014.

The regional embodied energy associated with fixed capital is further illustrated (Figure 4). Energy embodied in GFCF is frequently affected by the macroeconomic environment. For example, energy embodied in GFCF in the US was affected by the financial crisis and decreased sharply in 2008 and 2009. By contrast, energy embodied in FCS and depreciation is more stable. Because depreciation includes tangible wear and tear of equipment, housing, and so forth, as well as intangible wear and tear caused by technological progress, depreciation rates would be relatively stable if there were no major industrial revolution. GFCF embodied more energy than depreciation in every economy, leading to net embodied energy accumulation during the research period. As a result, FCS stored embodied energy not only at the global level but also at the national level. Owing to rapid capital accumulation, China exceeded the US and became the top embodied energy storage country in 2009.

International Energy Interaction. China was the largest embodied energy exporter from 2000 to 2014, with 5.4 EJ and 5.1 EJ of energy embodied in its exports to the US and the EU. By contrast, the US was the largest embodied energy importing country, and the EU was the largest embodied energy importing region. In general, embodied energy flows from more energy-intensive economies (e.g., China and Russia) to less energy-intensive ones (e.g., the EU, the US, and Japan). Thus, improving energy efficiency in energy-intensive economies is needed to reduce global energy consumption. In addition, all trade flows contained depreciation, a fundamental

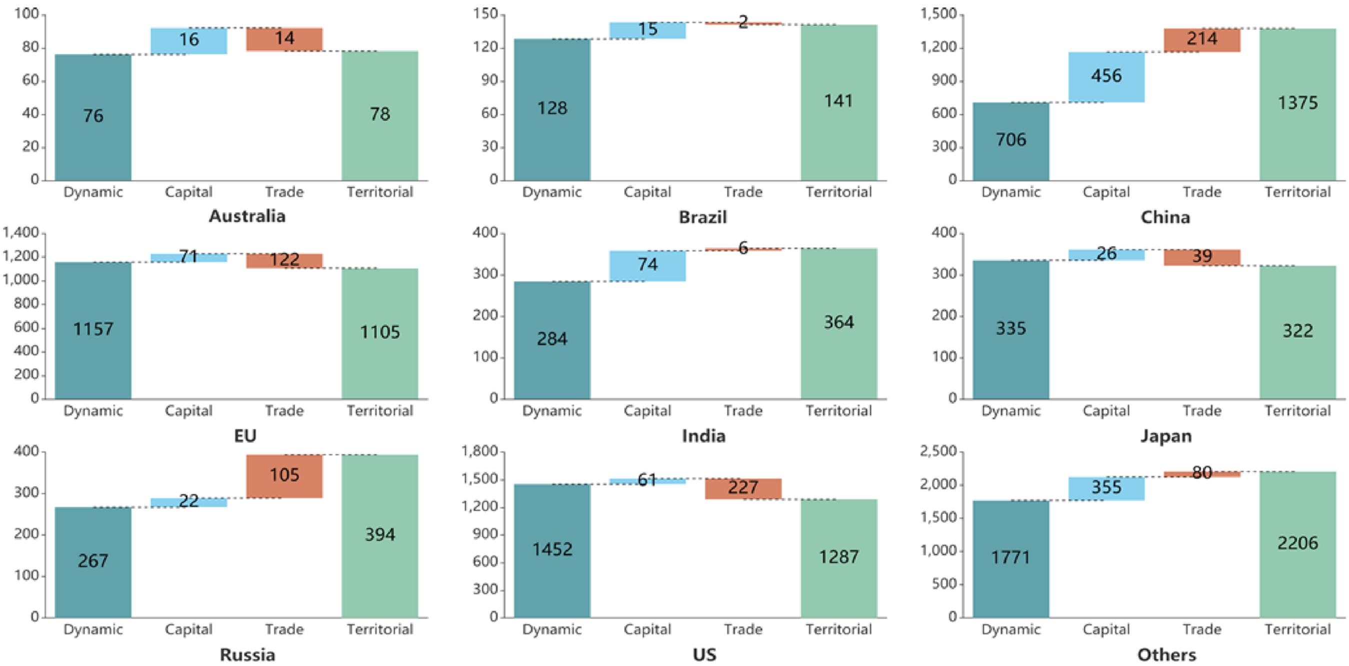

Figure 6. Decomposition of the deviation between territorial energy use and dynamic energy footprint (sum of 2001−2014). Dynamic indicates the dynamic footprint. Capital indicates energy embodied in the changes of fixed capital stock, inventories, and valuables. Trade indicates energy embodied in net export. Territorial indicates territorial direct energy use.

input of production. On average, 10% of the energy embodied in trade came from depreciation (Figure 5).

The gap between a country's territorial energy use and dynamic energy footprint results from energy embodied in international trade and FCS (Figure 6). Compared to FCS, which consistently delays consumption through the cross-period reallocation mechanism, that is, stores embodied energy in year *N* through GFCF and allocates embodied energy in the coming years through depreciation, the impact of international trade on countries varies. With given territorial energy use, a country can expand its final consumption and dynamic energy footprint through embodied energy trade deficit, that is, having more energy embodied in imports than in exports. For example, the US received 227 EJ of embodied energy trade deficit from 2001 to 2014, equivalent to 17% of its territorial energy use. However, as a zero-sum game, the global embodied energy trade deficit comes with an equal surplus. Major surplus receivers include China and Russia, with 214 EJ and 105 EJ energy embodied in net exports during the same period.

■ DISCUSSION

This paper constructs a dynamic energy input−output model to calculate the embodied energy flows and stocks from 2000 to 2014. From a global perspective, when direct energy use increased, so did the energy embodied in GFCF, depreciation, and FCS. In 2014, FCS had a storage capacity of 2043 EJ, which was about three times the world's direct energy use. For fast-developing countries like China, more energy was embodied in FCS for future use rather than in goods and services for current consumption. Meanwhile, net embodied energy usually flowed from high-intensity economies to lower-intensity economies, and around 10% of the energy embodied in trade came from depreciation.

This paper shows that on average, the energy embodied in the global FCS equals 3.6 times the annual dynamic energy footprint and the ratio continues to grow. This is related to continued economic development in developing countries. Along with economic development, the FCS of developing countries will continue to grow, which will affect the future dynamic energy footprint in two ways. First, the embodied energy in FCS will be gradually transferred to future final goods and services through depreciation. Second, once fixed capital assets (buildings, vehicles, etc.) are built, there will be energy consumed by them. In contrast, as energy efficiency improves, direct energy use may decrease; thus, embodied energy consumption associated with fixed capital will account for a higher share of the dynamic energy footprint. Therefore, when implementing long-term actions, the temporal reallocation mechanism (investment decisions made in this year will affect the dynamic energy footprint in the following years) should be considered. For example, if a country is phasing out its fossil energy power plants, it might build new nuclear or renewable power plants. Different energy infrastructures will affect the dynamic energy footprint in the following years differently. Considering this mechanism, the government should focus on both direct energy use and energy embodied in investment decisions to reduce accumulated fossil energy use in the long term.

In an ideal market, international trade would lead to efficient global outcomes, and countries would gain net benefits based on their comparative advantages. However, the real-world market is far from perfect for many reasons, one of which is the environmental externalities embodied in trade. If the economic cost of trading products produced in the exporting country is lower than that in the importing country, but the energy consumption is higher, this trade can reduce the economic cost of both trading parties but may increase the total energy consumption. Therefore, embodied energy and environmental impacts associated with trade need to be internalized as economic costs or considered in trade policies to sustain an efficient global trade structure.

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Overall, a comprehensive energy accounting system that reveals both direct and embodied energy flows along both temporal and spatial horizons is important for future policy design. Also, dynamic energy footprint can be an important part of this system. From a global perspective, improving the energy performance of the least energy-efficient countries, mainly developing countries, can help mitigate the negative effects caused by production outsourcing.[48] A global cap-and-trade system could be effective for energy conservation, but its political feasibility is low. A more practical alternative is to build a mechanism similar to the clean development mechanism based on the principle of common but differentiated responsibilities. Under this mechanism, a developed country can invest in or transfer technology to a developing country to increase its energy efficiency, and the saved energy will be regarded as the achievement of the developed country. The dynamic energy footprint indicators can serve as a baseline to design such a mechanism because it has both global and historical concerns. As the energy embodied in depreciation will be included in the dynamic energy footprint, developed countries will have an incentive to help developing countries improve their energy performances in both production technology and fixed capital. This will ultimately improve global energy efficiency.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c03152.

> Estimate fixed capital stock and depreciation; eliminate double counting of energy consumption; adjust pricing; change energy accounting standard; energy intensity (MJ/2010 USD) and energy embodied in major bilateral trade flows (EJ) of 2000−2014; sector matching; energy intensities; estimation data; dynamic energy footprint; and net energy outflows (ZIP)

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Author Contributions

Z.C. and P.C. planned the analysis, Z.C. and P.C. analyzed the data, Z.C., P.C., M.L., and B.X. contributed materials/analysis tools, and Z.C., P.C., M.L., and M.A. wrote the paper.

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Notes

The authors declare no competing financial interest.

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