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Hybrid input-output analysis of embodied energy security

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HIGHLIGHTS

• We introduce a hybridized approach to model energy flows through global trade.
• 23% of embodied energy traded between countries with no direct energy linkage.
• The global economy is very dependent on imports of indirect energy.
• The global import portfolio of indirect energy is diverse.
• China, Russia, and the U.S. are critical intermediary nodes in the indirect energy network.

ABSTRACT

National energy security depends on a stable network of international trade in not only primary energy (e.g., crude oil and natural gas) and secondary energy (electricity), but also embodied energy. The latter consists of both direct energy used to directly produce a final good (e.g., crude oil used to make synthetic rubber), and indirect energy incorporated in intermediate goods and services used to make a final product (e.g., coal used to smelt iron into steel that goes into the frames of cars). While studies have analyzed international trade in embodied energy, the global flow of the indirect component of this energy has not been explicitly examined. Here we develop and apply a new hybrid input-output database of energy flows within and among the world’s largest 136 economies so as to compare and contrast energy security metrics of indirect energy against direct energy. We find that 23% of the world’s embodied energy network is comprised of trade linkages in indirect energy between primary energy producing countries and other countries with which they do not have direct trade ties. We also find that the global economy is 90% more dependent on imports of indirect energy than direct energy and, unsurprisingly, that countries generally have many more trading partners in indirect energy than they do in direct energy. These differences in energy security metrics are assessed at the global, sectoral, and national levels over the years 2000–2015. The differences point to critical intermediary country nodes in the global trade network of indirect energy, principally the United States, China, and Russia.

1. Introduction

Energy security entails the uninterrupted availability of energy at an affordable price, and is often considered with respect to nations’ dependence on net imports of energy resources, refined fuels, and electricity [1-3]. Nations, however, not only consume energy directly, but also indirectly in the form of energy incorporated in goods and services during their production. Energy security therefore not only relies on the global flow of primary and secondary energies, but also on the trade of goods and services produced using energy. In fact, trade strategies for critical goods and services can also be viewed in the context of energy security; whichever of these is not produced domestically must be produced in other countries using the latter’s energy resources. Consequently, by shifting production overseas, a nation not only saves on energy used domestically, but also increases its dependence on foreign energy.

How much this dependence truly affects energy security remains to be determined. Such an evaluation first requires a clear distinction between several important types of energy. A nation’s economic output, and thus its citizens’ standard of living, depends on the nation’s use of primary energy, such as natural gas, and secondary energy, such as electricity [4]. In turn, this consumed energy is generally referred to as

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embodied energy and consists of two components, direct and indirect energy. Direct energy is the primary energy that an economic sector consumes in producing a good or service. Examples include coal used to smelt iron, natural gas used to make fertilizer, and enriched uranium to generate electricity. In contrast, indirect energy (also referred to as embedded energy in this paper) includes the energy in steel embedded in the iron used to forge the steel, the energy embedded in the fertilizer used to grow the crops, and the energy in a cell phone embedded in the electricity used to assemble the phone. Note that many goods and services involve multiple forms of indirect energy. In the case of the mobile phone, for example, its assembly also includes indirect energies from crude oil refined into the phone’s plastic components, and from natural gas burned in a furnace to make the phone’s glass components. Furthermore, in the current era of global supply chains, some of these components will have been produced domestically, while others will have been imported from overseas. Thus, the indirect energy requirements of a nation’s economic sectors are much larger, and have a much wider geographic scope, than their direct energy requirements.

There are at least three ways that a nation’s reliance on indirect energy imports could influence its energy security. The first is in terms of economic security. For example, say a nation imposes a sanction on primary energy imports from a major energy exporter. While the objective of the former would be to impact the latter’s direct energy exports, the sanctioning nation could still end up supporting the sanctioned nation if the latter’s primary exports were used by another country to make a non-energy good that the sanctioning nation imports. Secondly, the security of indirect energy imports is relevant to supply chain security. An international supply chain for a critical service, such as telecommunications, may seem secure because the equipment’s components are made and/or operated by sectors in different countries that are politically stable and have good relations with one another. The indirect energy in these components, however, may ultimately be sourced by yet another country that is politically unstable or a geopolitical adversary [5]. And third, indirect energy security bears on environmental security. Say a nation seeks to reduce its greenhouse gas emissions by shifting to greater reliance on domestically-sourced renewable energy. This effort is undermined if the nation continues to import goods and services rich in indirect energy produced using fossil fuels (i.e. “carbon leakage”) [6,7]. For all three types of security issues, the global market via international trade gives opportunities to reduce the risks stemming from a nation’s indirect energy imports. A nation cannot identify and preemptively act on these options, however, without first knowing where the risks associated with its indirect energy imports actually lie.

A spate of recent papers has evaluated embodied energy in the context of international trade, of which a few address energy security [8-10]. Of particular note is a series of papers led by G.Q. Chen and X.F. Wu that attempt to trace embodied energy flows through international trade from their sources to their sinks [6,11,12]. Chen et al. (2018) used the framework adopted by these authors and then employed network analysis metrics to evaluate energy security [8]. In these papers, embodied energy is estimated as the sum of direct and indirect energy inputs. In our study, we build on the existing literature by separating out and comparing direct and indirect energy flows, rather than combining them. Furthermore, in the recent papers just cited, energy flows are traced from the point at which direct energy is first consumed, and energy security is measured based on where a country sources its energy-intensive goods and services. Left unaddressed are how the energy security of the countries producing those energy-intensive goods and services may impact the energy security of consumers further downstream in the supply chain. When a country consumes a product that is manufactured abroad, the production’s energy requirements are generally excluded from its energy security measurements. In this study, we add this crucial component by linking the energy security of energy-consuming countries back to the energy security of countries that first produced, rather than exploited, the energy, thus expanding the boundaries of the global energy system.

Empirical methods grounded in economics and developed in industrial ecology have become important tools for estimating embodied energy and their associated emissions. Input-output models (IO) assess each sector’s direct and embodied requirements by arranging the major sectors of an economy along both the rows and columns of a matrix. While originally developed to examine the financial value of the goods and services flowing among sectors, IO has since also been modified to estimate sector-level energy consumption to better target energy efficiency policies and trace energy-related emissions. This approach is commonly called an environmentally extended IO analysis (EEIO). Studies have used EEIO to estimate the size and drivers of energy consumption in specific industries, such as construction [13,14], manufacturing [15], and agriculture [16], as well as entire national economies [17-19].

More recently, IO has been extended to include large-scale multi-regional input–output models (MRIO) that trace financial and material flows in international trade. Three databases that have been widely used for this purpose are the World Input-Output Database (WIOD), EXIOBASE, and the Eora Global Supply Chain database [20-23]. These databases rely on a direct input–output framework (DIO), in which researchers first calculate financial flows within an economic system and assign energy requirements ex-post using environmental extensions [24]. Energy requirements are therefore directly linked to financial requirements. Studies that build on these models, or the MRIO framework in general, have found that major economies import a large percentage of embodied energy from developing countries with energy-intensive industries [6,8]. This also means that the former are importers of energy-related emissions of the latter. For example, the United States is a net importer of carbon emissions associated with trade, while China is a net exporter [25].

An important limitation of DIO, in the context of global MRIO, is that it often aggregates energy flows such that the origins of this energy are not defined. Thus, while DIO is able to trace energy consumption through an economy starting from the points at which it first uses energy, it does not follow the energy value chain to the ultimate sources where the energy resources were first extracted [9]. This can be done, however, using an extension of IO known as hybrid-unit input–output (HIO) analysis which, like DIO, is based on the global MRIO framework. In HIO, rows and columns representing energy sources are inserted into the underlying IO matrix such that energy production and consumption are included as additional physical flows in the economic system. HIO is also commonly referred to as a mixed-unit IO analysis because its underlying IO table includes energy-to-monetary units and monetary-to-energy units (e.g. J/USD and USD/J). This is in contrast to DIO, which includes monetary transactions in the underlying IO table and a separate table of environmental extensions. A significant advantage of this is that HIO eliminates the assumption required by DIO that one dollar of output to one sector is equivalent to a dollar of output to another [26]. DIO uses this assumption to estimate energy flows from financial flows. However, sectoral differences in energy prices make clear that the proportionality assumption does not hold in reality. For example, electricity prices paid by industrial sectors are often lower than those paid by commercial sectors, which in turn are even lower than the prices charged to the residential sector [27]. Furthermore, HIO explicitly maps feedbacks between energy sectors and non-energy sectors. For instance, coal mining requires substantial amounts of electricity. Some of that electricity is generated in a much larger power plant fueled by coal. Therefore, there is some uranium-based primary energy that is required in the production of coal-based primary energy. HIO would capture this energy flow, while DIO would not.

1 DIO analyses are often referred to as hybrid IO because they combine a process-based life cycle approach to an input–output approach. We therefore note that in this study, we define HIO as a hybrid-unit model.
HIO was introduced in a seminal paper by Bullard and Herendeen (1975) [28], in which the authors apply a hybridized approach to the 1967 input-output table for the United States. Since it was introduced over 50 years ago, HIO has been used mainly to assess energy use by single economies or sectors. Treloar (1997) uses HIO to estimate the energy that is embodied in the Australian residential sector [29]. Liang et al. (2010) builds an HIO table that traces both energy and pollutants in Suzhou, China [30]. Lindner and Guan (2014) compiles a national-level HIO matrix to estimate total per capita energy consumption in China [31]. Methodological advancements have also been made since Bullard and Herendeen (1975), with some combining HIO with other modeling techniques. Examples include Kagawa and Inamura (2001) which applies a structural decomposition analysis to an HIO for Japan [32], and Igos et al. (2015) which combines a computable general equilibrium model with HIO for Luxembourg [33]. Other methodological advancements have focused more on the mechanics and validation of the HIO framework [34-36]. Yet few studies have applied HIO to a global MRIO framework, primarily because HIO is very data intensive [26,37].

While HIO is data intensive, it allows us to understand global energy security as a metric comprised of two links: (i) the link from primary energy exporters to primary energy imports (which is the link cited for most energy security studies) and (ii) the link from exporters of energy-intensive products to their importers. By combining the two links, HIO can trace energy from the primary energy exporter to the final energy sink (i.e. the importer of energy-intensive products). Whereas DIO addresses (ii), its relationship to (i) can only be evaluated using the HIO. We address this research gap by taking advantage of the Eora Global Supply Chain database and a growing library of other large international databases [21] to develop a single global energy database that traces the physical flows of 13 energy resources and the monetary flows of 26 non-energy sectors within and between 136 countries over 16 years (2000–2015). The result is what we call the Hybridized Option for Modeling Input-output Energy Systems (HOMIES). HOMIES advances our understanding of embodied energy in the global economy by: (1) explicitly (and thus endogenously) modeling the production of specific energy resources (e.g. coal, crude oil, petroleum); (2) representing energy flows from the point of production, rather than the point of consumption; (3) modeling energy inputs bidirectionally, allowing the user to trace the embodied energy used to extract and generate energy resources; and (4) representing primary-to-secondary energy conversion by disaggregating energy flows.

The indirect energy requirements resolved by HOMIES also effectivly elucidate the indirect energy security of the global economy. In this study, we assess the indirect energy dependence of global trade and the major trading nations. The former is measured using import dependence, or the fraction of imports over total consumption, while the latter is assessed based on the indirect energy import and export portfolios of the world’s largest energy trading nations. Our objective is to identify economic areas, both geographic and sectoral, in which indirect energy security contrasts sharply with direct energy security. These discrepancies have significant implications for nations’ energy security. They identify areas that may be more vulnerable to energy shocks than they appear to be based on international flows of direct energy. The origins of indirect energy imports may lie outside of a nation’s direct energy trade network. The nation may thus be dependent on a primary energy exporter without having the policy leverage to ensure sustained, affordable energy exports. Because of the highly spliced nature of some supply chains, nations may not be aware that indirect energy linkages even exist. This presents a crucial knowledge gap that has the potential to undermine national energy security.

We begin this paper by comparing existing IO methodologies to HOMIES. We then identify and quantify the primary energy resources that sourced the world’s direct and indirect energy requirements from 2000 to 2015, breaking these requirements down further into the fractions that were either produced domestically or imported from abroad. From there, we examine the direct vs. indirect energy intensity of each major sector in the global economy, and conclude by quantifying the import dependence and portfolio diversity of ten major nation’s indirect vs. direct energy requirements.

2. Methods and data

2.1. Input-Output analysis (IO)

IO analysis hinges on the following identity:

\[ x = Z + f \] (1)

where \( x \) is a vector of total output in an economic system, \( Z \) is a matrix of intermediate industry transactions among economic sectors (agriculture, mining, etc.), and \( f \) is a vector for final demand. Using Equation 1, a “direct requirements” matrix, \( A \), is solved:

\[ A = [a_{ij}] = Zx^{-1} \] (2)

in which \( x^{-1} \) is the diagonalized inverse (a matrix) of \( x \), and the matrix \( A \) consists of the direct input from every sector \( i \) in an economy that goes into producing one unit of output from each sector \( j \) in the economy (Fig. 1a). Finally, a “total requirements” matrix \( L \) is arived at by subtracting \( A \) from its corresponding identity matrix and inverting the difference:

\[ L = (1 - A)^{-1} \] (3)

This last equation is the Leontief identity, named after the economist who pioneered the use of Equations 1–3 to examine the inputs and outputs of an economy. The total economic output therefore equals \( x = Lf \).

The scope of analysis is extended to the global economy in MRIO by expanding the direct requirements matrix to include \( u \) regions and \( n \) (non-energy) sectors (Fig. 1b). The new direct requirements matrix represents the per-unit direct requirements by sector \( j \) in region \( r \) of output from sector \( i \) in region \( q \).

2.2. Direct Input-Output analysis (DIO)

DIO, used widely in existing literature, is effectively a two-step estimation approach, in which \( L \) is estimated as described in Section 2.1 and then multiplied by another matrix, \( V \), containing direct energy requirements (i.e. energy intensity) by each economic sector (Fig. 1c) [6]. Data on these energy inputs are in physical units and are published by organizations like the International Energy Agency [38]. DIO can be applied to a single nation or the global economy to analyze the sum of direct and indirect energy involved in sectoral transactions. As noted previously, others have referred to this sum as embodied energy, a convention that we will also follow here.

DIO includes the consumption of \( p \) energy resources by each of the \( n \) sectors in \( u \) regions, so \( E = [e'] \) and represents the region-specific direct energy inputs into each sector.\(^2\) Note then that \( E \) has \( p \) rows and \( n \) columns. The per-unit energy input for each sector (i.e. the direct energy intensity), \( V \), is obtained by dividing the total output of these sectors into \( E \):

\[ V = [v'] = E^{-1} \] (4)

Finally, multiplying \( V \) by \( L \) (from Equation 3) yields the total energy intensity of an economic system, which permits tracking of indirect energy flows originating from specific regions.

\(^2\) Here, \( u \) represents the total of the \( r \) (or \( q \)) regions represented in HOMIES, \( p \) and \( n \) are the total energy resources and non-energy sectors represented, respectively. \( i \) can represent either an energy resource or non-energy sector.
energy flows from the point of initial consumption. What cannot be tracked in DIO, in the context of global MRIO, is indirect flows of energy from their points of production [9]. This is because in DIO the input flow of energy resources is aggregated such that the originating region of these energy resources is lost. For instance, crude oil imported by China from Saudi Arabia is combined with the former’s crude oil imports from Indonesia. So, while DIO will capture how crude oil consumed by China ripples through the global economy, the analysis will not reveal whether, where, and how much Saudi Arabian crude is embodied in a region’s final consumption of Chinese exports.

DIO also suffers limitations in tracking direct energy flows when multiple forms of energy production are lumped together into the same sector. For instance, the “Mining and Quarrying” sector in Eora MRIO tables includes the production of coal, crude oil, natural gas, and uranium (for nuclear-generated electricity). As a result, the input from non-energy sectors to “Mining and Quarrying” is distributed evenly among each of its component energy resources, regardless of their very different production processes. In this case, DIO assumes that direct energy consumption (represented by E) is an exogenous input to the analysis, unaffected by flows from non-energy sectors. However, this assumption is erroneous if an energy system relies on one type of resource more than the others and/or if the system transitions away from a dominant energy resource, say coal, towards another, such as natural gas or renewable energy.

2.3. Hybrid Input-Output analysis (HIO)

HIO allows for more explicit tracking of direct and indirect energy flows than DIO. This is done by directly incorporating rows and columns for energy resources into the underlying financial transactions matrix (Z) thereby creating a hybrid-unit transactions matrix (Z’) as illustrated in Fig. 1d. Note that in HIO the underlying matrices expand to consist of (n+p) rows by (n+p) columns. Consequently, Z’ can be deconstructed into four submatrices, each with different units:

\[
Z' = E_z Z_{\theta} Z_{\phi}
\]

Following the mathematical notation of Guevara and Domingos (2017), \(E_z\) represents the flow of energy to energy sectors, and \(E_r\) represents the flow of energy to non-energy sectors [34]. The submatrix \(Z_\theta\) represents the flow from non-energy sectors to the production of energy resources, and the submatrix \(Z_\phi\) represents the flow from non-energy sectors to non-energy sectors. The transactions matrix in DIO would therefore be \([Z_\theta]\), a subset of the HIO transactions matrix. The rest of the mathematical framework is the same as the conventional IO analysis:

\[
A^\tau = Z' \hat{x}^{-1}
\]

where \(\hat{x}^{-1}\) is the diagonalized inverse of a hybrid total output vector of length \((n+p)\), and matrix \(A^\tau\) has the same dimensions as \(Z'\). \(A^\tau\) is functionally equivalent to the direct requirements matrix used in both conventional IO and DIO analyses, can also be decomposed into submatrices, each with a different unit:

\[
A^\tau = \begin{bmatrix} A'_{x} & A'_{r} \\ A'_{s} & A'_{\phi} \end{bmatrix}
\]

The submatrix \(A'_{x}\) has units of TJ/TJ, \(A'_{r}\) has units TJ/USD, \(A'_{s}\) has units USD/TJ, and \(A'_{\phi}\) has units USD/USD. Finally, the total hybridized requirements matrix is given by:

\[
L^\tau = (1 - A^\tau)^{-1}
\]

with the structure of the units in \(L^\tau\) being the same as that in \(A^\tau\).

Thus, HIO in the global context requires data on region- and resource-specific energy production, domestic transactions of these energy resources, and bilateral transactions of these energy resources. It also requires information on the use of non-energy sector output for energy production, which as mentioned already has historically been a prohibitive obstacle in transitioning from DIO to HIO. In this study, we compile the granular data needed for HIO in a database we call the Hybridized Option for Modeling Input-output Energy Systems or HOMIES.
2.4. HOMIES

HOMIES traces direct and indirect energy flows through the global economy using the HIO approach. As mentioned previously, direct energy is what is used to produce a good or service, while indirect energy is “embedded” in goods and services during their production (Fig. 2). We further define indirect energy here as energy embedded in the second or later stages of producing a good or service consumed by final demand. This embedded energy can either be from primary energy directly consumed in the first stage of the production process, or from primary energy used to generate secondary energy, e.g. electricity, that then gets used in the second or later stage of production (Fig. 2). Whereas direct energy is measured and recorded in underlying IO matrices (e.g. Z and A matrices in Equation 2), indirect energy is estimated using matrix L (in Equation 3). Energy flows going to final demand will be classified as direct or indirect based on whether the last stage in the production process used direct or indirect energy (Fig. 2).

We note here that the direct energy flows (A) and indirect energy flows (L) are derived by multiplying the energy component of the A’ and L’ matrices from Equations 7 and 8. Direct energy flows are thus calculated as the following:

$$A_{\text{direct energy}} = A^* f = \begin{bmatrix} A_{n, s}^* & 0 \\ 0 & 0 \end{bmatrix} f$$

(9)

where we set non-energy flows to 0 and multiply the technical coefficients (i.e. energy intensities) by final demand. We calculate indirect flows by calculating total energy flows (replacing L’ for A’ in Equation 9) and then subtracting them by $A_{\text{direct energy}}$.

We build HOMIES using Eora because it currently includes greater spatial disaggregation and temporal breadth than other MRIOs [39]. More specifically, Eora tabulates financial flows among 26 sectors in 189 countries from 1990 to 2015 and includes six final demand “sinks” as well as a direct energy input matrix (E in Section 2.2) for each year [22]. In addition to the 26 sectors represented in Eora, we incorporate 13 additional rows and columns to represent specific energy types. These include seven primary energy resources and six secondary energy resources. The primary energy resources are: bioenergy, coal, crude, natural gas, nuclear (uranium), hydro (potential energy), and renewables. Here, renewables are defined as solar, wind, and geothermal energy. Hydro and bioenergy are given their own categories to better align energy databases with agricultural and electricity data. We provide further detail on these data in Section 2.4.1. The secondary energy resources are: combustion-based electricity, hydro-generated electricity, nuclear-generated electricity, renewables-based electricity, refined petroleum, and losses. We have included a list of all represented regions, countries, non-energy sectors, and energy types in the Supplementary Material.

Data on the domestic flows of direct energy are derived from the International Energy Agency (IEA) World Energy Balances database (WEB) [40]. Of the 189 countries represented in Eora, we analyze the 136 that can also be found in WEB. This database includes the production of each energy type (in TJ), as well as the consumption of that energy by sector (e.g. electricity used in domestic textile manufacturing). However, it does not include bilateral information, i.e. the flow of energy from energy-producing country to a different energy-consuming country. This information is instead recorded in the BACI trade database, a harmonized compilation of UN COMTRADE trade data [41]. The latter data, which are given in tonnes and USD amounts, are converted to energy flows using each country’s unique annual average net calorific value (in TJ/kt) for every type of primary energy as published by the IEA [42]. We assume that the net calorific values (NCVs) are constant across all years of the study. By combining WEB to BACI, we are able to capture the flow of primary energy from its production through its domestic transformation to secondary energy and its consumption both domestic and abroad.

The data compilation process for HOMIES can be broadly divided into two steps. The first step is to scale physical energy flows among the 26 sectors and 13 energy types. The second step is to scale monetary flows among the sectors and energy types. Each step has a domestic component and an international trade component. In the former, we compile domestic transactions (e.g. Russian natural gas energy used in Russian machinery manufacturing). In the latter, we compile all bilateral transactions (e.g. Russian natural gas energy used in German machinery manufacturing). The resulting matrix is matrix $Z'$ in Section 2.3.7.

2.4.1. Scaling physical energy flows

For each country in each year, Eora represents energy inputs into sectors but does not specify the country in which this energy was produced. HOMIES builds on Eora by adding bilateral energy flows that specify the type of energy, the producing country, the consuming country, and the consuming sector. WEB provides data on the flow of specific energy resources into sectors that align closely with the 26 sectors represented in Eora. Among the sectors in WEB are 15 that directly correspond to those in Eora. Six of the remaining sectors in Eora fall under the larger umbrella sector in WEB titled “Commercial and Public Services”. Consequently, we divide the energy going to the single WEB group into sub-flows that go into the six related Eora sectors, with the energy in these sub-flows being scaled based on each of the latter sectors’ contribution to a country’s total economic output (in USD). The remaining five sectors in Eora have no corresponding sector in WEB. To overcome this, we exploit the Eora database’s own energy use matrix (E in Section 2.2). This matrix includes the flow of energy resources into the 26 sectors. We use WEB to calculate, for each country and for each energy resource, the fraction of energy demand that is met domestically. We then multiply these fractions with E to build the domestic component of energy flows into the five remaining sectors.

For the international trade component, we use BACI data to divide the imports of each energy type into 26 sectors. We assume that countries use their imported energy proportionally to the ways they use their domestically-produced energy. A table further detailing our correspondence between WEB and Eora sectors can be found in the Supplementary Material (Section 2).

To scale physical energy flows going into producing bioenergy, data from the FAO (Crop Production Database) and the IEA (Renewables and Waste Database) are used to calculate the fraction of agricultural output from each country used for bioenergy production [43,44]. We first calculate the amount of agricultural output (in tonnes) that is required to meet bioenergy demand (in TJ) for each country and year. Bioenergy demand (in TJ) is given in the Renewables and Waste Database for each country, year, and bioenergy commodity (e.g. biodiesels). We multiply

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6 We assume a global economic system consisting of only these 136 countries and do not include additional flows for exports to/imports from countries outside of this list.

7 An illustrative representation of HOMIES as it relates to the mathematical framework laid out in Section 2.3 can be found in the Supplementary Material.

8 The 6 Eora sectors are: Maintenance and Repair (15), Hotels and Restaurants (18), Post and Telecommunications (20), Financial Intermediaries, and Business (21), Public Administration (22), and Education, Health, Other Services (23).

9 Let’s say sectors A, B, C, D, E, F comprise “Commercial and public services”, and output from each sector A is described as $oA$. The energy flow to sector A would be equal to the energy flow to “Commercial and public services” multiplied by $[oA/(oA + oB + oC + oD + oE + oF)]$.

10 The 5 Eora sectors are: Wholesale Trade (16), Retail Trade (17), Private Households (24), Others (25), Re-export and Re-import (26)

11 We do not use this method to scale other the other 21 sectors because we aim to minimize assumptions regarding the energy system. We use actual data when actual energy flow data are available.
demand of each bioenergy commodity by its corresponding mean conversion efficiency and then divide the product by the commodity’s mean energy content (in TJ/tonne). We have included a table with these values for the represented bioenergy commodities in the Supplementary Material. From here, we are able to take the fraction of agricultural output from the Crop Production Database (in tonnes) that is used for bioenergy production (now also in tonnes). We then multiply this fraction by the flows of energy going into the Agricultural sector as a whole to yield the share consumed in bioenergy production.

The energy used to extract crude oil and natural gas is combined in WEB under “Oil and Gas Extraction”. We divide this flow into separate crude oil and natural gas components by calculating the fractions of each country’s production of the two resources using additional data from the IEA. These fractions are then in turn used to scale the amounts of energy going into “Oil and Gas Extraction” to yield the energy the country consumed producing oil and producing natural gas.

The energy inputs used to mine coal, refine petroleum, and generate electricity (for combustion, hydro, and nuclear based generation) are explicitly represented in WEB and do not need to be scaled. National use of input energy from uranium, solar and wind resources for generating electricity on the other hand are not included in WEB. We estimate the amounts of these primary energy types with a back-calculation that uses efficiency data for existing generation technologies provided by the U.S. Energy Information Administration [45,46]. For uranium, we first compile nuclear-based electricity generation by country and year. We assume that the only energy use for uranium is electricity generation. We then estimate the amount of nuclear energy required to generate a TJ of nuclear electricity, assuming an average efficiency of 35% for nuclear power plants. We link this to the World Mining Database to estimate domestic production. Finally, we link the remaining amount to the BACI database to estimate the bilateral trade flows used to meet energy demand. This procedure, as well as our correspondence table for relating IEA and HOMIES energy types, can be found in the Supplementary Material (Section 6).

2.4.2. Scaling monetary flows to energy production

While Eora already maps out monetary flows between sectors and their energy inputs, it does not track the flow of money from all the sectors that goes into producing/extracting primary energy. However, this information is critical for establishing bidirectional flows of embodied energy between energy and non-energy producing sectors. This information is estimated in HOMIES by: (i) identifying which Eora sector includes the production of a given primary energy type (e.g. the sector “Mining and Quarrying” includes coal mining); (ii) estimating the fraction of the sector’s total output that goes into producing the energy type; and (iii) multiplying this fraction by the total monetary flow going into the sector to yield the share used to produce an energy type. Note that this approach is identical to how we scale the physical energy flows into producing primary energies, except in this case we are estimating monetary flows going into the production.

For bioenergy, the fraction of agricultural output used to produce bioenergy is multiplied by the monetary flows into “Agriculture”. Coal, crude oil, natural gas, and uranium on the other hand all fall under “Mining and Quarrying”, so the respective proportions of the total monetary flow going into this sector need to be determined for each energy type, which we do using historical data from the World Mining Database [47]. This database includes mining production by resource, country, and year, allowing for the determination of the fraction of total mining that went into extracting each of the four primary energies (i.e. coal, crude, natural gas, uranium). These fractions are then weighted by the export price of each resource as given in the BACI trade database. This weighting is done to reflect the varying costs of producing the different types of resources (e.g. it is less costly to mine for coal than it is to mine for uranium, and labor costs can vary widely by country). The resulting fractions are then multiplied by monetary flows going into “Mining and Quarrying”, thereby dividing the flow into five separate sub-flows: one each for the production of coal, crude oil, natural gas, uranium, and non-energy mining and quarrying activities.

Petroleum production (i.e. crude oil refining) falls under the Eora sector “Petroleum, Chemical, and Non-Metallics”. WEB separates out the amounts of electricity (in TJ) used by oil refineries vs. chemical manufacturing and non-metals manufacturing, so dividing the electricity used in oil refining by the total electricity used across all three types of manufacturing gives the fraction used to produce petroleum products. Multiplying this fraction by the monetary flows going into “Petroleum, Chemical, and Non-Metallics” divides the flow into its energy (refining) and non-energy (chemical and non-metallic)
components. In doing this, we assume electricity consumption is an adequate proxy for other capital inputs.\textsuperscript{12}

In Eora, electricity is included in the “Electricity, Gas, and Water” sector. This sector does not directly correspond to any sector in WEB, preventing us from using the latter to separate out the energy component of the former. The OECD, however, publishes detailed supply-use tables (the Z matrix in Section 2.1) for 45 countries in which electricity, gas, and water are broken out. We use these tables to estimate the fraction of monetary input to the three utilities that goes into electricity, doing this calculation for each of the 45 countries. We then use k-means clustering to extrapolate the electricity fractions for the 45 OECD countries to the 136 countries included in Eora and HOMIES. Finally, we multiply each country’s electricity fractions by the monetary flows in Eora going into the country’s “Electricity, Gas, and Water” sector to yield the sub-flow directed towards electricity generation.

Since electricity is generated from primary energies, its monetary flow is itself sub-divided into monetary flows to fossil fuel electricity generation, nuclear electricity generation, hydro electricity generation, and renewables-based generation.\textsuperscript{13} To calculate these sub-flows, the electricity generation mix is determined for each country in each year. Then, because some forms of electricity generation are more expensive than others (e.g. renewables vs. fossil-fuel generation), we further scale the monetary flow to each generation type using Levelized Cost of Electricity (LCOE) data from the U.S. National Renewable Energy Laboratory (NREL), the Energy Information Administration (EIA), and the Federal Energy Regulatory Commission (FERC), as well as from existing literature [48-51]. For each year, the mean LCOE, by generation type, are converted to weights.\textsuperscript{14} Finally, the monetary flow that goes toward electricity generation in Eora are multiplied by these weights to further divide them into flows by generation type.\textsuperscript{15}

\subsection*{2.5. Application of HHI and HOMIES in this study}

This analysis focuses on direct and indirect energy flows originating from the production of coal, crude oil, natural gas, uranium, and renewables (i.e. solar, wind, geothermal). By tracing embodied energy flows from their primary energy sources to their consumption sinks, we are able to break down: (i) whether the energy going into a sector leaves in the sector’s output as direct or indirect energy, (ii) where both direct and indirect energy are sourced, and (iii) where direct and indirect energy are demanded. This information is illustrated conceptually in Fig. 3 for a hypothetical country (Country A) that trades with all other countries grouped as “rest of world” (ROW).

Fig. 3a and 3b represent direct energy flows to Country A, while Fig. 3c and 3d illustrate indirect energy flows into the country. Green outlines and arrows follow the flow of domestically-sourced energy whereas blue outlines and arrows follow the flow of energy sourced abroad. Again, direct energy flows are flows of primary energy that have undergone fewer than two transformations before reaching final demand. An example would be natural gas used for cooking in the final stage of producing prepared food. Indirect energy flows include the energy consumed at all stages leading up to the assembly of the final product. For prepared foods, this may include the energy used to plant, fertilize and harvest crops, transport the crops to a processing facility, and then transport the processed crops to a restaurant.

Note that domestically-sourced energy can be used abroad and re-imported. For example, coal extracted in the United States may be exported by China and used to produce steel that, in turn, is imported by the United States. In this case, the United States would be importing energy originally in its coal export that is now direct energy in the Chinese steel. Alternatively, the United States’ coal that is exported to China could be used to produce steel that China then exports to Japan, where the steel is used to manufacture cars that are exported to the United States. In this case, the returning energy flow to the United States would be as indirect energy because the original energy in the coal would have been incorporated into more than one production process.

\subsection*{2.6. Measuring energy security}

In this study, we assess energy security at the global, sectoral, and national levels using two metrics. The first is import dependence, which we calculate by dividing imported energy consumption by total energy consumption. In the energy security literature, import dependence is used to measure how vulnerable a country’s energy system is to foreign shocks [52-54]. Here, we apply import dependence to both direct energy and indirect energy. Once primary energy is transformed and embedded into goods and services, these products carry embedded primary energy when they are exported. The import dependence of indirect energy estimates the fraction of this embedded energy that was sourced abroad. If this value is low, it means the country’s domestic primary energy resources are able to sustain global production processes that are required to meet its final demand. On the other hand, if this value is high, the country relies on global production processes that are fueled primarily by foreign resources. It is therefore more vulnerable to energy shocks abroad.

The second metric we use is the Herfindahl-Hirschman Index (HHI). HHI is used extensively to measure the size of firms in an industry and the competition among them [55], but the index is also used as a metric of energy security [52-54,56,57]. The HHI is defined as:

$$HHI_e = \sum \frac{s_i^2}{\sum s_j^2}$$

where $s_i^2$ represents the squared fraction of either imports or exports in fuel $e$ going from nation $i$ to nation $j$. The HHI ranges between approximately 50 and 10,000.\textsuperscript{16} The higher a country’s HHI, the more it relies on a few exporters/importers for a particular energy type, while the lower a country’s HHI, the more exporters/importers it is working with and the more equal each exporter’s/importer’s fraction. For instance, if a country imports 90% of its oil from country A and 10% of its oil from country B, the HHI of the importer portfolio would be equal to $(0.9^2 + 0.1^2) = 8.200$. Alternatively, if the country imports 10% of its oil from each of 10 different exporters, the country’s HHI would equal 10(0.1^2) = 1,000. It is important to consider HHI in conjunction with import dependence and not as a standalone metric, as HHI alone only addresses the portion of a country’s energy use that comes from imports. This alludes to the difference between vulnerability (i.e. conditions that can exacerbate the impact of a trade disruption) and exposure (i.e. the scale of impacts from a trade disruption). HHI can address vulnerability while import dependence can address exposure [58].

\begin{itemize}
\item \textsuperscript{12} e.g. the proportion of electricity used for petroleum compared to chemicals/non-metals is equal to the proportion of steel used for petroleum compared to chemicals/non-metals.
\item \textsuperscript{13} For the purposes of this analysis, we do not further divide fossil fuel generation into coal, natural gas, and crude oil.
\item \textsuperscript{14} This is calculated by dividing the mean LCOE for a given generation type (e.g. fossil fuels) by the sum of mean LCOE across generation types.
\item \textsuperscript{15} While this is a “best-case” price, we do not use the magnitude of the LCOE per se. We simply care about the LCOE of specific generating resources relative to one another. We are therefore working with the assumption that while the LCOE may change by region, the relation of various LCOE will remain generally consistent.
\item \textsuperscript{16} We assume a minimum HHI of about 50 given that there are about 200 potential trade partners for each country, and if each of these partners receive an equal fraction of the country’s trade, we would have an HHI equal to $200 \times \frac{(0.50)^2}{(0.50)^2} = 50$. In the parentheses, we divide 100% by the number of linkages (2 O : 100 : 200).
\end{itemize}
2.7. Assumptions and limitations of this study

When building HOMIES, we required several underlying assumptions where corresponding data were not available. First, we assume that countries use imported energy resources proportionally to how they use domestic energy resources. This essentially means that in HOMIES, countries draw from a resource pool that includes both domestic and imported energy.

Secondly, we assume that electricity requirements by a subsector are proportional to non-energy requirements by that subsector. This only applies to the instance in which we seek to divide out the energy component of the “Petroleum, Chemical, and Non-metallics” sector in Eora. Third, we assume that renewable primary energy sources (i.e. wind, solar, geothermal) do not require non-energy sector input. Electricity generated from renewable energy, on the other hand, does require input from non-energy sectors. For example, solar primary energy is used to generate electricity, but the sun does not require industrial input to produce this energy. Fourth, we assume that LCOE is proportional to the relative capital intensities of electricity generation by resource. This means that, for a given year, the monetary inputs required to produce a TJ of electricity will be divided into the generation types (e.g. fossil fuels, renewables, hydro, nuclear) based on the LCOE. This reflects the fact that, until recently, capital costs for solar/wind have been significantly higher than those of conventional resources like coal and natural gas.

We note that building HOMIES required considerable data compilation and we recognize that our estimates of embodied energy undoubtedly have uncertainty stemming from measurement error, or error that we cannot quantify. We have attempted to address these uncertainties by validating data across sources at each stage of the data compilation. Figures related to this validation can be found in Section 8 of the Supplementary Material. We find that the underlying energy input data that are in Eora do not always align with our input data derived from WEB. One likely reason for this is differences in the aggregation of industries to fit the 26-sector Eora setup. Other reasons include inconsistencies in measurement reporting (both in terms of accuracy and completeness), different approaches used to measure and/or estimate energy consumption, variation in the degree of independent verification of reported measurements, and differences in the sources of the underlying data (e.g. using input–output accounts from national statistical

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Footnote:
17 To validate this assumption, we compared the prices of imported energy and domestic energy and found that they are approximate. For instance, the United States’ average imported crude oil price in HOMIES is $53.16/bbl in 2015, compared to $46.17/bbl for domestically produced crude [64]. In China, HOMIES estimates an average import price of $73/tonne for coal compared to $83/tonne for domestically produced coal [65].
agencies vs. using proprietary data from industry). Discrepancies in embodied energy estimates are therefore not only reflective of differences in research objectives and methods, but also data interpretation and even the data themselves.

Furthermore, while HOMIES provides a more explicit regional representation of energy production and inputs than DIO models, our method still suffers from issues common in all IO analyses. In particular, and even the data themselves.

ences in research objectives and methods, but also data interpretation

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have been aggregated into regions to make the contrast between the two flows mapped by DIO and HOMIES. In these chord diagrams, countries DIO. This is illustrated in Fig. 4, which compares the embodied energy flows among all countries.

We estimate the footprint by multiplying matrix \( L \cdot f \) by a vector of final demand \( f \). If we wanted total energy consumption of a country, we would

energy embodied in them.

We estimate that, on average, 23% of world trade in embodied energy was conducted by countries that do not have apparent energy trade linkages. This percentage indicates the degree to which national economies rely on energy systems outside of their direct trade networks, and suggests that the embodied energy importers represent a significant component of the global energy system. Furthermore, these implicit energy linkages present significant implications for global energy security. First, the outsourcing of economic activity abroad can be viewed as an energy security strategy, especially when a country does not have energy resources of its own. However, when an importer does not produce goods and services domestically, it is more dependent on foreign energy systems to meet its final demand. If a foreign energy system that powers the production of a critical good or service (e.g. steel) experiences an energy shock, this shock will reverberate through the supply chain to the importer of the product. Thus, our understanding of energy security as the uninterrupted supply of affordable energy must be adjusted to include both direct and indirect energy flows. Second, energy flows into a country can be categorized as being sourced (i) domestically, (ii) by an existing trade partner, or (iii) by a country with which it does not have direct trade ties. Energy flows from (iii) are often beyond the scope of the country’s policy leverager, exposing it to a potential energy, economic, or societal shock. For example, in the case above, the United States is a third party to energy trade discussions among Russia, Europe, and China. However, it is dependent on the stability of these energy linkages in order to maintain critical supply chains, such as those that source inputs used in the U.S. to produce automobiles, medical equipment, and electronic products. These supply chains underpin the U.S. economy because it is used across economic sectors. The energy security of the supply chains, however, is contingent on the stability of foreign energy systems because they rely upon a globalized production process.

3. Results and discussion

The main objectives of this study are to (i) compare the uses of direct and indirect energy, thereby identifying areas where they diverge, and (ii) examine these differences with respect to energy security metrics. A country may seem energy secure in terms of direct energy, but if it relies on one or more critical products that are manufactured abroad, then it is also energy import dependent, albeit indirectly. Using HOMIES, we can expand our understanding of energy security beyond the immediate production and use of energy in a given country or sector. We first compare the global energy trade network resolved by HOMIES to the network resolved by existing methods (i.e. DIO). We then use HOMIES to compare the import dependence of direct and indirect energy flows at the global and sectoral level. Finally, we estimate key energy security metrics at the national level and discuss mechanisms that drive differences in direct and indirect energy security.

3.1. Implicit energy linkages

Because HOMIES traces energy flows from the point at which primary energy resources are first produced rather than first consumed, energy flows mapped by HOMIES will differ from the flows mapped by DIO. This is illustrated in Fig. 4, which compares the embodied energy flows mapped by DIO and HOMIES. In these chord diagrams, countries have been aggregated into regions to make the contrast between the two methods clearer. 18

In the DIO chord diagram, the biggest source of embodied energy is China, followed by the E.U. and South Asia. This is because these regions are the world’s largest net exporters of goods and services, many of which are manufactured by economic sectors that consume massive amounts of primary energy. In the HOMIES result, however, only a fraction of the embodied energy in Chinese exports originates in China. Instead, primary energy in these exports is mostly from the Persian Gulf and West Asia. In fact, according to HOMIES, the Persian Gulf, Africa, and West Asia regions are the largest sources of primary energy embodied in the global economy.

Because HOMIES explicitly models the link between the extraction of primary energy and its transformation into embodied energy, our analysis shows energy linkages between countries that do not trade directly in primary energy resources. This is exemplified in the flow of indirect energy into the United States. When we consider primary energy from the point of extraction (i.e. use HOMIES), we find that there is a significant energy flow from Russia to the United States. 19 This is because Russian energy, primarily in the form of natural gas and crude oil, is used in Europe and China to produce goods and services. When these goods and services are exported to the United States, so too is the energy embodied in them.

We estimate that, on average, 23% of world trade in embodied energy flows among countries that do not trade in primary energy, and dividing by that year’s sum of embodied energy flows among all countries.

21 We estimate the footprint by multiplying matrix \( L' \) by a vector of final demand \( f' \). If we wanted total energy consumption of a country, we would multiply \( L' \) by the total output of the underlying transactions matrix. However, this would no longer be consumption-based accounting. Recall that the aim in calculating the energy footprint is to attribute energy consumption to the final end-use sink.

18 A table corresponding region to countries can be found in the Supplementary Material.
19 We present a figure related to these results in the Supplementary Material.
Fig. 5b, leading indirect primary energy demand to be much larger than direct primary energy demand. For instance, world imports of crude oil reached 43.1 million barrels/day in 2015 [59]. In HOMIES, all of this energy constitutes just 25.3% of that year’s indirect energy imports.

Our results indicate that, on average, 23% of the direct energy that countries consume is derived from primary energy resources sourced abroad. For indirect energy consumption, the average is nearly two times greater at 44%. However, the import dependence of indirect energy varies by primary energy resource. For example, 69% of the crude oil in the indirect energy consumed by all nations comes from foreign sources, on average. This oil was largely produced in the Middle East and North America, which together comprised 51% of global production in 2015 [60]. How this energy is subsequently exported as indirect energy varies by region, however. In the case of the Middle East, most of the crude oil produced is exported as primary energy (64% in 2015) [59], which is then transformed into secondary energy in the form of refined petroleum products made outside the Middle East. A large fraction of these petroleum products, which are a form of direct energy, are then exported and used in yet more countries to make additional goods and services that now contain Middle Eastern oil in the form of indirect energy. In contrast, most of the crude oil produced in North America is refined and consumed in the region, contributing to the vast majority of the continent’s indirect energy being domestically sourced (82% in 2015). And the fraction of North American produced goods and services that are then exported abroad contain North American crude oil.

Natural gas is different. Some 66% of the global requirement for this form of primary energy is sourced domestically. At least through 2015, this difference was due to the fact that natural gas exports were largely restricted to being moved through land-based pipelines, relatively few of which cross national boundaries. Oil on the other hand can also be moved by ship, a much more flexible form of transport that has greatly contributed to oil being a globally traded commodity.

A significant fraction of indirect energy comes from uranium, a form of primary energy that is only used to generate electricity, a secondary and thus indirect use of primary energy. Uranium ends up comprising a large part of global indirect energy consumption because of its very high specific energy (500TJ/tonne) and the low efficiency of nuclear power plants. Thus, while roughly a third or less of the energy in uranium gets embedded as indirect energy in goods and services, the amount of primary energy that went into producing that indirect energy is huge [46]. Relatedly, the spikiness to the uranium component of indirect energy import dependence (Fig. 5d) stems from volatility in uranium markets and trading over the study period [61].

Our results show that the import dependence of both indirect energy from coal and natural gas has increased over the study period and, given the current state of the global energy economy, will likely continue doing so. For coal, this increase is driven by China’s emergence into the global economy. Whereas China uses much of the direct coal energy it extracts domestically, its goods and services are increasingly exported to other countries. Consequently, China’s indirect energy supply chain is increasing in magnitude and in breadth. For natural gas, the shale gas boom in the United States has led to an increase in indirect natural gas embedded in the goods and services the country produces. As the United States continues to export these goods and services, the natural gas component of their embedded energy will increase.

The divergence in direct vs. indirect import dependence, as well as the growth of the latter for coal and natural gas, signals vulnerabilities in the global energy system. It suggests that the global economy is more reliant on a stable primary energy market than we currently understand it to be. This is particularly significant for the supply chains of manufactured critical products like computers and automobiles. These supply chains have many production steps, each requiring different energy

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22 This is the average across 2000–2015
inputs. They are also highly globalized such that the steps may occur in different countries with drastically different energy systems. The importing country, in many cases, therefore relies on the energy trade structures of all countries in the supply chain while having little policy leverage outside its own borders. Potential exceptions to this are importers that have both abundant energy resources and a large capacity for producing their own goods and services, rendering them less vulnerable to unforeseen disruptions to this dependence. Even in these cases, however, it may take such importers time to develop and/or adapt domestic production facilities so as to make the affected goods and services.

3.3. Sectoral energy security metrics

The indirect energy import dependence of the global economy is driven by its non-energy sectors, which also can be assessed in terms of energy intensity. Direct energy intensity describes the per-unit energy use at the final stage of a supply chain. For example, this would include the primary and secondary energy (e.g. natural gas and electricity, respectively) that is used to manufacture a car. Indirect energy intensity, on the other hand, describes the sum of energy intensities (i.e. energy requirements per unit of output) that is used in all of the preceding links in the supply chain. This also includes the per-unit energy that is used in the supply chain of each of these links. In our car example, this would therefore include the direct primary and secondary energy used to produce the car radio, the energy used to mine the copper used in the radio, and so on. Recall that embodied energy is the sum of direct and indirect energy. Therefore, embodied energy intensities (i.e. direct + indirect intensities) will be significantly larger than the direct energy intensities we present below. The global averages for these are shown in Fig. 6, where each sectoral intensity is further broken down into the fraction derived from domestic vs. foreign sourced primary energy. These were computed by calculating the annual direct and indirect energy intensities for each sector in each country, and then weighting these by each country’s total economic output each year to arrive at a sector-by-sector weighted average for the world.

The vast majority of sectoral direct energy intensities (85%) is ultimately derived from domestic sources of primary energy. Note that this percentage includes cases in which a country that exported primary energy re-imported a fraction of it used to produce a good or services from overseas without the product undergoing any further transformation (e.g. A[2] in Fig. 3). Indirect energy intensities on the other hand involve a much greater fraction of primary energy sourced from abroad, with the average exceeding 50%. Unsurprisingly, this is particularly true of the transportation sector, which runs on refined petroleum products. While most countries have refineries and can produce their own petroleum products, all the refineries require crude oil as input. Crude oil is a primary energy exported by relatively few countries, the majority of which surround the Persian Gulf [62]. Consequently, as of 2015, not only did the global transportation sector have one of the

Fig. 5. Global energy consumption and import dependence, 2000–2015. (a) illustrates global direct energy demand (A[1]-A[2] and B[1]-B[2] in Fig. 3); (b) illustrates global indirect energy demand (C[1]-C[4] and D[1]-D[4] in Fig. 3). Lighter hues represent the components of each resource footprint that were originally sourced abroad (i.e. not in the country that ultimately uses it). Darker hues represent the component that was originally sourced domestically. (c) illustrates the direct net import dependence by resource, while (d) illustrates the indirect net import dependence.
highest indirect energy intensities (Fig. 6b), but it was also the most reliant on indirect energy imports.

Further examination of Fig. 6 reveals that when ranked by energy intensity, most sectors fall at or near the same ranking in terms of both direct and indirect energy intensities. There are, however, a subset of sectors that rank higher in indirect energy intensity than direct energy intensity, and vice versa. An example of the first type is transport equipment, which includes the manufacture of cars, planes, and maritime vessels. More than half of this sector’s indirect energy intensity (Fig. 6b) is derived from primary energy extracted overseas. We interpret this to reflect the complex global supply chains relied upon by manufacturers of transport equipment. For instance, a car produced in Germany may involve steel imported from China, plastics from the United States, and copper from Chile. Each of these materials requires energy input in their countries of production, which itself may be extracted domestically or abroad. When all of these direct and indirect energy flows are considered, the energy intensity of the sector adds up and expands geographically. An example of the second type is chemical and non-metallic mineral products manufacturing. This sector ranks relatively high in direct energy intensity (Fig. 6a) but last in indirect energy intensity (Fig. 6b). As a result, this sector, at least globally, appears to be significantly less reliant on foreign sources of primary energy than just about any other sector.

3.4. Country-level energy security metrics

We now move to country-level dependencies on direct and indirect energy, which we assess in terms of import dependence (as previously
and embodied (red) energy consumption between 2000 and 2015. Hirschman Index (HHI). The histogram in Fig. 7a displays the distribution of import dependencies at the country-year level for direct (blue) and embodied (red) energy consumption between 2000 and 2015. The dependencies range from 0% (all energy consumed was sourced domestically) to 100% (all energy consumed was imported). The plot shows that a majority of countries over most of the study period had a direct energy import dependence of < 50%, but an indirect energy import dependence of > 50%. Thus, even nations that were close to achieving energy independence in terms of direct energy still remained dependent on other countries’ energy systems for indirect energy.

Trends in the mean import dependence of both direct and indirect energy have stayed relatively constant at the global level, but vary significantly by region. Year-on-year changes in import dependence are plotted in Fig. 7b. The plot shows that China’s import dependence of direct and indirect energy has increased markedly. North and Central America on the other hand have experienced a gradual decline in import dependence, largely due to the shale gas boom in North America. In all regions, the import dependence of indirect energy is greater than the import dependence of direct energy. However, the degree of this disparity varies by region. In East Asia, for instance, the difference is relatively small (17.3% in 2015) because the region has few domestic energy resources and thus relies heavily on energy imports to meet its direct energy demand. Where the difference is greatest is in regions that (i) have abundant domestic energy resources sufficient to meet final direct energy demand, but (ii) rely heavily on imports of goods and services requiring highly globalized supply chains. These regions, which include the Persian Gulf countries and Oceania, may have a false sense of energy security given that their economies are largely but indirectly powered by foreign energy systems. We include a table with regional import dependences in Section 10 of the Supplementary Material.

Tables 1 and 2 present the import and export HHI and number of trade linkages for the ten countries with the greatest embodied energy imports in 2015 (Table 1) and the greatest embodied energy exports in 2015 (Table 2). Collectively, the top ten importers consumed 61% of the world’s embodied energy imports while the top ten exporters supplied 54% of the world’s embodied energy exports.

For the top ten embodied energy importers, as well as almost all countries (see Sections 9 and 10 in the Supplementary Material), indirect energy portfolios include many more linkages than direct energy portfolios (Tables 1 and 2). This is because primary energy that is embedded in the goods and services demanded by an importer can originate in countries outside of the importer’s direct trade network. While producers of primary energy may export this energy to only a handful of countries (i.e. fewer direct linkages), the importers’ subsequent use of the primary energy to produce and export a variety of goods and services spreads that primary energy as indirect energy to a larger group of importing countries (i.e. more indirect linkages). For example, as mentioned previously, the United States is one of the three largest importers of indirect energy containing primary energy sourced from Russia (Table 2), a country that exports very little direct energy to the United States. Russia, however, is a major exporter of direct energy to the E.U. and China, and these states use a significant amount of that energy to produce goods and services that are then exported, along with the indirect energy they contain, to the United States (B[1] and D[2] in Fig. 3). Thus, while energy systems in Russia and the United States may not interact directly, the systems are still dependent on one another through trade intermediaries.

Recall that 23% of the global embodied energy network is comprised of indirect linkages between countries that do not directly trade those energy resources. The importers listed in Table 1 rely on these implicit energy linkages to varying degrees. For instance, 23% of the United States’ indirect energy imports originate in countries from which it does not directly import energy resources. On the other hand, only 6% of China’s indirect energy imports are based on implicit linkages. Implicit linkages can increase the vulnerability of a national economy to energy shocks beyond their direct trade network. This vulnerability is exacerbated when the nation is unaware of where these risks lie. Of the importers listed in Table 1, the United States, the United Kingdom and Italy are most reliant on implicit energy linkages.

The discrepancy between direct and indirect portfolio diversities is pronounced for Canada and Kazakhstan. Both countries have a much higher HHI and thus smaller, more concentrated consumer network for their direct energy exports than their counterparts. The two countries’ indirect energy export portfolios, on the other hand, are much more diverse. This is driven by these countries’ uranium exports which, again because of its very high energy density, leads to large uranium indirect energy flows through the global economy. Kazakhstan was the largest uranium exporter in 2015, followed by Canada. Because uranium-based energy can only be used once it has been transformed into electricity, direct energy importers will only be those countries that utilize nuclear power generation. However, once this electricity is consumed the uranium energy is embodied in the resulting goods and services. These goods and services have a much wider range of uses, and thus export destinations, explaining why Canada and Kazakhstan have concentrated direct export portfolios but more diverse indirect export portfolios. 79% of Kazakhstan’s primary energy exports and 52% of Canada’s primary energy exports, when we consider physical energy units (TJ), are in the form of uranium. This means that the majority of the energy exported by these countries can only be used in intermediary countries that use nuclear-generated electricity, indicating that these energy pathways are critical for their energy export security. This is mainly driven by uranium’s high energy content, however. These patterns do not inherently translate to economic security. In 2015, uranium exports constituted 1.4% ($2.3 billion) and < 1% ($1.7 billion) of Kazakhstan and Canada’s GDPs, respectively [63]. Uranium places these countries as critical suppliers in the global energy system because it is a low-cost resource with high energy content. However, because the resource can only be used through select intermediaries, these countries’ economic dependence on it is limited.

Given that the number of trade linkages is used to solve for the HHI (Equation 9), it’s reasonable to assume that both would be highly correlated, but for some countries it is not. This is particularly significant in the context of energy security, as it signals a country’s dependence on a handful of trading partners out of many. Concentrated portfolios generally mean concentrated risk. Russia, for example, has concentrated direct and indirect energy import portfolios, even though the number of its import linkages is comparable to that of Korea or India. This is largely because of Russia’s crucial energy ties with countries that were once part of the Soviet Union. Kazakhstan alone supplied 43% of Russia’s embodied energy imports in 2015, with Ukraine supplying an additional 14%. Additionally, Russia acts as an intermediary for the energy flows from these countries to the global energy economy. For example, Russia can transform these primary energy imports into electricity, which it can then export to Europe and Asia.

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24 Each observation is an individual country in a given year
25 The same information for all countries can be found in the energy security table in the Supplementary Material.
26 Energy importers (Table 3, Column 2) do not necessarily represent where the primary energy is first used, but where the embodiment of this energy is consumed after undergoing transformations. This is why Russia, the United States, and China are presented as the largest energy importers; not only are their primary energy resources used directly in a large number of countries, but their goods and services, produced using domestically extracted primary energy, are exported abroad as well.
27 Sections 9 and 10 of the Supplementary Material include importer and exporter energy security metrics for 2010 and 2015.
28 Based on BACI bilateral trade data [42].
Table 1
Embodied energy security metrics for top 10 indirect energy importers (2015). The first column lists the three largest sources of indirect energy flows into the country. The second and third columns list the Herfindahl-Hirschman Index (HHI) for direct and indirect flows; larger values indicate a more concentrated (less diverse) portfolio. The fourth and fifth columns list the number of energy trade linkages. The sixth and seventh columns list the import dependences. The final column lists indirect energy imports of the country. The eighth column lists the % of indirect energy import that come from energy exporters with which the importer has no direct trade ties. The ninth column lists the total energy sink for that country (EJ). Uranium flows are represented as “U”.

| Importer | Top 3 import flows                                      | HHI (Direct) | HHI (Indirect) | Linkages (Direct) | Linkages (Indirect) | Import dep. (Direct) | Import dep. (Indirect) | % indirect from implicit linkages | Embodied sink (EJ) |
|----------|---------------------------------------------------------|--------------|----------------|-------------------|---------------------|----------------------|----------------------|-------------------------------|------------------|
| USA      | Canada (Crude)                                          | 637.94       | 330.03         | 399               | 685                 | 15.59%               | 39.06%               | 22.82%                        | 38.86            |
|          | Venezuela (Crude)                                       |              |                |                   |                     |                      |                      |                               |                  |
|          | Saudi Arabia (Crude)                                    |              |                |                   |                     |                      |                      |                               |                  |
| China    | Kazakhstan (U)                                          | 573.08       | 367.24         | 318               | 661                 | 25.36%               | 40.85%               | 6.12%                         | 36.05            |
|          | Saudi Arabia (Crude)                                    |              |                |                   |                     |                      |                      |                               |                  |
|          | Russia (Crude)                                          |              |                |                   |                     |                      |                      |                               |                  |
| Japan    | Australia (Coal)                                        | 876.59       | 333.93         | 294               | 642                 | 67.12%               | 86.45%               | 16.79%                        | 16.52            |
|          | China (Coal)                                            |              |                |                   |                     |                      |                      |                               |                  |
|          | UAE (Crude)                                             |              |                |                   |                     |                      |                      |                               |                  |
| France   | Niger (U)                                               | 1152.32      | 453.24         | 370               | 660                 | 57.18%               | 68.50%               | 9.12%                         | 12.89            |
|          | Netherlands (U)                                         |              |                |                   |                     |                      |                      |                               |                  |
|          | Kazakhstan (U)                                          |              |                |                   |                     |                      |                      |                               |                  |
| India    | Indonesia (Coal)                                        | 700.19       | 443.82         | 312               | 620                 | 31.51%               | 55.57%               | 5.03%                         | 12.26            |
|          | Saudi Arabia (Crude)                                    |              |                |                   |                     |                      |                      |                               |                  |
| Germany  | Russia (Crude)                                          | 697.87       | 293.40         | 366               | 663                 | 56.58%               | 74.27%               | 17.42%                        | 12.24            |
|          | USA (U)                                                 |              |                |                   |                     |                      |                      |                               |                  |
|          | Norway (Gas)                                            |              |                |                   |                     |                      |                      |                               |                  |
|          | Germany (Crude)                                         |              |                |                   |                     |                      |                      |                               |                  |
| UK       | Russia (Crude)                                          | 907.43       | 276.98         | 372               | 664                 | 66.29%               | 77.96%               | 21.37%                        | 11.42            |
|          | Canada (U)                                              |              |                |                   |                     |                      |                      |                               |                  |
|          | USA (U)                                                 |              |                |                   |                     |                      |                      |                               |                  |
| Korea    | Australia (Coal)                                        | 629.11       | 341.52         | 303               | 610                 | 52.70%               | 76.79%               | 12.32%                        | 7.13             |
|          | Saudi Arabia (Crude)                                    |              |                |                   |                     |                      |                      |                               |                  |
|          | China (Coal)                                            |              |                |                   |                     |                      |                      |                               |                  |
| Italy    | Russia (Crude)                                          | 952.30       | 230.87         | 304               | 646                 | 47.30%               | 70.43%               | 20.05%                        | 6.10             |
|          | Russia (Gas)                                            |              |                |                   |                     |                      |                      |                               |                  |
|          | France (U)                                              |              |                |                   |                     |                      |                      |                               |                  |
| Russia   | Kazakhstan (U)                                          | 1645.96      | 1270.63        | 309               | 618                 | 23.95%               | 32.39%               | 8.37%                         | 6.02             |
|          | Ukraine (U)                                             |              |                |                   |                     |                      |                      |                               |                  |
|          | USA (U)                                                 |              |                |                   |                     |                      |                      |                               |                  |
While export portfolio diversity varies a lot by country, there isn’t one form of primary energy that causes exporters to have a more concentrated export portfolio. In fact, Saudi Arabia, the world’s largest crude oil exporter, has a relatively low HHI, indicating that its export portfolio is rather diverse.\(^\text{28}\) We interpret this to be because of the universal demand for crude oil along with the limited number of countries that export it. Venezuela, another major crude exporter, is an exception to this interpretation. It has a very high export HHI despite having more trade linkages than Saudi Arabia. The reason in this case is because Venezuela sends 60% of its indirect energy exports through just three of its linkages as compared to Saudi Arabia, which sends 43% of its indirect energy exports through its top three linkages. Indonesia, like Venezuela, has more trade linkages than Saudi Arabia. However, unlike Venezuela, Indonesia has a much more balanced HHI. It primarily exports its coal to India, China, and Japan. These countries use this energy to produce goods and services that are then exported to other countries, thereby diversifying the final consumption sink of Indonesian coal exports. This explains its relatively low HHI and high number of trade linkages.

4. Conclusion

In this study, we estimate the direct and indirect energy security of countries, sectors, and the global economy and identify areas where they contrast. To do this, we present a new hybrid-unit input–output database, HOMIES, that not only connects the physical flows of energy to non-energy sectors, but also the reverse flow of non-energy goods and services into energy production. This allows us to trace energy flows from the point of primary energy production to final consumption and address the bidirectional feedback between energy and non-energy production processes.

Contrary to many recent studies employing DIO and HIO, we find that the production sources of embodied energy to the global economy are not the countries with the largest energy intensive manufacturing industries (e.g. China) but those countries that initially supply the primary energy consumed for manufacturing (e.g. Russia and Saudi Arabia). Rather, manufacturing-intensive countries act as intermediary nodes in the flow of embodied energy from production source to final demand sink. Using HOMIES, we identify energy linkages between producers of primary energy and importers of goods and services that only exist through their intermediary nodes. Our results suggest that these linkages account for 23% of the world’s embodied energy trade network. The importers in these linkages rely on energy transactions that occur outside of their direct trade networks. This reliance, however, does not inherently make an importer economically vulnerable. For instance, the United States has both abundant energy resources and the capacity to manufacture goods and services domestically, albeit at a much higher cost. It is therefore important to contextualize the implications of implicit energy linkages with each nation’s availability of resources and economic status.

Additionally, our results suggest that the import dependence of indirect energy (44%) is much greater than the import dependence of direct energy (23%). It is also much greater than the global trade dependence of primary energy (33%).\(^\text{29}\) We also find that indirect energy import dependence varies by primary energy source. Crude oil is the most import dependent form of energy whereas coal is largely sourced domestically before being embodied in goods and services. This is intuitive, as crude oil is demanded universally but can only be extracted in a few regions, while many countries have coal resources that they largely consume domestically.

Together, these results indicate that the global economy is (i) more

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\(^{28}\) It is relatively low, considering that Saudi Arabia exports primarily one energy commodity (crude oil). In other words, the portfolio of trade partners is diverse even if its portfolio of exports isn’t.

\(^{29}\) Trade dependence is calculated for transportable primary energy resources (bioenergy, coal, crude oil, natural gas, uranium) by dividing total trade by total production.
dependent on primary energy imports and (ii) a significant share of these imports originate in countries beyond the importer’s direct trade network. The latter in particular has significant implications for our understanding of global energy security. Importers that have implicit linkages to foreign primary energy transactions have little policy leverage over the stability of these transactions. They are third party to energy transactions that fuel their supply chains, some of which may be critical to their economies (e.g., automobiles, agriculture). In some instances, these implicit linkages may even be unknown to the importer. On the other hand, primary energy exporters rely on consistent demand for their energy exports. When there is an economic shock in a final demand sector (e.g. food and beverages), this shock reduces demand for intermediate goods and services that go into the sector’s supply chain. These intermediate goods and services then reduce their demand for primary energy. Thus, the primary energy exporter’s economy is also dependent on implicit energy linkages. This has played out most recently in the wake of the COVID-19 pandemic, which has curbed global demand for and supply of Chinese exports. This in turn reduces demand for both primary energy and manufactured inputs in China. This then reduces demand for primary energy in the countries that export manufactured inputs to China. Primary energy producers that are linked to these production processes are therefore impacted by economic shocks that appear to be distant. This lack of awareness increases the vulnerability of importers and exporters to foreign energy shocks. Energy shocks include production disruptions (e.g. Fukushima disaster in Japan), price shocks (e.g. oil price volatility), and transport disruptions (e.g. geopolitical instability in the Strait of Hormuz). While markets may adjust long-term to these shocks, the short-to-intermediate-term impacts can be significant. Our results underscore the need to include implicit energy linkages in energy security evaluations.

Finally, metrics of embodied energy security at the country level allow us to identify critical energy import and export intermediaries in the global energy trade network. First, our observation that indirect energy portfolios have more trade linkages than direct energy portfolios suggests that the global economy’s dependence on indirect energy is relatively secure. Having more trade linkages benefits the importer of goods and services because the energy requirements of their supply chains are met using a wider variety of energy resources. An upstream energy disruption in one supply chain would not wholly impact the importer’s economy. It also benefits the exporter of primary energy because the demand for energy exports are based on a wider-ranging demand for final products. If there is an economic shock that impacts one final demand sector, it would not necessarily impact the entire flow of primary energy out of the country. In other words, a greater number of trade linkages reduces the global economy’s exposure to potential shocks in indirect energy flows. Second, exporters of indirect energy that have a high HHI combined with many linkages tend to be critical sources of primary energy. This primary energy, however, is funneled into the global economy via a handful of importers who use the primary energy in manufacturing exports. For Venezuela, these intermediary trading partners are the United States, China, and India. For Kazakhstan, the main intermediary is Russia. Such intermediary exporters are critical to supplying the global economy with embodied (direct and indirect) energy. Being relatively small in number, however, a disruption in trade through one of these countries could translate into a broader shock to the world trade in energy. In order to fully evaluate the vulnerability of these links in the global energy system, future energy security assessments should be reframed to explicitly include indirect energy flows.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.115806. Datasets for the HOMIES matrices can be found at https://figshare.com/projects/Hybridized_Option_for_Modeling_Input-Output_Energy_Systems_HOMIES_/88832.
