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Introducing final- and useful-stage energy and exergy extensions for the EXIOBASE Multi-Regional Input-Output Model

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Abstract

Environmentally Extended Multi-Regional Input-Output (EE-MRIO) models are increasingly used to account for the upstream (supply chain) requirements and implications of any level of final demand. Energy use is recognised to be a key driver of anthropogenic climate change and reducing energy use (at least in higher-income regions) is considered to be a key lever to meet climate targets. However, the availability of energy extensions for EE-MRIO models is very limited, preventing the quantification of energy use embodied in supply chains. Here, we introduce and document a novel set of energy extensions for the EXIOBASE EE-MRIO model. The extensions we introduce cover energy use at both the final and useful stage of the energy conversion chain. Further, we isolate extensions capturing the energy industry own energy use, energy used for non-energy purposes, as well as final-to-useful conversion losses. We provide these extensions both in energy and exergy terms — exergy is a quality-adjusted measure of energy closely linked to economic activity when quantified at the useful stage. For comprehensiveness, we also compute and release the country-level production- and consumption-based (footprint) energy accounts. The dataset we release is the most detailed set of final- and useful-stage energy extensions for a major EE-MRIO model.

Background and summary

Environmentally Extended Multi-Regional Input-Output Models are widely used tools in the fields of ecological economics and industrial ecology. An input-output model is essentially a tool representing, as a set of matrices, the transactions that occur in an economy during a given time period (usually a year) both in terms of intermediate and final consumption. Usually, transactions are represented in monetary terms, although physical and hybrid models exist too [1]. These models were first introduced by Wassily Leontief [2] and are a key tool to understand the linkages and dependencies between economic sectors (or *industries*, in the input-output terminology — which we adopt henceforth). Specifically, if we denote the final demand vector as $\mathbf{y}$, the total (or gross) output vector as $\mathbf{x}$, and the Leontief inverse matrix as $\mathbf{L}$, it can be shown (see the Methods section explaining the calculation of the energy footprints) that:

$$\mathbf{x} = \mathbf{L}\mathbf{y}, \tag{1}$$

which is the standard formulation of the Leontief model. This demand-driven model forms the basis of any

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input-output analysis, and allows determination of the total output ($\mathbf{x}$) required to satisfy any level of final demand ($\mathbf{y}$).

An Environmentally Extended Input-Output Model provides satellite accounts and extension vectors that allow translation of the total output by industry $\mathbf{x}$ into the corresponding level of environmental impact, or into a socio-economic implication (e.g., labour requirements). Satellite accounts inform regarding the level of total environmental impact (e.g., greenhouse gas emissions), while extension vectors inform regarding the environmental impact per unit of monetary output (e.g., greenhouse gas emissions by thousand dollars of production). In this article, we refer to satellite accounts in energy terms as *energy accounts*, while by *energy extensions*, we refer to both energy accounts and extension vectors. Recently developed Multi-Regional Input-Output Models, such as Eora [3], EXIOBASE [4, 5], FIGARO-E3 [6], GLORIA [7], the GTAP-MRIO [8], and WIOD [9], provide a wide range of satellite accounts and extension vectors and have therefore been key enablers for the ecological economics and industrial ecology communities. For instance, these models have been used to determine consumption-based greenhouse gas emissions (questioning the extent to which higher-income countries are reducing their emissions versus offshoring emitting industries abroad [10]), and to show the stark inequality of consumption-based emissions across income groups [11].

The use of energy extensions therefore allows analysts to quantify the upstream energy requirements associated with the consumption profile of any country or final demand sector and, more generally, the energy requirements associated with any level of final demand. Developing energy extensions for EE-MRIO models is important for several reasons. First, energy consumption (specifically, fossil fuel combustion) is recognised to be the most important driver of anthropogenic climate change [12]. Second, and following, reducing (or at least curtailing) energy consumption in higher-income countries is key for meeting climate targets, and there is increasing focus on energy demand reduction as a key element of comprehensive climate change mitigation strategies [13]. Third, current global supply chains are extremely complex and interconnected, and many products cross borders multiple times before getting to their end-user. Specifically, manufacturing (and often energy-intensive) industries are often delocalised from higher-income to lower- or middle-income countries ([14]). A production-based approach to energy use therefore only gives a partial vision of the energy requirements of a country and may mask all the supply chain energy use occuring abroad. Developing energy extensions for EE-MRIOs is therefore crucial to allow analysts to comprehensively quantify the supply chain energy use of countries.

The need for energy extensions (i.e., both energy accounts and extension vectors) for EE-MRIOs raises the question of the design of these energy extensions. In other words, what should these extensions represent, and how should they be built? Unsurprisingly, the answer depends on the question to be answered. Generally speaking, making available a wide range of extensions will make possible a wide range of studies. The input-output literature distinguishes supply and use designs for energy extensions [15, 16]. Simply put, supply-side extensions represent energy supply by MRIO industry (e.g., energy extracted from the environment), while use-side extensions represent energy use by MRIO industry. Readers are referred to the work of Owen et al. [15] and Wieland et al. [16] for a discussion of these two design options. Most major EE-MRIOs (see Table 1) include a supply-side energy extension representing energy extraction from the environment.

Use-side extensions, however, are not commonly released. The most commonly available use-side extensions (see Table 1) are the gross, net, and emission-relevant energy extensions. Gross energy use refers to the sum of all energy use by MRIO industries, including energy products transformed into other energy products (e.g., crude oil entering an oil refinery and transformed into gasoline and diesel). There is therefore double-accounting of some energy flows in gross energy accounts [17]. Net energy, in contrast, refers to the end-use of energy products and therefore excludes energy products transformed into other energy products (and usually includes both non-energy uses and losses in transformation processes, therefore adding up to primary energy). (Note that the term net energy here has a different meaning than in the field of net energy analysis, where it refers to the energy available to society once the energy requirements of the energy sector have been subtracted.) Emission-relevant energy use refers to energy products used for combustion (either by the end-use, or by a power or heat plant), and which therefore causes CO_2 emissions. (Bioenergy may be included or excluded depending on the convention used). Although these extensions are valuable, there is also a need to develop detailed energy extensions that align closely with the three conventional energy stages in energy analysis: the primary, final, and useful energy stages.

Table 1: Summary of the energy extensions available in the official releases of Eora, EXIOBASE, FIGARO-E3, GLORIA, and WIOD. In the case of GTAP, energy accounts ("volumes" in the GTAP terminology) are developed in the distinct GTAP-E model [35], which records "imports, production, intermediate usage, private consumption, and exports of energy" by GTAP country and sector. Without access to the commercial database, the documentation is not sufficient to identify whether gross, net, or final energy use extensions are built.

MRIO	Energy extensions included
Eora	Unclear documentation, energy accounts deprecated (private correspondance with developing team)
EXIOBASE	Primary energy supply, gross energy use, net energy use, emission-relevant energy use
FIGARO-E3	Primary energy supply, net and final energy use, non-energy uses, energy industry own energy use, transformation and distribution losses
GLORIA	Primary energy supply
WIOD	Gross energy use, emission-relevant energy use

Primary energy refers to the energy extracted from the environment (e.g., wind energy harnessed by a wind turbine, and crude oil extracted from the ground) and is therefore aligned with supply-side (specifically, energy extraction) extensions. (This may not always be the case, for instance when the scope of a model is national, the supply-side extensions include both domestic energy extraction and the energy imports [16].) The final energy stage refers to the energy delivered to the end-user, e.g., the electricity or fuel purchased by a household or a firm. The useful energy stage refers to the energy that actually contributes to delivering an energy service after conversion in an end-use device (e.g., the kinetic energy of a vehicle, or the heat that maintains a house) and, therefore, takes into account the efficiency of end-use conversion devices (e.g., engines, heaters, etc.). To our knowledge, only the FIGARO-E3 [6] (released in 2025) model includes a clearly documented final energy extension (as well as energy losses, energy industry own use, and non-energy use extensions). Although a final energy extension was built for EXIOBASE 3.8.2 [18, 19] it was not openly released. (Additional energy accounts released in EXIOBASE 3.8.2 were unclearly documented.) Furthermore, to our knowledge, no EE-MRIO includes a *useful* energy extension.

Conducting the analysis at the useful energy stage provides a quantification of energy as close as possible to the energy service delivered, and is critical to account for the thermodynamic efficiency of processes (and thus, also energy inefficiencies and losses). The availability of useful energy stage extensions would be valuable for a wide range of future studies, for instance monitoring energy efficiency targets or looking into the question of energy-GDP decoupling from a consumption-based perspective. Last, to our knowledge, no EE-MRIO includes energy extensions quantified in exergy terms. Exergy is quality-adjusted quantification for energy that gives the capacity of an energy product to deliver mechanical work (instead of heat). Exergy has been shown to be strongly linked to economic activity when quantified at the useful stage [20, 21]. Releasing exergy extensions and particularly useful exergy extensions is therefore crucial to look into energy-economy analysis and modelling from a consumption-based perspective. In practice, the lack of final- and useful-stage energy and exergy extensions has meant that most studies working at the final (e.g., [22–24]) energy stage have built their own custom energy extensions. (We note that researchers routinely need to build their own extensions, even when working with more common extensions such as net energy use accounts [25, 26].) Further, to our knowledge, no input-output study adopts a useful stage perspective.

Here, we introduce and document a novel set of energy extensions (accounts and vectors) for the EXIOBASE EE-MRIO model. The extensions are developed for EXIOBASE 3.11.2 [27], and will be updated for future EXIOBASE releases. This work brings together a new and open access procedure developed to build energy accounts for EXIOBASE using the residence principle [28] and the recently developed Country-Level Primary-Final-Useful (CL-PFU) energy and exergy database [29, 30]. The extensions we introduce cover energy use both at the final and useful energy stages. Further, to allow analysts the highest level of granularity possible, we isolate extensions capturing the energy industry own energy use, energy used for non-energy purposes (e.g., feedstock in the chemical industry), as well as final-to-useful conversion losses. We provide

these extensions both in energy and exergy terms. For comprehensiveness, we also compute and release the resulting footprints (consumption-based approach) for the whole set of extensions produced. The developed dataset is to date the most comprehensive and detailed set of final- and useful-stage energy extensions for a major EE-MRIO model, and should support analysts through a wide range of studies.

Methods

We first describe the construction of the energy accounts and energy extension vectors and then present the input-output calculations that we used to quantify the energy footprints for each energy extension.

Building the energy accounts and energy vectors

The starting point to build the energy accounts and vectors is the new and open source procedure developed by Rasul et al. [28] to build gross enery accounts for EXIOBASE. Some of the key benefits of this newly developed procedure include a high consistency in the integration of physical and monetary data and the transparency and reproducibility of the method. The procedure is fully documented in the corresponding article [28], and the code can be found open access in the associated Github repository. To briefly summarise the procedure followed by Rasul et al. [28], the gross energy accounts are first built by aligning the International Energy Agency's World Energy Balances to the United Nations' (UN) System of Environmental Economic Accounting (SEEA). Then, the resulting accounts are transformed from the territorial to the residential principle using a transport model. The resulting gross energy accounts are obtained at the IEA region, IEA flow, IEA product level of granularity (e.g., Australia, Iron and steel, electricity). Last, these gross energy accounts are allocated to a MRIO industry (i) aggregating IEA regions to EXIOBASE regions, and (ii) using proxies derived from the monetary supply use tables (to ensure consistency between the physical and monetary data).

To build the set of energy extensions introduced in this article, we take as input the gross energy accounts produced by Rasul et al. [28] and then follow three steps to develop the new set of energy accounts. Table 2 summarises in which step each of the energy accounts is built. The first step is to use a mask to produce final-stage energy accounts (note that this step is also used in Rasul et al. [28] to build net and emission-relevant energy accounts from the gross energy accounts). Masks are essentially selectors of the couples (IEA flow, IEA product) that need to be included (or excluded) for a given energy account. Essentially, these masks are tables of IEA product by IEA flow with ones where the couple should be part of an energy account, and zeros when it should not. For example (Electricity, Iron and steel) would have a 1 in the mask associated to the final energy account, but 0 in the mask associated with the non-energy uses account. The resulting energy accounts are therefore built at the tuple (MRIO industry, IEA region, IEA flow, IEA product) level, although only the accounts aggregated by MRIO industry can be included in the dataset released (because the detailed IEA data are proprietary and licensed). However, as the procedure and code used is open access (see repository), the detailed energy accounts (and therefore extension vectors) can be built by anyone with a licence to the IEA's World Energy Balances. Furthermore, all masks used are available as part of the dataset developed and hosted on a Zenodo repository [31].

The second step is to apply energy-to-exergy coefficients (e.g., ratio of exergy to energy content for a given energy product) directly to the energy accounts to derive the corresponding accounts in exergy terms. These exergy coefficients, which are IEA product-specific, are obtained from the CL-PFU database and are also available as part of the dataset developed. (See Zenodo repository [31].)

In the third step, we multiply each final energy (or exergy) account at the MRIO industry, IEA region, IEA flow, IEA product level by the corresponding final-to-useful energy (or exergy, respectively) efficiency (η_E, or η_X, respectively), which we obtain from the CL-PFU database. By doing so, we obtain the useful energy (or exergy, respectively) accounts. Multiplying the final energy (or exergy) accounts by $(1 - \eta_E)$ (or $(1 - \eta_X)$, respectively) then yields the final-to-useful energy (or exergy) loss accounts. In the rare cases in which there is no match between the final-to-useful energy and exergy efficiencies and the final energy and exergy accounts, we use an efficiency calculated from the CL-PFU database at the economy-wide (IEA region, IEA product) level (occurrences represent less than 5% of final energy consumption in each year and for each EXIOBASE region, and less than 1% of global final energy consumption). If there is still no match when

using an economy-wide efficiency, we use an efficiency derived for the global, economy-wide, IEA product level (occurrences represent less than 2% of final energy consumption in each year and for each EXIOBASE region, and less than 0.1% of global final energy consumption). For example, there is no efficiency available in the CL-PFU for the use of anthracite in the Croatian non-metallic minerals sector. We first attempt to use the average economy-wide efficiency of anthracite in Croatia. Because this value is not available either, we use the average global economy-wide efficiency of anthracite derived from the CL-PFU database. These situations occur very rarely and can either be due to (i) the IEA's World Energy Balances being processed differently when building the net energy accounts [28] and in the CL-PFU database [29] (i.e., residence vs territorial principle), and (ii) differences in the version of the IEA's World Energy Balances used to build EXIOBASE's gross energy accounts (July 2026 release) and the CL-PFU (July 2022 release) — the effect of which should be limited as data is rarely (and when so, marginally) retrospectively modified in new World Energy Balances releases.

After all the energy accounts are built, the energy extension vectors are simply calculated by dividing the energy account of each MRIO industry by its total economic output. In matrix terms, if we note $\mathbf{f}$ the vector of a given energy account (energy units), and $\mathbf{x}$ the total output (monetary units) by MRIO industry (see section "Calculating the energy footprints" for more explanations on $\mathbf{x}$), then the corresponding energy extension vector $\mathbf{e}$ can be built as:

$$\mathbf{e} = \mathbf{f}\widehat{\mathbf{x}}^{-1}, \tag{2}$$

where the hat notation (i.e., $\widehat{\mathbf{x}}$) refers to a diagonalised vector (a matrix with the vector on its diagonal and zeros elsewhere). Last, we also determine the product-level energy accounts. To do so, we allocate the energy account of each industry to the products it produces using its production share structure. For instance, if product p represents 20% of the output (in monetary terms) of an industry i, then 20% of the energy account of industry i is allocated to product p. In practice, we use the supply matrix $\mathbf{V}$ (directly available from the supply use tables underlying the EXIOBASE input-output model) to determine the product shares matrix $\mathbf{C}$:

$$\mathbf{C} = \mathbf{V}^{\mathrm{T}}\widehat{\mathbf{V}\mathbf{i}}^{-1}, \tag{3}$$

where post-multiplying by $\mathbf{i}$ (the unit vector, filled with ones), yields a vector containing the row sums of a matrix. Each coefficient c_{ij} then represents the share of product i in the output of industry j. The product-level energy account $\mathbf{f_p}$ is then determined as:

$$\mathbf{f_p} = \mathbf{C}\mathbf{f}. \tag{4}$$

The product-level energy extension vectors can then be calculated following Equation (2), replacing the vector of total output by industry $\mathbf{x}$ by the vector of total output by product $\mathbf{x_p}$, and replacing the energy account by industry $\mathbf{f}$ by the energy account by product $\mathbf{f_p}$.

Calculating the energy footprints

Once the energy accounts and energy extension vectors have been built, we follow a standard input-output methodology to calculate the energy footprints. An input-output model can be defined with two basic matrices. First, the transaction matrix $\mathbf{Z}$ represents the purchases of intermediary goods and services across industries (specifically, the coefficient z_{ij} represents purchases by industry j of the output of industry i). Second, the final demand matrix $\mathbf{Y}$ represents purchases of final goods and services by each final demand sector. Specifically, the coefficient y_{ij} represents purchases by final demand sector j (e.g., households, government expenditures, etc.) for the output of industry i). Then, one can obtain the vector of total output by industry, $\mathbf{x}$, as:

$$\mathbf{x} = \mathbf{Z}\mathbf{i} + \mathbf{Y}\mathbf{i}, \tag{5}$$

Table 2: Summary of the energy extensions built, as well as step in which each energy account is built.

Energy extension	Step	Description
Energy use — Final	Step 1	Final energy consumption, including the energy industry final energy consumption. Excludes non-energy uses.
Energy use — Final, energy industry own use	Step 1	Final energy consumption of the energy industry for energy purposes (as opposed to feedstock and transformation purposes). Excludes non-energy uses.
Energy use — Non-energy uses	Step 1	Final energy consumption for non-energy uses. Includes non-energy uses for the energy industry.
Exergy use — Final	Step 2	Final exergy consumption, including the energy industry final exergy consumption. Excludes non-energy uses.
Exergy use — Final, energy industry own use	Step 2	Final exergy consumption of the energy industry for energy purposes (as opposed to feedstock and transformation purposes). Excludes non-energy uses.
Exergy use — Non-energy uses	Step 2	Final exergy consumption for non-energy uses. Includes non-energy uses for the energy industry.
Energy use — Useful	Step 3	Useful energy consumption, including the energy industry useful energy consumption. Excludes non-energy uses.
Energy use — Useful, energy industry own use	Step 3	Useful energy consumption of the energy industry for energy purposes. Excludes non-energy uses.
Energy use — Final-to-useful conversion losses	Step 3	Energy losses in the conversion of final energy into useful energy. Does not consider non-energy uses (neither considered as useful energy nor as conversion losses).
Exergy use — Useful	Step 3	Useful exergy consumption, including the energy industry useful exergy consumption. Excludes non-energy uses.
Exergy use — Useful, energy industry own use	Step 3	Useful exergy consumption of the energy industry for energy purposes. Excludes non-energy uses.
Exergy use — Final-to-useful conversion losses	Step 3	Exergy losses in the conversion of final exergy into useful exergy. Includes both the exergy content of non-valuable by-products (e.g., waste heat) and the irreversibility of the conversion (i.e., exergy destruction). Does not consider non-energy uses (neither considered as useful exergy nor as conversion losses).

so that each coefficient x_i represents the total output of industry i. From these matrices and vectors, the direct requirements matrix $\mathbf{A}$ can be determined as:

$$\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1}, \tag{6}$$

The coefficient a_{ij} represents the direct purchases (or requirements) of industry j for the output of industry i to produce one unit of output. (Note that $\mathbf{Z} = \mathbf{A}\widehat{\mathbf{x}}$.) Substituting $\mathbf{Ax}$ for $\mathbf{Zi}$ in Equation (5), and noting $\mathbf{y} = \mathbf{Yi}$ the final demand vector, then yields:

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y}, \tag{7}$$

from which Equation (8), which constitutes the standard demand-driven Leontief model, is directly obtained:

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}. \tag{8}$$

The $(\mathbf{I} - \mathbf{A})^{-1}$ matrix, which is often referred to as the Leontief inverse matrix and noted $\mathbf{L}$ (as in the "Background & summary" section), represents the total requirements matrix. Each coefficient l_{ij} represents the total requirements of the output of industry i required to satisfy one unit of final demand for the output

of industry j. For a given energy extension vector $\mathbf{e}$, the energy footprint matrix $\mathbf{E}$ can then be determined as:

$$\mathbf{E} = \widehat{\mathbf{e}}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Y}, \tag{9}$$

where the coefficient e_{ij} represents the energy embodied by industry i to satisfy final demand by sector j. In the context of a EE-MRIO, industries and final demand sectors are location-specific, so that the energy footprint of a given country s can be determined by summing the relevant columns of matrix $\mathbf{E}$ (and the location of energy use can be determined by summing the relevant rows in matrix $\mathbf{E}$).

Figure 1.a and 1.b show the production-based and consumption-based accounts over time for Brazil, China, the European Union (EU, obtained aggregating results for the 27 EXIOBASE EU countries), India, South Africa, and the United States in terms of final energy and useful exergy, respectively. Using both energy accounts, higher-income regions (the European Union and the United States) tend to have higher consumption-based than production-based accounts, while the opposite is true for lower- and middle-income countries.

Data records

The dataset associated with this work can be found on the Zenodo repository "Final- and useful-stage energy and exergy extensions for the EXIOBASE Multi-Regional Input-Output Model" (version 1.0.0), doi: 10.5281/zenodo.22871201. The current version of the dataset (1.0.0) is released under CC-BY-SA-NC 4.0. The files contained in the dataset are presented in Table 3.

Table 3: File description.

File	Description
energy_accounts_ixi.csv	Contains the energy and exergy accounts at the industry level. In the "eQuant" column, "E" stands for energy, and "X" for exergy.
energy_accounts_pxp.csv	Contains the energy and exergy accounts at the product level. In the "eQuant" column, "E" stands for energy, and "X" for exergy.
energy_extensions_ixi.csv	Contains the energy and exergy accounts at the industry level. In the "eQuant" column, "E" stands for energy, and "X" for exergy.
energy_extensions_pxp.csv	Contains the energy and exergy accounts at the product level. In the "eQuant" column, "E" stands for energy, and "X" for exergy.
energy_pba_cba_accounts.csv	Contains the total energy and exergy production-based accounts (PBA column) and consumption-based accounts (CBA column) at the EXIOBASE 3 region level. In the "eQuant" column, "E" stands for energy, and "X" for exergy.

Technical validation

It is worth noting that prior to this work, extensive validation was conducted for the CL-PFU database. First, energy conservation conditions were verified. These validations include ensuring that industry-level and product-level energy flows are balanced [32, 33]. Industry-level balances are checked comparing, for each energy industry, the sum of the energy output and energy losses with an industry's energy input, which should be equal. Product-level balances are checked ensuring that the total use of a given energy product equals the total supply of the energy product. Such conditions are checked for each region of the CL-PFU database. Second, the obtained aggregated final-to-useful energy and exergy efficiencies were checked to ensure that they are aligned with previous work and to explain any observed differences [29].

Then, the technical validation of the dataset obtained for this article is conducted in four steps. In the first step, we check the consistency of the final energy accounts built for EXIOBASE (production-based perspective) with the IEA's reported total final energy consumption (territorial perspective). To do so, we compare these two accounts, excluding the final energy use corresponding to marine and aviation bunkers

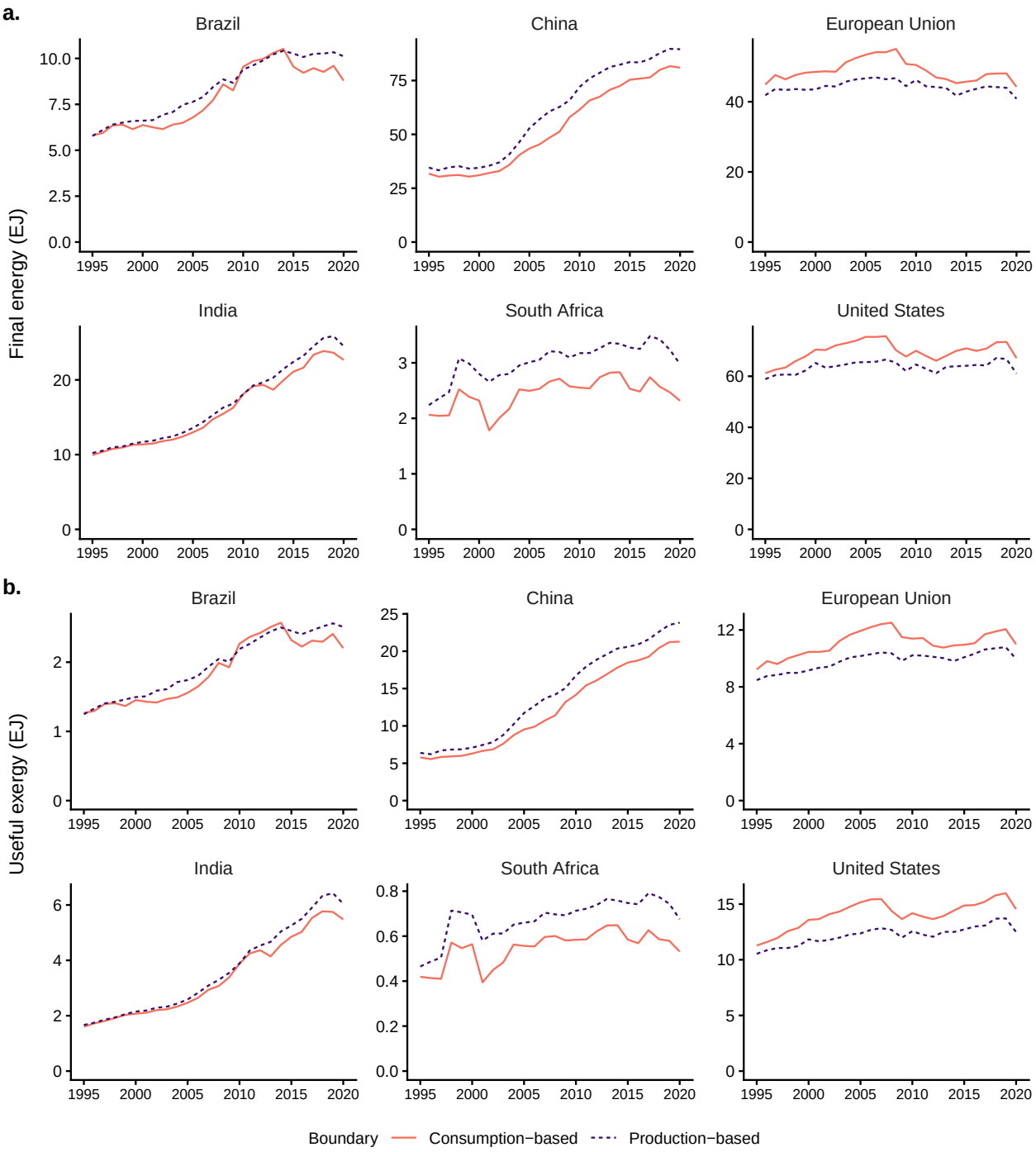


Figure 1: Production-based and consumption-based (footprint) energy accounts over time for a selection of countries, in terms of (a) final energy, and (b) useful exergy.

(international navigation and aviation), because large differences are expected — and observed — between the production-based (residential principle) and the territorial perspectives for specific countries. Once adjusted in this way, some differences are expected between the final energy accounts, but these should remain limited. Table 4 shows the results obtained.

In the second step, we check the consistency of our final exergy, useful exergy, and final-to-useful exergy loss accounts. This is done by ensuring that the sum of the useful exergy and final-to-useful exergy loss accounts equals the final exergy accounts. The same test is done at the footprint level: the sum of the useful exergy and final-to-useful exergy losses footprint should equal the final exergy footprint. These conditions are verified for all EXIOBASE regions. Note that the energy accounts cannot be verified in the same way, which is due to heat pumps and air conditioners. Indeed, these end-use devices use electricity (final energy input) to move heat from one place to another (useful energy output). With this definition of energy outputs and inputs, these end-use devices have final-to-useful energy efficiencies higher than 100% — so that the sum of useful energy and final-to-useful energy losses (zero) is higher than the final energy (electricity) input. (In the few cases in which η_E is higher than 100% for a given energy flow, we replace $(1 - \eta_E)$ by zero to calculate the final-to-useful energy losses.)

In the third step, we compare the final-to-useful energy and exergy efficiencies obtained with the developed energy and exergy accounts (production-based perspective) and those obtained directly from the CL-PFU database (for the EXIOBASE regions that align directly with a CL-PFU database region). Table 5 shows that the CL-PFU database and EXIOBASE final-to-useful efficiencies are similar for all regions. There are minor differences, which is expected considering the data processing involved in developing the EXIOBASE accounts. Particularly, the EXIOBASE energy accounts use the residential principle (energy use by the *residents* of a country), while the CL-PFU database adopts the territorial principle (energy use within the *geographical boundaries* of a country), in line with the IEA's World Energy Balances. (See Usubiaga et al. [34] for a discussion of the territorial and residencial principles for emissions — and by extension energy use — accounting.)

The fourth and last step is to ensure that the consumption-based final-to-useful energy and exergy efficiencies are sensible for each EXIOBASE region, i.e. that their value is between zero and one, and that the difference with production-based final-to-useful energy and exergy efficiencies is reasonable. Table 6 shows the consumption-based final-to-useful energy and exergy efficiencies alongside the production-based values.

Code availability

The code used to build the final- and useful-stage energy and exergy extensions is shared under MIT license and is available at the following Zenodo repository: "Code to generate the final- and useful-stage energy and exergy extensions for EXIOBASE3" (code version 1.0.0), doi: 10.5281/zenodo.22873773.

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Author contributions

Author contributions for this paper are shown in Table 7.

Competing interests

The authors declare no competing interests.

Table 4: Relative difference observed between the production-based final energy accounts of EXIOBASE and the total final energy reported in the IEA's World Energy Balances (territorial approach) for each EXIOBASE region (excluding rest of world regions). For this comparison, we exclude marine and aviation bunkers from the energy accounts. Differences obtained every 5 year in the 1995–2020 time period.

Country	1995	2000	2005	2010	2015	2020
Australia	0.00	0.00	0.00	0.00	0.01	0.02
Austria	0.09	0.10	0.10	0.10	0.12	0.10
Belgium	0.01	0.01	0.01	0.03	0.05	0.05
Brazil	0.00	0.00	0.00	0.00	0.00	0.01
Bulgaria	0.01	0.02	0.02	0.02	0.03	0.03
Canada	0.00	0.03	0.01	0.01	0.02	0.02
China	0.01	0.00	0.00	0.01	0.01	0.04
Croatia	0.03	0.06	0.07	0.07	0.09	0.11
Cyprus	0.04	0.04	0.05	0.06	0.07	0.06
Czechia	0.00	0.00	0.00	0.00	0.00	0.00
Denmark	0.03	0.03	0.04	0.04	0.03	0.02
Estonia	0.01	0.01	0.01	0.01	0.02	0.05
Finland	0.00	0.00	0.00	0.00	0.01	0.00
France	0.02	0.02	0.01	0.02	0.01	0.02
Germany	0.02	0.02	0.02	0.02	0.02	0.02
Greece	0.01	0.02	0.02	0.02	0.02	0.02
Hungary	0.04	0.05	0.06	0.06	0.05	0.00
India	0.00	0.01	0.01	0.01	0.01	0.00
Indonesia	0.23	0.24	0.24	0.28	0.14	0.08
Ireland	0.02	0.02	0.02	0.02	0.04	0.00
Italy	0.01	0.01	0.00	0.00	0.00	0.01
Japan	0.03	0.03	0.03	0.03	0.03	0.03
Latvia	0.05	0.06	0.07	0.08	0.10	0.08
Lithuania	0.14	0.15	0.15	0.17	0.23	0.55
Luxembourg	0.31	0.39	0.45	0.43	0.41	0.38
Malta	0.01	0.01	0.01	0.02	0.02	0.01
Mexico	0.01	0.01	0.01	0.01	0.01	0.09
Netherlands	0.03	0.03	0.03	0.03	0.02	0.01
Norway	0.00	0.00	0.00	0.01	0.01	0.02
Poland	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	0.00	0.00	0.01	0.01	0.00	0.01
Romania	0.01	0.01	0.02	0.02	0.05	0.06
Russia	0.00	0.00	0.00	0.00	0.00	0.02
Slovakia	0.00	0.00	0.00	0.06	0.06	0.00
Slovenia	0.02	0.02	0.02	0.00	0.00	0.03
South Africa	0.03	0.04	0.01	0.01	0.01	0.02
South Korea	0.01	0.01	0.02	0.02	0.00	0.03
Spain	0.00	0.00	0.00	0.00	0.00	0.00
Sweden	0.05	0.05	0.01	0.01	0.01	0.01
Switzerland	0.02	0.02	0.02	0.02	0.01	0.02
Taiwan	0.07	0.07	0.06	0.06	0.06	0.06
Türkiye	0.01	0.02	0.02	0.02	0.03	0.03
United Kingdom	0.00	0.00	0.00	0.00	0.00	0.00
United States	0.00	0.00	0.00	0.00	0.00	0.00

Table 5: Comparison of the production-based final-to-useful energy (E) and exergy (X) efficiencies, as obtained with the Country-Level Primary-Final-Useful database and with the EXIOBASE energy accounts. Results for 2015 and for all EXIOBASE regions except rest of the world regions, which do not have a direct correspondance in the CL-PFU database.

Country	CL-PFU (E)	EXIOBASE (E)	CL-PFU (X)	EXIOBASE (X)
Australia	0.46	0.46	0.21	0.22
Austria	0.58	0.61	0.22	0.21
Belgium	0.62	0.62	0.23	0.23
Brazil	0.50	0.51	0.22	0.22
Bulgaria	0.59	0.58	0.25	0.26
Canada	0.50	0.49	0.20	0.21
China	0.56	0.56	0.23	0.24
Croatia	0.61	0.58	0.21	0.22
Cyprus	0.59	0.61	0.24	0.25
Czechia	0.66	0.66	0.22	0.22
Denmark	0.62	0.53	0.20	0.29
Estonia	0.67	0.64	0.21	0.23
Finland	0.60	0.59	0.22	0.23
France	0.61	0.60	0.21	0.22
Germany	0.64	0.63	0.21	0.22
Greece	0.56	0.55	0.20	0.23
Hungary	0.68	0.64	0.21	0.22
India	0.59	0.59	0.22	0.22
Indonesia	0.48	0.45	0.18	0.21
Ireland	0.55	0.51	0.22	0.26
Italy	0.63	0.63	0.22	0.23
Japan	0.61	0.60	0.23	0.23
Latvia	0.63	0.59	0.18	0.19
Lithuania	0.60	0.53	0.23	0.23
Luxembourg	0.50	0.56	0.24	0.26
Malta	0.66	0.65	0.25	0.26
Mexico	0.49	0.48	0.21	0.22
Netherlands	0.63	0.61	0.22	0.24
Norway	0.57	0.54	0.25	0.28
Poland	0.61	0.61	0.21	0.21
Portugal	0.50	0.50	0.26	0.26
Romania	0.61	0.59	0.22	0.22
Russia	0.64	0.63	0.25	0.26
Slovakia	0.62	0.62	0.21	0.21
Slovenia	0.56	0.56	0.22	0.22
South Africa	0.52	0.52	0.21	0.22
South Korea	0.65	0.61	0.25	0.27
Spain	0.54	0.53	0.23	0.23
Sweden	0.60	0.60	0.24	0.24
Switzerland	0.63	0.62	0.20	0.21
Taiwan	0.63	0.59	0.24	0.27
Türkiye	0.59	0.58	0.22	0.22
United Kingdom	0.56	0.55	0.21	0.23
United States	0.54	0.53	0.19	0.19

Table 6: Comparison of the production-based (PB) and consumption-based (CB) final-to-useful energy (E) and exergy (X) efficiency as obtained with the EXIOBASE energy accounts. Results for 2015 and for all EXIOBASE regions except rest of the world regions, which do not have a direct correspondance in the CL-PFU database.

Country	PB-E	CB-E	PB-X	CB-X
Australia	0.46	0.49	0.22	0.24
Austria	0.61	0.58	0.21	0.23
Belgium	0.62	0.58	0.23	0.24
Brazil	0.51	0.52	0.22	0.23
Bulgaria	0.58	0.59	0.26	0.26
Canada	0.49	0.54	0.21	0.20
China	0.56	0.55	0.24	0.24
Croatia	0.58	0.59	0.22	0.22
Cyprus	0.61	0.61	0.25	0.24
Czechia	0.66	0.62	0.22	0.22
Denmark	0.53	0.55	0.29	0.26
Estonia	0.64	0.63	0.23	0.23
Finland	0.59	0.62	0.23	0.24
France	0.60	0.59	0.22	0.23
Germany	0.63	0.60	0.22	0.22
Greece	0.55	0.58	0.23	0.22
Hungary	0.64	0.63	0.22	0.22
India	0.59	0.59	0.22	0.21
Indonesia	0.45	0.46	0.21	0.21
Ireland	0.51	0.55	0.26	0.24
Italy	0.63	0.59	0.23	0.23
Japan	0.60	0.57	0.23	0.24
Latvia	0.59	0.61	0.19	0.20
Lithuania	0.53	0.55	0.23	0.24
Luxembourg	0.56	0.55	0.26	0.26
Malta	0.65	0.64	0.26	0.26
Mexico	0.48	0.48	0.22	0.22
Netherlands	0.61	0.58	0.24	0.24
Norway	0.54	0.56	0.28	0.28
Poland	0.61	0.61	0.21	0.21
Portugal	0.50	0.51	0.26	0.25
Romania	0.59	0.59	0.22	0.23
Russia	0.63	0.67	0.26	0.22
Slovakia	0.62	0.63	0.21	0.21
Slovenia	0.56	0.57	0.22	0.23
South Africa	0.52	0.50	0.22	0.22
South Korea	0.61	0.61	0.27	0.24
Spain	0.53	0.53	0.23	0.24
Sweden	0.60	0.60	0.24	0.26
Switzerland	0.62	0.55	0.21	0.24
Taiwan	0.59	0.57	0.27	0.26
Türkiye	0.58	0.56	0.22	0.23
United Kingdom	0.55	0.54	0.23	0.24
United States	0.53	0.53	0.19	0.20

Table 7: Author contributions following CRediT (Contributor Roles Taxonomy).

	E.A.	K.R.	M.K.H.	P.E.B.
Conceptualisation	✓	✓	✓	
Data curation	✓	✓	✓	✓
Formal analysis	✓			
Funding acquisition				✓
Methodology	✓	✓	✓	
Software	✓	✓	✓	
Validation	✓	✓	✓	
Visualization	✓			
Writing–original draft	✓			
Writing–review & editing	✓	✓	✓	✓

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