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Developing a Multi-Regional Physical Supply Use Table framework to improve the accuracy and reliability of energy analysis

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ABSTRACT

Physical Supply Use Tables overcome some of the main limitations of the commonly used Energy Extended Input Output Analysis by describing the Energy Conversion Chain in energy terms only. In this paper, we build on recent advances in the field to construct a Multi-Regional Physical Supply Use Table framework. We use data from the International Energy Agency and have developed open source R packages, thereby enabling easy adoption of the present work. The new framework enables analysts to take into consideration the trade in energy products and to track energy flows across regions. In addition, we expand the existing Physical Supply Use Table framework to provide the mathematical structure with symmetry, by adding a resource extraction matrix at the upstream end of the Energy Conversion Chain, thereby enabling reverse Input–Output calculations.

Then, we demonstrate two important applications of the new multi-regional framework. First, we show how the framework can be used for energy security analysis, how the primary energy supply can be broken down by region of origin, and how the exposure to overseas suppliers can be quantified by energy product, and final demand sector. Second, we show how energy-related greenhouse gas emissions can be accounted for and disaggregated in terms of energy use by the energy industry, downstream energy use by final demand sectors, and methane leakages and flaring. The framework, which consistently binds energy products supplied to the economy to the Energy Conversion Chain, may be helpful for numerous subfields of energy analysis and modelling.

1. Introduction

1.1. Energy analysis: a crucial tool for current challenges

Energy analysis is an essential tool to study some of the large and current energy challenges. Indeed, as fossil-fuel-based energy consumption is responsible for most greenhouse gas emissions and therefore is a key driver of anthropogenic climate change [1], energy analysis has a crucial informative role to play in climate change mitigation. First, energy analysis can inform the discussion of whether absolute energy-GDP decoupling is possible or not [2] — and assess the role of different factors in the evolution of the energy-GDP relationship [3] — as well as explore the magnitude of the energy rebound induced by energy efficiency improvements, either at the sectoral level [4], or at the economy-wide level [5]. Second, energy analysis can help identify

options for reducing energy consumption, be it through increases in efficiency [6], or through the development of alternative provisioning systems to satisfy needs and provide material well-being [7]. Third, energy analysis can help with planning the transition to a renewable energy system, raising important issues regarding the intermittency of renewable electricity production [8] and the influence of climate change on that intermittency [9], the critical minerals required for the development of renewable energy technologies [10], and the land use requirements of such technologies [11]. Fourth, current concerns regarding the exhaustion of non-renewable natural resources [12], as well as to the structural decline of fossil fuel extraction returns — measured in terms of Energy Return On Energy Investment — can be assessed through energy analysis methods, both at the primary [13] and final [14] energy stages.

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1.2. Physical Supply Use Tables for energy analysis

A widely used tool for energy analysis is Energy Input Output (EIO) analysis; of which Miller and Blair [15] provide a very comprehensive summary. Following Miller and Blair, it is possible to distinguish between (i) the traditional approach to EIO, more commonly known as Energy Extended Input Output (EEIO) analysis,¹ (ii) hybrid EIO analysis, and (iii) physical EIO analysis [16]. When using traditional EEIO, energy footprints are calculated by pre-multiplying the total requirement matrix (i.e. the Leontief inverse, calculated in monetary terms) by a direct energy intensity vector, or by a matrix of direct energy coefficients [15]. The traditional EEIO approach is widely used for a broad set of applications, for instance to assess production-based and consumption-based national energy accounts [17], to analyse energy flows embodied in global trade [18,19], or to understand the drivers of energy consumption reduction [20].²

However, although the traditional EEIO approach comes with some important advantages, mainly its simplicity and the availability of data, it comes with serious limitations. Indeed, the traditional EEIO approach fails to (i) conform to the principle of energy conservation, (ii) consistently capture the interdependence between energy products demanded by economic activities and the energy industry. Alternatively, one may adopt a physical description of energy flows, which observes the energy conservation condition and can be used to formulate a hybrid EIO model, describing energy flows in physical units, and representing the rest of the economy in monetary terms.³ However, to formulate such a hybrid EIO model, it is necessary to formulate first a purely physical EIO model, to which we now turn.

Recently, Heun et al. [28] argued for a “unifying energy analysis framework,” based on Physical Supply Use Tables (PSUTs). The authors demonstrated how such tables may be used to construct, from a “Make and Use” approach [29], Physical Input Output Tables (PIOTs). From these PIOTs, a wide range of physical EIO analyses can then be performed, hence avoiding the issues inherent to traditional EEIO analysis. A recent example is the work of King [30], who describes a physical EIO method to calculate energy returns of an Energy Conversion Chain (ECC).⁴ Noteworthy features of the PSUT framework introduced by Heun et al. [28] are that it allows analysts to perform both energy and exergy analysis across the primary, final, and useful stages of the ECC – as well as across the energy services stage – even in the case of inhomogeneous units. The PSUT framework therefore enables a physical representation of energy flows, from the primary extraction to the end-use conversion of energy, thereby enabling incorporation of physical end-use efficiencies. PSUTs have also been used by Guevara [31] to construct PIOTs representing the energy industry. Guevara and co-authors formulated the *multi-factor energy input–output model* by coupling such PIOTs with Monetary Input Output Tables (MIOTs) [16], which were used to conduct a structural decomposition of primary energy consumption in Portugal [32] and to analyse potential drivers

¹ Energy Extended Input Output analysis is akin to Environmentally Extended Input Output analysis, and it may sometimes be referred to as such. Environmentally Extended Input Output analysis may however apply to other types of environmental analysis.

² The EEIO approach has been used for a long time, and the seminal works of Bullard and Herendeen [21], Bullard et al. [22], and Costanza [23] in the context of the development of a normative energy theory of value (see [24,25]) are worth noting here.

³ The hybrid approach has for instance been used in the Life Cycle Assessment literature [26], or to assess the economic effects of a carbon tax [27].

⁴ The Energy Conversion Chain is defined here as the chain of processes whereby energy is extracted in its primary form, then transformed in final energy carriers, and eventually consumed in end-use devices.

of energy-GDP decoupling [33]. These recent applications of a PSUT framework show its potential for enhancing energy analysis.⁵

In this paper, we acknowledge the diversity of methods and tools available for energy analysis, and at the same time, recognise the additional value that PSUTs can bring to the field. A current limitation of the PSUT framework presented in Heun et al. [28] is that its scope remains national, meaning that import flows are represented as part of the supply mix, and that export flows are represented as part of the national final demand. Such a description remains incomplete, for it hides flows across countries and prevents identification of the upstream supply chain related to energy imports by a given country. This is particularly problematic for those countries that import a significant portion of their energy supply; for instance fossil fuel importing countries. A solution is to expand the national PSUT framework into a Multi-Regional Physical Supply Use Table (MR-PSUT) framework, so that imports and exports are explicitly linked to other regions’ supply and uses. Such work has for instance been conducted for agricultural products by Bruckner et al. [38], who developed the Food and Agriculture Biomass Input–Output (FABIO) Model to describe agricultural flows across countries. Regarding the energy industry, it is noteworthy to refer to the studies by Guevara et al. [39] and Rocco et al. [40], in which a three region MR-PSUT framework is used to describe the energy industry. The gap that this paper attempts to fill is to provide a clear description of the methodology and process to develop an energy MR-PSUT framework in a fully reproducible way, as well as to showcase applications of the framework.

1.3. Aim, contribution, and content

The aim of this paper is threefold: first, to provide a clear description of how a MR-PSUT framework can be constructed in a fully reproducible and adaptable way; second, to expand the usual PSUT formulation to take account of energy resources extraction and alteration of the supply mix; third, to demonstrate the framework with two simple applications: energy security analysis, and the accounting of greenhouse gas emissions from the energy industry. Section 2 introduces the structure of the expanded PSUT framework, and explains how the MR-PSUT framework is constructed from International Energy Agency (IEA) data. This work contains three key contributions: first, the PSUT structure introduced by Heun et al. [28] is expanded to facilitate the accounting of energy resources extraction on the upstream end of the ECC, and the modelling of a change in the supply mix (Section 2.1.1). Second, the construction of a MR-PSUT framework, based exclusively on IEA data is detailed (Section 2.2). Third, the new MR-PSUT framework is built using two open source R packages developed by the authors, IEATools [41] and ECCTools [42], therefore enabling full reproducibility of the work, and straightforward adaptation of the new framework to any further work. Section 3 presents and discusses the application of the framework to energy security, and Section 4 presents and discusses the application of the framework to the accounting of energy-related greenhouses gas emissions. Then, Section 5 provides the conclusions.

2. The Multi-Regional Physical Supply Use Table framework

In this section, we (i) introduce the expansion of the PSUT framework originally presented by Heun et al. [28], and (ii) present the methodology applied to construct the MR-PSUT used in this paper.

⁵ It is worth noting that PSUT and PIOT frameworks have also gained recent interest outside the field of energy analysis [34]. Examples include the study of paper and wood flows across Germany [35], the estimation of economy-wide material flow indicators using PSUTs of the Czech Republic [36], the estimation of energy-related ecological footprint of Galicia, Spain [37], as well as the calculation of cropland footprints embodied in agricultural products trade [38].

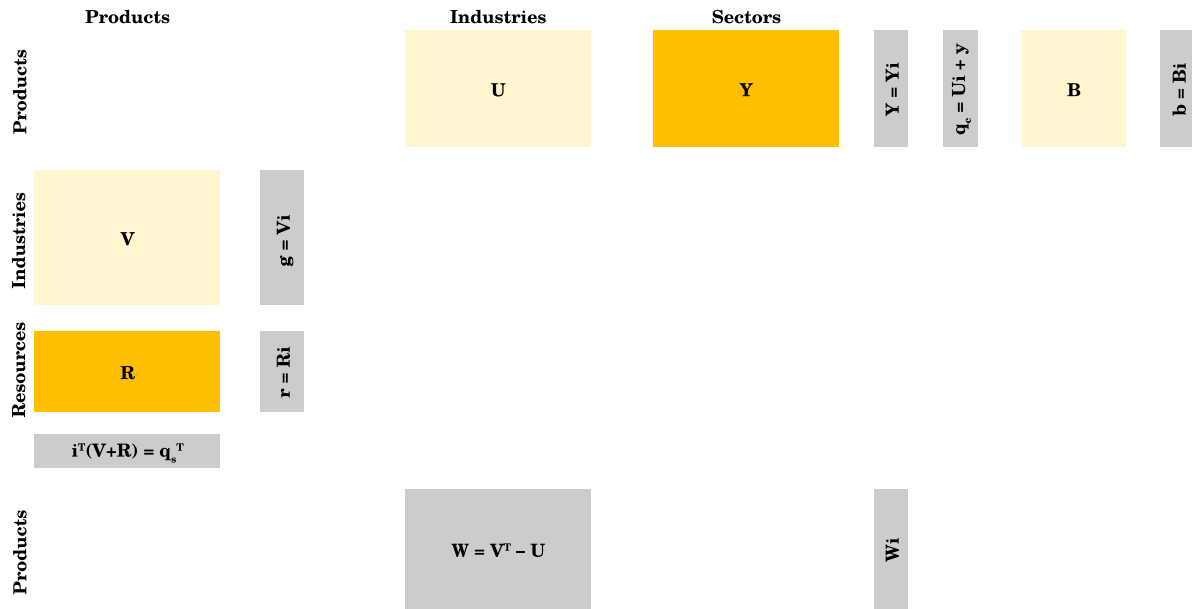


Fig. 1. Graphical representation of the expanded PSUT framework. Adapted from Heun et al. [28]. See Table 3 for matrix and vector definitions. The resource matrix **R** and the balancing matrix **B** are expansions of the original framework.

Table 1
Matrix dimensions notations. Adapted from Heun et al. [28].

Notation	Meaning
$p \times p$	Products in both rows and columns, for instance \mathbf{A} .
$i \times i$	Industries in both rows and columns, for instance $\hat{\mathbf{g}}$.
$p \times i$	Products in rows, and industries in columns, for instance \mathbf{U} .
$i \times p$	Industries in rows, and products in columns, for instance \mathbf{V} .
$p \times s$	Products in rows, and sectors in columns, for instance \mathbf{Y} .
$p \times u$	Products in rows, and units in columns, for instance \mathbf{S}_{units} .
$r \times p$	Resource stocks in rows, and products in columns, for instance \mathbf{R} .
$p \times r$	Products in rows, and resource stocks in columns, for instance \mathbf{R}^T .

2.1. Description of the expanded PSUT framework

2.1.1. Expanded PSUT framework matrices

Matrix dimension notations. Following Heun et al. [28], Table 1 presents the matrix dimension notations that will be used when introducing matrices. Products (i.e. energy carriers – gasoline, electricity, etc.), are denoted by p , industries (i.e. any installation or device transforming one energy product into another energy product – oil refinery, gas heater, etc.) by i , resource stocks by r , and final demand sectors by s . Note that a diagonalised vector (matrix with vector coefficients in the diagonal and zeros off the diagonal) is noted with a hat, e.g. $\hat{\mathbf{g}}$. See Appendix A for a comprehensive nomenclature table.

Original PSUT framework. The original PSUT framework by Heun et al. [28] consists of four basic matrices. First is the \mathbf{U} matrix, or “use” matrix, a product-by-industry matrix representing intermediary uses of products, by industry. Second is the \mathbf{V} matrix, or “make” matrix, an industry-by-product matrix representing the products supplied, by industry. Third is the \mathbf{Y} matrix, or “final demand” matrix, a product-by-sector matrix which describes the final use of products by final demand sector. Fourth is the auxiliary product-by-unit \mathbf{S}_{units} matrix, which deals with inhomogeneous units in the framework. For the sake of simplicity, and because the examples presented in Sections 3 and 4 only deal with homogeneous units, the \mathbf{S}_{units} matrix is not further included in this paper. In addition, the \mathbf{W} matrix, or “value added”

matrix, may be derived from \mathbf{V} and \mathbf{U} , to represent the difference between supplied and used products for each industry.

Decomposition of the U matrix. To formulate the MR-PSUT framework, we decompose the \mathbf{U} matrix in two complementary matrices, each with product-by-industry dimensions. The \mathbf{U}_{feed} matrix (where *feed* stands for feedstock) includes those products that are consumed by a given industry to be transformed into other energy products, i.e. what may be referred to as feedstock products (for instance, crude oil in a refinery). In complement, the \mathbf{U}_{eiou} matrix (where *eiou* stands for energy industry own use) represents those products that are used by a given industry to provide the necessary energy to operate the industrial process (for instance, high temperature heat used to distil crude oil in a refinery).

Addition of the resource matrix. A “resource” matrix, noted \mathbf{R} , of resource-stocks-by-product dimensions, representing products extracted from resource stocks, is added to the basic matrix structure. In the rest of the article, we designate as “resource products” those products that are extracted from resource stocks, and for which the coefficients of the resource matrix may be different from zero. Adding the \mathbf{R} matrix provides the framework with symmetry, with now two end-points; the upstream \mathbf{R} matrix, as well as the downstream \mathbf{Y} matrix. The symmetry enables both upstream analysis (i.e. finding the upstream effects of changes in final demand), as well as downstream analysis (i.e. finding the downstream effects of changes in resource extraction levels). (See an example in Appendix B.)

Addition of the balancing matrix. A “balancing” matrix, noted \mathbf{B} , of flexible column size and product row size, is also added. The balancing matrix fundamentally enables three things: first, dealing with potential imbalances in the ECC (Section 2.2); second, modifying the supply structure of the ECC to answer specific research questions, thereby allowing the simulation of different supply scenarios; third, altering the final demand matrix, while conserving energy balance. To modify the supply structure in such a way that the supply of a given industry i is upscaled or downscaled by a factor λ , one can proceed according to Table 2. To modify the final demand matrix, one simply has to relocate columns of the \mathbf{Y} matrix to the balancing matrix.

Graphical representation. A graphical representation of the expanded PSUT framework is presented in Fig. 1. The representation elucidates some useful aggregation vectors, found in Table 3. It is important to

Table 2

Changes to do on matrices, \mathbf{V} , \mathbf{U} , and \mathbf{B} when the supply mix needs to be altered so that the output of an industry i is upscaled (case where $\lambda > 1$), or downscaled (case with $0 \leq \lambda < 1$), by a factor λ . Note that the process is valid with $\lambda = 0$, i.e. when industry i is altogether removed from the supply mix.

Value of λ	Changes to matrix \mathbf{V}	Changes to matrix \mathbf{U}	Changes to matrix \mathbf{B}
$0 \leq \lambda < 1$	Row corresponding to industry i is multiplied by λ .	Column corresponding to industry i is multiplied by λ .	First, the column of \mathbf{U} corresponding to industry i needs to be multiplied by $(1 - \lambda)$ and then to be added to matrix \mathbf{B} . Second, the row of \mathbf{V} corresponding to matrix \mathbf{V} needs to be transposed, multiplied by $(\lambda - 1)$, and added to the matrix \mathbf{B} .
$\lambda > 1$	Row corresponding to industry i is multiplied by λ .	Column corresponding to industry i is multiplied by λ .	First, the column of \mathbf{U} corresponding to industry i needs to be multiplied by $(\lambda - 1)$ and added to the \mathbf{B} matrix. Second, the column of \mathbf{V} corresponding to industry i needs to be transposed, multiplied by $(1 - \lambda)$, and added to matrix \mathbf{B} .
$\lambda = 1$	The case is trivial and no change needs to be made.	The case is trivial and no change needs to be made.	The case is trivial and no change is needed.

Table 3

Useful aggregation vectors in the PSUT framework; mathematical definition and description. Adapted from Heun et al. [28].

Aggregation vector	Description
$\mathbf{y} = \mathbf{Y}\mathbf{i}$	Final demand by product.
$\mathbf{Y}^T\mathbf{i}$	Final demand by sector.
$\mathbf{g} = \mathbf{V}\mathbf{i}$	Total output by industry.
$\mathbf{q}_c = \mathbf{U}\mathbf{i} + \mathbf{y}$	Total output by product, calculated from a consumption-side perspective.
$\mathbf{q}_s = (\mathbf{R} + \mathbf{V})^T\mathbf{i}$	Total output by product, calculated from a supply-side perspective.
$\mathbf{f} = \mathbf{U}^T\mathbf{i}$	Total input by industry.
$\mathbf{U}_{\text{etou}}^T\mathbf{i}$	Energy consumption by industry, for own use.
$\mathbf{U}_{\text{feed}}^T\mathbf{i}$	Feedstock consumption by industry, for transformation purposes.
$\mathbf{r} = \mathbf{R}\mathbf{i}$	Total resources output, by resource stock type.
$\mathbf{h} = \mathbf{R}^T\mathbf{i}$	Total resources output, by resource products type.
$\mathbf{W}^T\mathbf{i}$	Value added, in energy terms, by industry. Values ought to be zero or negative.
$\mathbf{W}\mathbf{i}$	Value added, in energy terms, by product. Negative values represent resource products extracted from resource stocks, and positive value represent energy products available to final demand.

note that the vector \mathbf{q} may be calculated from either a supply side perspective (noted \mathbf{q}_s), or from a consumption side perspective (noted \mathbf{q}_c). Both formulations are equivalent when the balancing matrix is the $\mathbf{0}$ matrix, but differ when any flows are redirected to the balancing matrix. In what follows, \mathbf{q} will be used in situations where both vectors are equivalent ($\mathbf{0}$ balancing matrix), \mathbf{q}_c when the consumption side vector should be used, and \mathbf{q}_s where the supply side vector should be used.

Energy conservation. Before carrying on with the formulation of the Input Output structure, the energy conservation conditions should be verified. Observing such conditions, which are akin to observing the first law of thermodynamics, ensures that physical flows in the PSUT framework are consistent. Two equations should be verified; first, the use and supply of all products must be balanced:

$$\mathbf{R}^T\mathbf{i} + \mathbf{W}\mathbf{i} - (\mathbf{y} + \mathbf{B}\mathbf{i}) = \mathbf{0}, \quad (1)$$

and second, the total output of each industry should equal the total industry input, minus energy losses within each industry:

$$\mathbf{g} - \mathbf{W}^T\mathbf{i} - \mathbf{U}^T\mathbf{i} = \mathbf{0}. \quad (2)$$

Once these conditions are verified, one may carry on with the formulation of the PIOT structure.

2.1.2. PIOT structure

IO model selection. First, an IO model should be chosen [43,44]. Appendix C presents the different IO models described by Eurostat [43],

and discusses their validity focusing on the case of an energy PSUT framework. Following Heun et al. [28], we select the Industry Technology Assumption model as the most accurate description of the energy industry. Indeed, the Industry Technology Assumption considers that “all products produced by an industry are produced by the same input structure” [43, p.309], and is most appropriate for describing numerous cases of joint and by-products (see the Eurostat manual for an extensive discussion [43]), which is the case when describing the energy industry.

IO matrices formulation. Now that the IO model has been selected, the IO structure is formulated in Table 4. Matrix definitions and notations follow Eurostat guidelines where possible [43].

Estimating the effects of a change in final demand. Based on the IO structure, one can estimate the upstream effects of a change in final demand in all PSUT framework matrices. The new matrices are noted with a prime (e.g. \mathbf{Y}' , \mathbf{U}' , \mathbf{V}') and presented in Table 5.

Estimating the effects of a change in primary energy extraction from resource stocks. Similarly, one can exploit the symmetry of the expanded PSUT framework to estimate the downstream effects of a change in the level of extracted, or available resources. To do so, a symmetric IO structure has to be constructed, which is described in Table 6 — symmetric matrices are noted with a star (*). The downstream changes induced by a new resource matrix \mathbf{R}'' are shown in Table 7 and noted with two primes (e.g. \mathbf{U}'' , \mathbf{V}'' , \mathbf{Y}''). Note that the subsequent calculations rely on the perfect substitution assumption, according to which an industry producing outputs from a given combination of input products will be equally capable of producing the outputs from any of the input products, with no limiting inputs.

Finally, we note that everything presented and discussed in Sections 2.1.1 and 2.1.2 remains valid when working with a MR-PSUT framework, the only difference comes from the matrices dimensions. If we are working with i industries, p products, s final demand sectors, and n regions, then the MR-PSUT framework will comprise $n \times i$ industries, $n \times p$ products, and $n \times s$ final demand sectors. Matrix sizes will be accordingly scaled.

2.2. Building the Multi-Regional Physical Supply Use Table framework

In this section, we describe how to construct the MR-PSUT framework from IEA data [45] using as an example the period 2000–2017. Furthermore, the R code used to construct the tables is available in the associated online repository (see Data statement). As shown in Fig. 2, the process to build the multi-regional tables from the national PSUTs can be divided into four steps: (i) region selection and aggregation, (ii) constructing the regional PSUTs, (iii) specifying the multi-regional \mathbf{R} , \mathbf{V} , \mathbf{U} , and \mathbf{Y} matrices, and (iv) defining the multi-regional \mathbf{B} matrix. The specification process gathers all regional tables into a single multi-regional table, with each product and industry specified respectively by region of origin and region of location of the industry.

Table 4

Physical Input–Output matrices definition, and matrix coefficients meaning. Adapted from Heun et al. [28].

Matrix definition	Matrix name	Matrix coefficients meaning
$\mathbf{Z} = \mathbf{U}\hat{\mathbf{g}}^{-1}$ $p \times i$	Direct requirement matrix (product-by-industry)	Coefficient (k, l) represents the needed input of product k to produce one unit of output of industry l . Note: replacing the \mathbf{U} matrix by respectively \mathbf{U}_{eiou} and \mathbf{U}_{feed} gives the decomposition of \mathbf{Z} in respectively \mathbf{Z}_{eiou} and \mathbf{Z}_{feed} , which may assist in conducting different types of supply chain analysis.
$\mathbf{C} = \mathbf{V}^T\hat{\mathbf{g}}^{-1}$ $p \times i$	Product shares matrix	Coefficient (k, l) represents the share of product k in the production of industry l .
$\mathbf{D} = \mathbf{V}\hat{\mathbf{q}}_s^{-1}$ $i \times p$	Market shares matrix	Coefficient (k, l) represents the share of product l by industry k in total supply of product l .
$\mathbf{O} = \hat{\mathbf{r}}^{-1}\mathbf{R}$ $r \times p$	Resource shares matrix	Coefficient (k, l) represents the share of the resource product l extracted from the resource stock k .
$\mathbf{A} = \mathbf{Z}\mathbf{D}$ $p \times p$	Direct requirement matrix (product-by-product)	Coefficient (k, l) represents the directly (excluding supply chain) needed input of product k to produce one unit of product l . Note: replacing the \mathbf{Z} matrix by respectively \mathbf{Z}_{eiou} and \mathbf{Z}_{feed} gives the decomposition of \mathbf{A} in respectively \mathbf{A}_{eiou} and \mathbf{A}_{feed} .
$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$ $p \times p$	Total requirement matrix (product-by-product)	Coefficient (k, l) represents the total (including whole supply chain) needed input of product k to produce one unit of product l .
$\mathbf{L} = \mathbf{D}(\mathbf{I} - \mathbf{A})^{-1}$ $i \times p$	Total requirement matrix (industry-by-product)	Coefficient (k, l) represents the total (including whole supply chain) needed output of industry k to produce one unit of product l .

Table 5

Estimating the effects of a change in the final demand matrix. The new final demand is noted \mathbf{Y}' , and induced matrices by the new final demand are noted with a prime.

New matrix	Description
$\mathbf{y}' = \mathbf{Y}'\mathbf{i}$	New final demand by product.
$\mathbf{g}' = \mathbf{L}\mathbf{y}'$ $i \times p$	New total output by industry.
$\mathbf{q}' = \mathbf{L}\mathbf{y}'$ $p \times p$	New total output by product.
$\mathbf{U}' = \mathbf{Z}\hat{\mathbf{g}}'$	New “use” matrix to fulfil \mathbf{Y}' .
$\mathbf{V}' = \mathbf{D}\hat{\mathbf{q}}'$	New “make” matrix to fulfil \mathbf{Y}' .
$\mathbf{W}' = \mathbf{V}'^T - \mathbf{U}'$	New value added matrix.
$\mathbf{R}'^T\mathbf{i} = \mathbf{y} - \mathbf{W}\mathbf{i}$	New resource output vector, by resource product.
$\mathbf{R}' = \mathbf{O}(\hat{\mathbf{i}}^T\mathbf{R}')$	New resource matrix to fulfil \mathbf{Y}' .
$\mathbf{r}' = \mathbf{R}'\mathbf{i}$	New total resource output vector, by resource stocks.

Table 6

Symmetric Physical Input–Output structure, matrices definition, and coefficients meaning.

Matrix definition	Matrix coefficients meaning
$\mathbf{Z}^* = \mathbf{V}^T\hat{\mathbf{f}}^{-1}$ $p \times i$	Coefficient (k, l) represents the output of product k when industry l receives one unit of input, independently of the energy product (perfect substitution assumption).
$\mathbf{C}^* = \mathbf{U}\hat{\mathbf{f}}^{-1}$ $i \times p$	Coefficient (k, l) represents the fraction of product k in industry l inputs.
$\mathbf{D}^* = \mathbf{U}^T\hat{\mathbf{q}}_c^{-1}$ $i \times p$	Coefficient (k, l) represents the fraction of product l used by industry k .
$\mathbf{O}^* = \hat{\mathbf{q}}_c^{-1}\mathbf{Y}$ $p \times s$	Coefficient (k, l) represents the fraction of product k used by final demand sector s .
$\mathbf{A}^* = \mathbf{Z}^*\mathbf{D}^*$ $p \times p$	Coefficient (k, l) represents the amount of product k that is made available by direct transformation when supplying one unit of product l . Direct transformation refers to transformation through a single industry.
$\mathbf{L}^* = (\mathbf{I} - \mathbf{A}^*)^{-1}$ $p \times p$	Coefficient (k, l) represents the total amount of product k that is made available when supplying one unit of product l to the Energy Conversion Chain.
$\mathbf{L}^* = \mathbf{D}^*(\mathbf{I} - \mathbf{A}^*)^{-1}$ $i \times p$	Coefficient (k, l) represents the total output of industry k that is induced when one unit of product l is made available to the Energy Conversion Chain.

The whole process is conducted using the **IEATools** [41] and **ECC-Tools** [42] open source R packages.

2.2.1. Regions selection and aggregation

To limit the size of the matrices and to simplify calculations in the examples presented in Sections 3 and 4, we aggregate regions in

Table 7

Estimating the effects of a change in the resource matrix. The new resource matrix is noted \mathbf{R}'' , and matrices induced by the new extracted resources are noted with a prime.

New matrix	Note
$\mathbf{h}'' = \mathbf{R}''^T\mathbf{i}$	New total resources output vector, by resource products.
$\mathbf{q}'' = \mathbf{L}^*\mathbf{h}''$ $p \times p$	New total output by product induced by \mathbf{R}'' .
$\mathbf{Y}'' = \hat{\mathbf{q}}''\mathbf{O}^*$	New final demand matrix that can be fulfilled by \mathbf{R}'' .
$\mathbf{y}'' = \mathbf{Y}''\mathbf{i}$	New final demand by product that can be fulfilled by \mathbf{R}'' .
$\mathbf{U}'' = \hat{\mathbf{q}}''(\mathbf{D}^*)^T$	New “use” matrix induced by the resource matrix \mathbf{R}'' .
$\mathbf{V}'' = \mathbf{L}^*\mathbf{h}''(\mathbf{Z}^*)^T$ $i \times p$	New “make” matrix induced by the resource matrix \mathbf{R}'' .
$\mathbf{W}'' = \mathbf{V}''^T - \mathbf{U}''$	New value added matrix.

our example following a concordance matrix of IEA regions to the 49 regions of the Multi-Regional Input–Output Model EXIOBASE [46,47]. Further, and still to limit matrix sizes, we aggregate the EU27 countries (EU28 minus the United Kingdom), which are different regions in EXIOBASE, to a single region, leaving only 23 regions remaining. The concordance matrix for the aggregation is available in the associated online repository. Note, however, that the MR-PSUT framework is independent of and works with any aggregation. Once all energy flows are aggregated by region, we adapt trade flows so that only net trade is registered for each new region.⁶

2.2.2. Building regional PSUTs

The next step is to produce regional PSUTs for each region. The construction of national PSUTs from IEA data was thoroughly described by Heun et al. [28], and the same methodology is adopted here. The **IEATools** open source R package is used to construct national tables, and a thorough description of the process involved can be found in the documentation associated with the package [41].

2.2.3. Specifying the multi-regional matrices

Specifying the multi-regional \mathbf{R} and \mathbf{V} matrices. Specifying the multi-regional \mathbf{R} and \mathbf{V} matrices is straightforward, as flows constituting both matrices correspond respectively to domestic extraction and production. As such, we ascribe each of the product output, industry, and

⁶ Indeed, as a result of the aggregation, a newly aggregated region may be found to both import and export a given energy product, which would be an issue in the following steps. Hence, we determine and retain the corresponding imports or exports for relevant products.

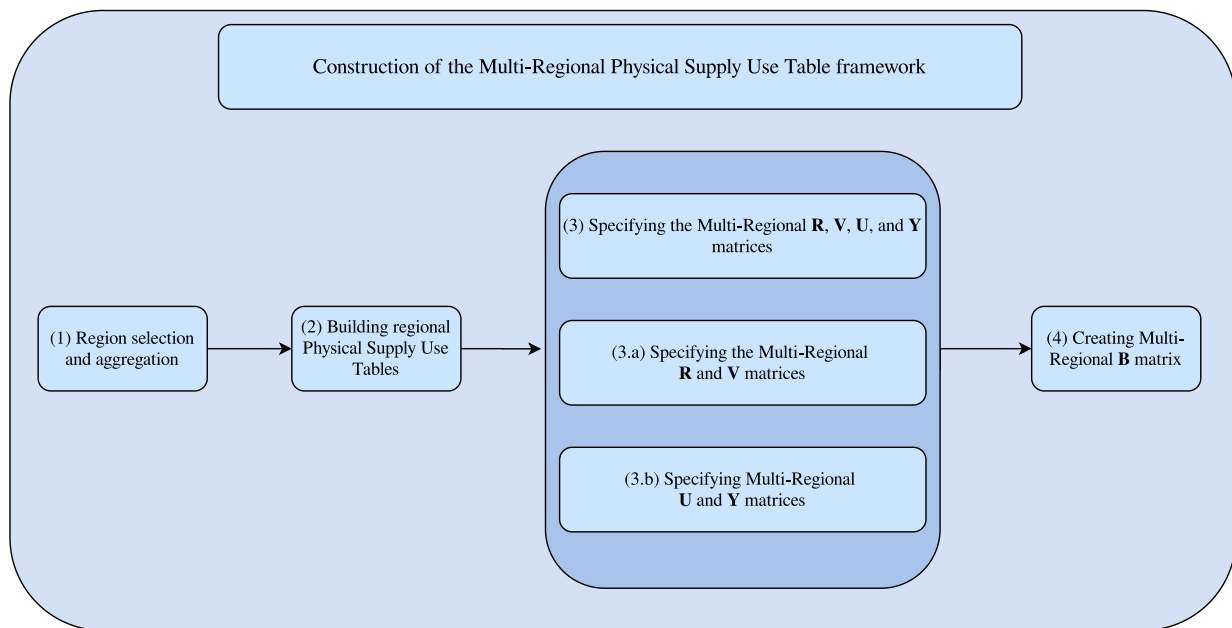


Fig. 2. Graphical representation of the process followed to construct the Multi-Regional Physical Supply Use Table framework.

resource stock to the region of occurrence. In practice, for each regional \mathbf{R} and \mathbf{V} matrices, we prefix each column (product) and row (industry, or resource stock) by the region name. Then, we drop all rows of the \mathbf{V} matrix that correspond to imports of energy products. Finally, we gather respectively all \mathbf{R} and \mathbf{V} matrices in a multi-regional \mathbf{R} and \mathbf{V} matrix, filling coefficients that do not belong to any regional matrix with zeros.

Specifying the multi-regional \mathbf{U} and \mathbf{Y} matrices. Each industry of the matrix \mathbf{U} and final sector of the matrix \mathbf{Y} are respectively domestic industries and domestic final demand sectors of the region. Hence, we prefix each region name to each column name of regional \mathbf{U} and \mathbf{Y} matrices. The next step is to specify each consumed product by region of provenance. Here, we combine two assumptions. First, we define the global market assumption, according to which imports of a given energy product come from an assumed global market for that energy product. Second, we apply the imports proportionality assumption, according to which “imported commodities are proportionally distributed over the target sectors (individual industries and final demand categories) of an importing region” [48, p.1]. The steps needed to specify \mathbf{U} and \mathbf{Y} are described in Appendix D.

2.2.4. Creating the multi-regional balancing matrix

Next, we remove “stock changes” and “statistical differences” flows from the supply mix and we locate them in the \mathbf{B} matrix, as described in Table 2. This adjustment is necessary, because otherwise, “stock changes” supplying a product (for instance gasoline) would not be translated into primary resources extraction (in this case crude oil), thereby introducing flaws in the calculations.⁷ By removing such flows from the supply mix, we assume that products coming from stock changes come instead from the rest of the supply mix. Considering that a product drawn from stocks is a product that was produced in one of the previous years, and then consumed in the present year, the assumption is reasonable, if the goal is to determine the primary energy extracted to fulfil a given final demand, independent of the

⁷ We note that the decision to remove stock changes and statistical differences from the supply mix is a decision that the analyst must take depending on the research question, it may be more suitable to keep these flows in some situations.

year of extraction. We also relocate “stock changes” and “statistical flows” that belong to final demand in the “balancing” matrix (\mathbf{B}). In addition, the minor imbalances that appear when building the MR-PSUT framework due to inconsistencies in IEA data can be corrected by adding a balancing column to the \mathbf{B} matrix.⁸

In the next sections, we present two examples of applications of the MR-PSUT framework. All calculations are conducted using the R open source **Recca** package [49].

3. Application to energy security

Energy security is a crucial aspect of energy policy, particularly for those countries and regions that do not have significant energy resources (for instance, the EU27 [50]). We show in this section how the MR-PSUT framework can be used to determine the origin of energy products (at the extraction stage) consumed in a given region, which helps to inform energy security issues.

3.1. Calculations methodology

3.1.1. Determination of Total Primary Energy Supply, and breakdown by region of origin

Our first step is to use the MR-PSUT framework to determine the Total Primary Energy Supply (TPES) for each country. This is because the TPES reported by the IEA for each country in the World Energy Extended Balances data set [45] are incorrect for two reasons. First is the treatment of energy imports and exports. Energy imports are accounted as primary energy supply, although these may refer to final energy products such as electricity or gasoline, while energy exports are subtracted from the primary energy supply, which fails to capture, and subtract, all the primary energy that was needed to produce the energy products exported. Second, energy products supplied by stock changes are also included as primary energy supply, even though they

⁸ Such imbalances are to be expected because (i) IEA data does not cover the whole world, (ii) some countries may report a given energy product with a different name, and (iii) the regional balances may be inaccurate — which can be due to poor reporting, or to illegal energy flows and energy smuggling. The balancing column in \mathbf{B} is therefore a good measure of inconsistencies appearing in IEA data when constructing the MR-PSUT framework.

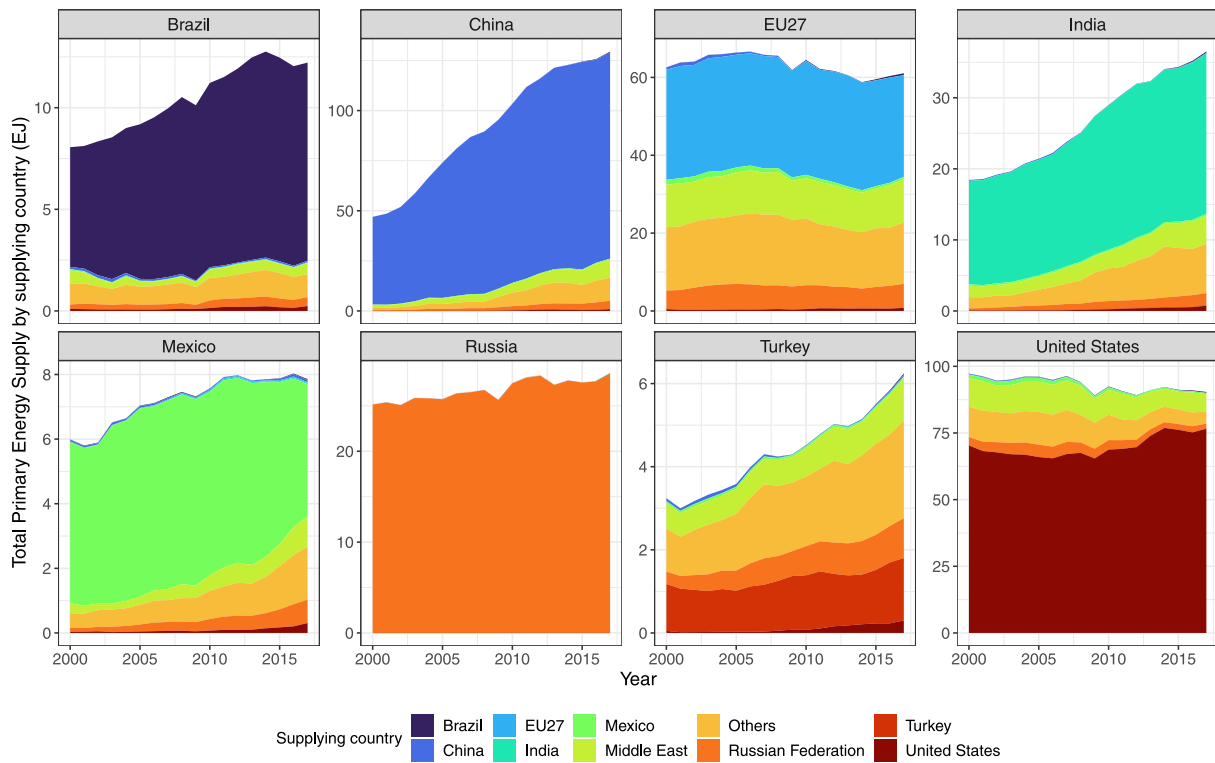


Fig. 3. Total Primary Energy Supply for different regions, broken down by supplying region.

may also be final energy products that have been produced in another year. Hence, and following the new IEA terminology (see World Energy Extended Balances, 2020 edition [51]), we refer to the number reported by the IEA as the “Total Energy Supply” (TES). To determine the actual TPES by region, we define for each region τ the national demand Y_τ where only final demand sectors of region τ are included. Then, we compute the new R_τ matrix following Table 5. The TPES of region τ , noted E_τ can then be calculated by summing up all coefficients of R_τ , namely:

$$E_\tau = \mathbf{i}^T \mathbf{R}_\tau \mathbf{i}. \quad (3)$$

Then, we disaggregate the TPES by supplying region s . The TPES supplied by region s , noted $E_{\tau,s}$, can be calculated by summing all coefficients corresponding to a resource stock (rows) located in region s , and is written as:

$$E_{\tau,s} = \mathbf{i}^T \hat{\mathbf{k}}_s \mathbf{R}_\tau \mathbf{i}, \quad (4)$$

where $\hat{\mathbf{k}}_s$ is the vector that selects resource stocks located in region s (with ones for resource stocks located in region s , and zeros elsewhere). Similarly, the TPES of region τ supplied by a given energy source type t (for instance, bioenergy), and noted $E_{\tau,t}$, can be calculated by adapting Eq. (4):

$$E_{\tau,t} = \mathbf{i}^T \hat{\mathbf{k}}_t \mathbf{R}_\tau \mathbf{i}, \quad (5)$$

where $\hat{\mathbf{k}}_t$ is the vector that selects resource stocks belonging to energy sources of type t (with ones for resource stocks of type t , and zeros elsewhere).

3.1.2. Exposure to overseas supply by energy source

Adapting Eqs. (4) and (5), the primary energy supply of region τ supplied by region s from a given energy source type t , can be calculated as:

$$E_{\tau,s,t} = \mathbf{i}^T \hat{\mathbf{k}}_t \hat{\mathbf{k}}_s \mathbf{R}_\tau \mathbf{i}. \quad (6)$$

Using Eq. (6), it is possible to determine the contribution of each region s to the primary energy supply by energy source t in country τ , and hence to analyse the exposure of each energy source t to overseas supply.

3.1.3. Exposure to overseas supply by final demand sector

We define, for each region τ and for each final demand sector u , the final demand matrix $Y_{\tau,u}$. Then, following Table 5, we determine the corresponding resource matrix $R_{\tau,u}$. The primary energy supply of region τ for final demand sector u provided by region s can then be determined as:

$$E_{\tau,s,u} = \mathbf{i}^T \hat{\mathbf{k}}_s \mathbf{R}_{\tau,u} \mathbf{i}. \quad (7)$$

Using Eq. (7), it is possible to determine the contribution of each region s to the primary energy supply of sector u in country τ , and hence to analyse the exposure of each final demand sector u to overseas supply.

3.2. Energy security: results

3.2.1. Determination of the Total Primary Energy Supply, and breakdown by region of origin

Fig. 3 shows the TPES for a set of eight selected regions, by supplying region (Eq. (4)). The TPES has increased over time for almost all these regions, particularly steeply in the case of China, India, and Brazil, due to their recent rapid economic growth. Some regions, such as the United States (US), China, or Brazil, predominantly consume domestically extracted energy, and have therefore a limited exposure to overseas energy suppliers. The share of domestic TPES in the US has increased since 2010 alongside the surge in US tight oil production [52], while it has decreased in Mexico as domestic oil production decreased by 37% between 2000 and 2017 [1, p. 144]. Remarkably, in the case of Russia, the country is a net exporter for almost all energy carriers, meaning that virtually all its primary energy supply

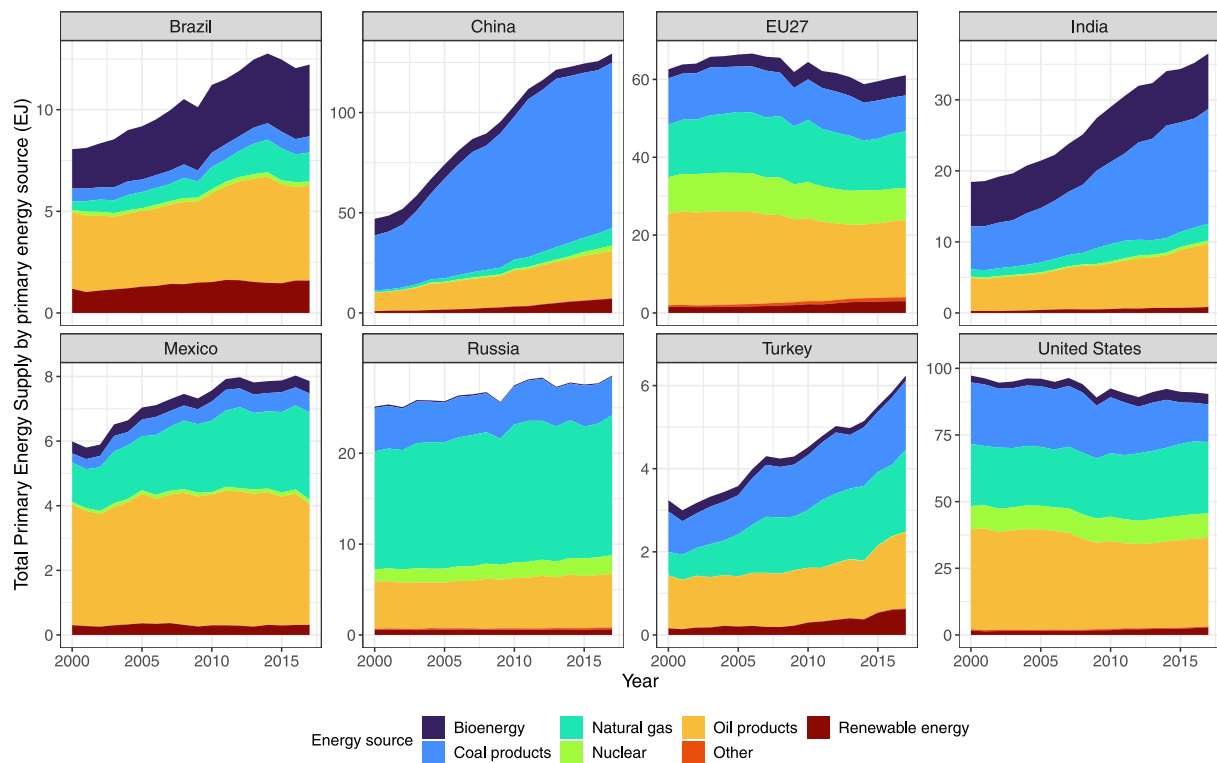


Fig. 4. Total Primary Energy Supply for different regions, broken down by primary energy source.

is domestic.⁹ Conversely, regions such as the EU27 or Turkey have a very high exposure to overseas suppliers.

Before breaking down the supply of each energy source by region of origin, we separate in Fig. 4 each region's TPES by energy source (Eq. (5)). Fig. 4 shows that all regions remain highly dependent on fossil fuel energy, and that the overall increase in renewable energy during recent years has been very modest.¹⁰ In the case of India and Brazil, a significant share of national TPES is based on bioenergy sources, although that share has declined in the Indian case, due to a surge in the reliance on fossil fuels, particularly coal products. The EU, Russia and the US are the only regions shown here to base a significant share of their regional TPES on nuclear fuels (i.e. on uranium), which may increase artificially their domestic TPES (further discussed in Section 3.3). We note that a graph similar to Fig. 4 could be obtained directly from the IEA World Energy Extended Balances, but for the inconsistencies described in Section 3.1.1 (e.g. energy imports and stock changes accounted as primary energy supply). (Appendix E shows and discusses the TES graphs obtained when directly using IEA data.)

3.2.2. Exposure to overseas supply by energy source

Fig. 5 shows the exposure to overseas suppliers by energy source in the case of China, the EU27, India, and the United States, both in 2000 and 2017 (Eq. (6)). The exposure to overseas suppliers is in general particularly high for fossil fuels. Oil products come in all cases with the highest exposure, followed by natural gas, and then by coal

⁹ Virtually, for two reasons. First, there are minor imports of primary energy in our calculations in Russia, but these are so small that they do not appear in the figure. Second, the methodology described in Section 2.2 is based on net energy trade flows, which hides gross energy flows. We discuss this issue further in Section 3.3.

¹⁰ We note, however, that the quantification of the primary energy of renewable electricity is subject to methodological issues, and that the convention used is of crucial importance. See Sousa et al. [53] or Miller et al. [54] for a comprehensive discussion.

products. Hence, the reduction of fossil fuel consumption would tend to reduce each region's dependence on imported energy – assuming that substitutes are not overseas supplied – particularly in the case of the EU27 and India. Then, bioenergy, renewable energy, and nuclear energy present low exposures to overseas supply – although this result is, in the case of renewable energy and nuclear energy, crucially dependent on the boundaries of the Energy Conversion Chain adopted (see Section 3.3). The exposure of China and India to overseas suppliers, for oil products and natural gas, has increased in recent years, as demand and imports have surged as consequence of rapid economic growth. Conversely, the US has reduced its import dependence as oil products and natural gas come increasingly from domestic sources, as a consequence of the tight oil boom in the US. Lastly, the EU27's exposure to overseas supply, when looking at fossil fuels, increases over time, as fossil fuel extraction activities are being phased out in the EU27.

3.2.3. Exposure to overseas supply by final demand sector

Fig. 6 shows the exposure to overseas supply by final demand sector in the case of China, the EU27, India, and the United States, in 2000 and 2017 (Eq. (7)). Road transportation has in almost all cases the highest exposure to overseas supply – due to the fact that road transportation consumes mostly oil products – and reaches the highest levels in the case of the EU27 and India. The exposure to overseas supply of Chinese sectors has increased in the period 2000–2017, as the country relies increasingly on imported oil products and natural gas. In most cases, the exposure of the rail sector is significant, which is partly due to the fact that rail transportation still relies on diesel as a fuel, but also due to the fact that electric trains may be consuming fossil fuel based electricity. Last, the US exposure has dramatically decreased, again due to the tight oil boom in the US.

3.3. Implications, limitations, and recommendations

This first example shows that the MR-PSUT framework, as it tracks energy flows across regions, can be used to determine the region of

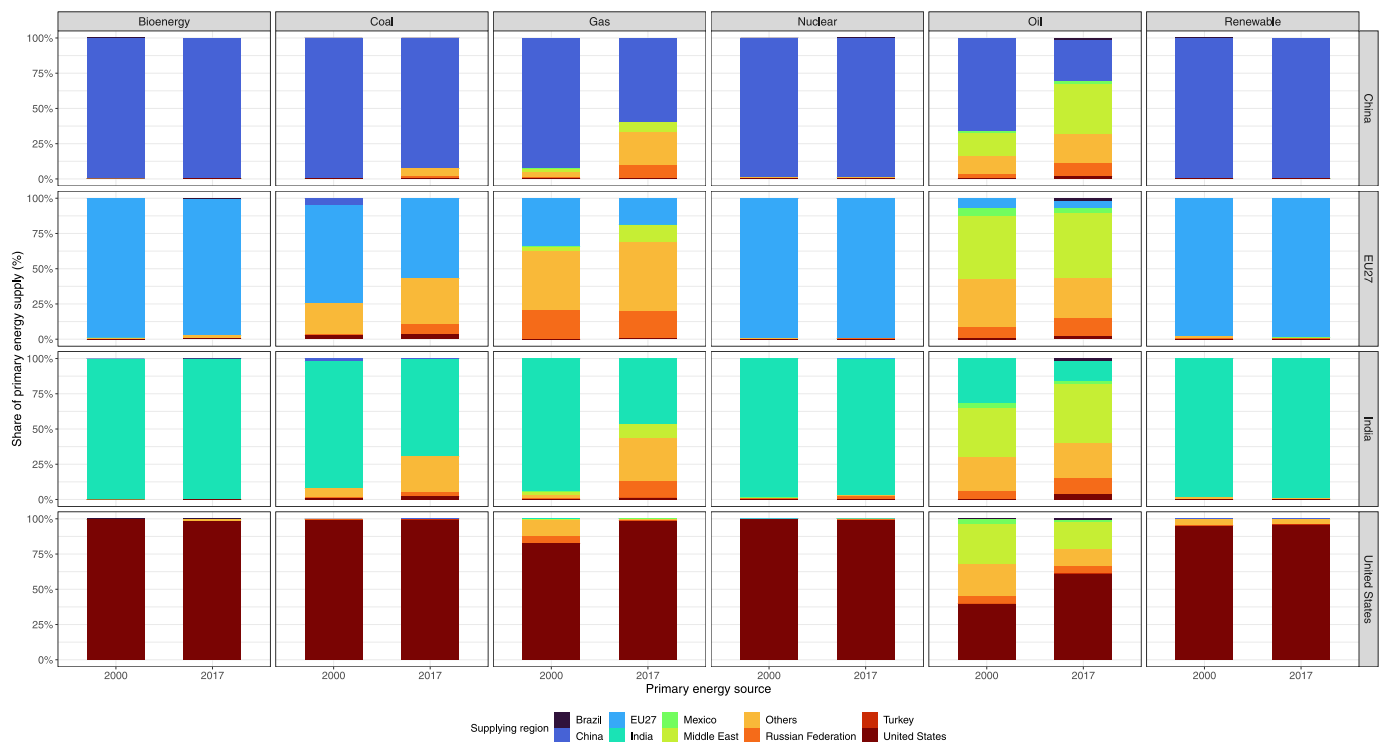


Fig. 5. Primary Energy Supply for different energy sources, broken down by supplying region.

origin of a given final energy product, and hence can be used in the broad field of energy security [55,56] — particularly, to assess the reliance of a given region on overseas primary energy supply, either for a given product or for a given final demand sector. There are however three limitations that any analyst needs to consider. First, the global market assumption is a simplifying assumption. Indeed, the global trade of energy products occurs in such a way that some regions are chief suppliers of other regions (for instance, the EU imports considerable amounts of natural gas specifically from Norway, Algeria, and Russia). The trade of energy products is heavily reliant on installed infrastructure: in the case of natural gas, pipelines are built only when long-term contracts ensure their viability, while gasification and liquefaction plants constrain exporting and importing capacities through gas tankers [57]. The MR-PSUT framework is however not dependent on such a global market assumption, and the trade linking process (Section 2.2) could well be performed with bilateral trade data. The ECCTools package enables users to use bilateral trade data to refine the trade-linking process. Considering that the main purpose of this paper is to introduce the MR-PSUT framework, its structure and potential applications, the global market assumption is sufficient here, but further studies applying the framework to energy security would benefit from use of bilateral trade data.

Second, the MR-PSUT framework has been constructed using net energy flows, i.e. considering that each region is either an importer or an exporter of a given energy product (or alternatively, does not trade the given energy product). Such an assumption is also simplifying to the extent that some energy products, such as electricity, are imported and exported depending on the supply and demand of electricity, and indeed, such a situation is likely to increase as electricity generation moves increasingly towards renewable energy, which is highly dependent on climatic conditions [8]. Hence, results yielded by the MR-PSUT framework should be seen as the energy balance over a year, expressed in net energy terms, and it should be kept in mind that such results may hide some energy trade between regions.

Third, an important limitation is related to the upstream boundary of the energy industry. Results in Section 3.2.2 show that the exposure

to overseas supply is zero in the case of nuclear energy. However, nuclear fuels are extracted in a handful of countries [58, p. 87], which invalidates the conclusion of nuclear energy being mostly domestically produced. This limitation is however not related to the MR-PSUT framework, but rather to the input data — the IEA's World Energy Extended Balances data [45] do not include flows corresponding to nuclear fuels extraction. Improving the input data to explicitly represent nuclear fuels extraction would overcome such a limitation. The boundary of the energy industry is also worth keeping in mind when looking at renewable energy, which may be domestically produced, but which (i) relies on numerous rare minerals and metals [59,60], many of which are extracted in a handful of countries [61], and (ii) relies on systems (e.g. solar panels, wind turbines...) which may not be produced domestically. The concept of energy security is indeed complex and multidimensional [62,63], and should not be analysed with the MR-PSUT framework only — in a similar vein, the fact that primary energy is domestically produced may contribute to a region's energy security, but does not guarantee altogether that energy supply is secure (one can think about possible strikes, dependence on private companies and technology, etc.).

4. Application to the accounting of greenhouse gas emissions

The energy industry, and particularly, fossil fuel consumption, is responsible for most greenhouse gas emissions worldwide. We show in this example how energy-related greenhouse gas emissions can be accounted for and disaggregated in terms of energy use by the energy industry, downstream energy use (i.e. energy use by final demand sectors), and methane leakages and flaring, and then ascribed to the final demand region.

4.1. Calculations methodology

4.1.1. Determination of energy-related greenhouse gas emissions by energy product

For this analysis, we differentiate greenhouse gas emissions in terms of (i) emissions due to energy use in the energy industry (i.e. energy use

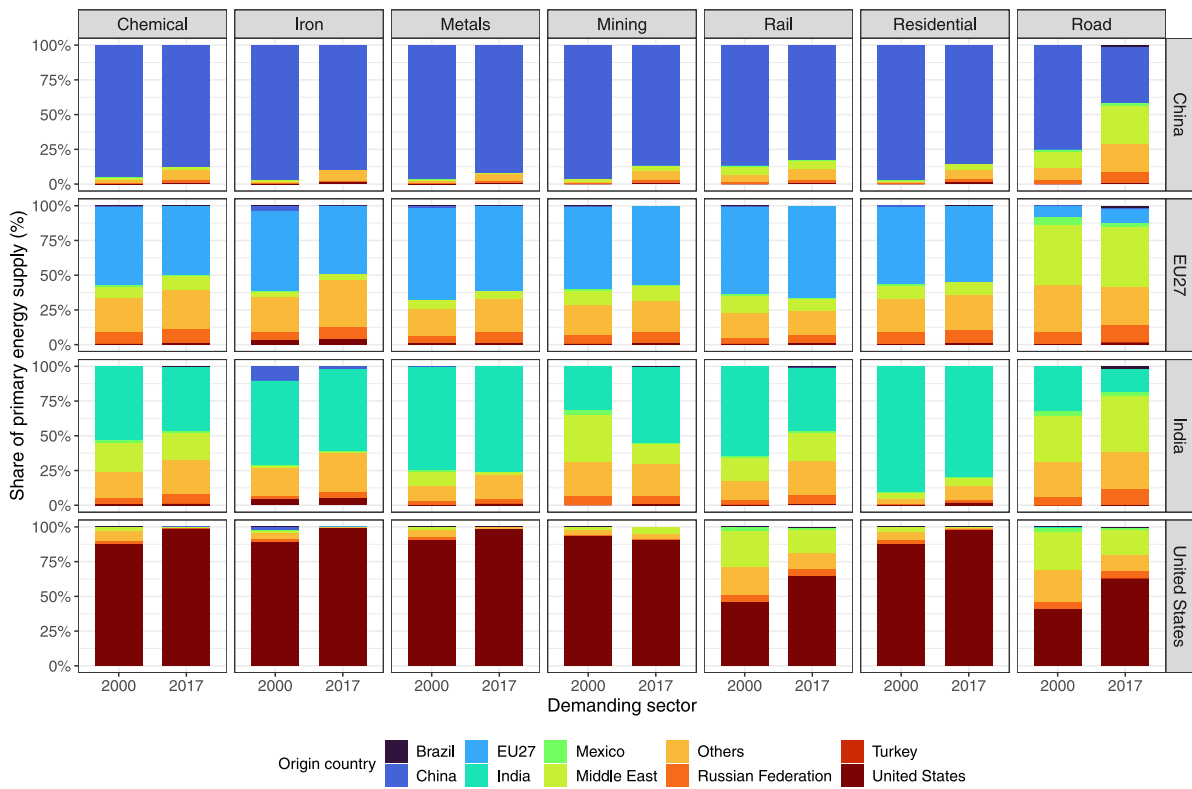


Fig. 6. Primary Energy Supply for different final demand sectors, broken down by supplying region. Metals: Metallic ores processing and metal refining.

for extracting primary energy products, and refining and transforming them into final energy products), (ii) emissions due to downstream energy use (i.e. energy use by final demand sectors), and (iii) emissions due to methane flaring and leakages in the extraction process (fugitive emissions). We exclude transportation emissions because transportation sectors are included as final demand sectors in the MR-PSUT framework.

To calculate these emissions, we start by defining the CO₂ equivalent extension vector \mathbf{e}_c as the greenhouse gas emissions due to the combustion of one unit of each resource product. In addition, we define the CO₂ equivalent extension vector \mathbf{e}_f as the fugitive emissions (methane flaring and leakages) due to the extraction of one unit of each resource product – in the rest of the paper, we use CO₂ emissions to mean CO₂ equivalent emissions – and greenhouse gas emissions.¹¹ The CO₂ extension vectors are constructed using IEA data and are further described in Appendix F.

To determine energy-related CO₂ emissions for each energy product, we take advantage of Input Output multipliers, which are defined as the effect of a change in final demand on total aggregate output [15]. Hence, output multipliers capture both the direct and indirect effects, i.e. the total effects, of an increase in the final demand vector \mathbf{y} . The vector of energy-related CO₂ emissions by product due to combustion, i.e. the vector of combustion-related CO₂ multipliers [39,64], is defined as:

$$\mathbf{m}_c^T = \mathbf{e}_c^T \hat{\mathbf{k}}_p \mathbf{L} \mathbf{i} \quad (8)$$

where \mathbf{k}_p is the vector that selects resource products; i.e. for which the value is one for resource products, and zero otherwise. Then, we

¹¹ Accounting for CO₂ emissions at the extraction of resource products avoids the double accounting of CO₂ emissions. Indeed, an energy product may undergo numerous transformations before being consumed, but eventually, the CO₂ content of the resource product being extracted from the ground, is released in the atmosphere.

determine the vector of emissions due to energy use by the energy industry, by energy product, as:¹²

$$\mathbf{m}_{eiou}^T = \mathbf{m}_c^T \mathbf{Z}_{eiou} \mathbf{L} \mathbf{i} \quad (9)$$

The vector of emissions due to downstream energy use by energy product is then calculated as:

$$\mathbf{m}_d = \mathbf{m}_c - \mathbf{m}_{eiou} \quad (10)$$

Then, the vector of fugitive emissions by product due to methane flaring and leakages is defined as:

$$\mathbf{m}_f^T = \mathbf{e}_f^T \hat{\mathbf{k}}_p \mathbf{L} \mathbf{i} \quad (11)$$

and the vector of total energy-related CO₂ emissions, i.e. the vector of CO₂ multipliers, is defined as:

$$\mathbf{m}_{CO_2} = \mathbf{m}_{eiou} + \mathbf{m}_d + \mathbf{m}_f \quad (12)$$

To understand better the energy-related CO₂ emissions by energy product, we quantify the primary energy embodied in each energy product and we break it down by primary energy type. We follow Guevara et al. [39] to define a vector of primary energy multipliers as:

$$\mathbf{m}_e^T = \mathbf{k}_p^T \mathbf{L} \quad (13)$$

Then, we decompose the embodied primary energy by resource product following Eq. (14):

$$\mathbf{M}_e = \hat{\mathbf{k}}_p \mathbf{L} \quad (14)$$

We can then simply aggregate by primary energy type (e.g. oil products).

¹² Note that \mathbf{Z}_{eiou} is defined as $\mathbf{U}_{eiou} \hat{\mathbf{g}}^{-1}$, according to Table 4.



Fig. 7. Energy-related CO₂e emissions for a unit of energy product delivered, disaggregated in terms of (i) emissions due to energy use by the energy industry, (ii) emissions due to downstream energy use by final demand sectors, and (iii) fugitive emissions due to methane flaring and leakages. Unit: kgCO₂ equivalent per GJ.

4.1.2. Determination of energy-related greenhouse gas emissions by final demand sector

For each region τ , we determine the vector of energy-related CO₂ emissions due to combustion \mathbf{f}_c by sector (so, the vector containing in coefficient k the energy-related CO₂ emissions by final demand of sector k) as:

$$\mathbf{f}_c^T = \mathbf{e}_c^T \widehat{\mathbf{k}}_p \mathbf{L} \mathbf{Y}_\tau, \quad (15)$$

and the vector of fugitive emissions due to methane flaring and leakages \mathbf{f}_f as:

$$\mathbf{f}_f^T = \mathbf{e}_f^T \widehat{\mathbf{k}}_p \mathbf{L} \mathbf{Y}_\tau. \quad (16)$$

Then, the vector of total energy-related CO₂ emissions is defined as:

$$\mathbf{f}_{CO_2} = \mathbf{f}_c + \mathbf{f}_f. \quad (17)$$

4.2. Accounting for greenhouse gas emissions: results

4.2.1. Determination of energy-related greenhouse gas emissions by energy product

Fig. 7 shows the energy-related CO₂ emissions intensity by energy product (Eqs. (9)–(12)), in 2010 and 2017, for China, the EU27, Russia, and the United States. Emissions due to the downstream use of energy products are considerably higher than emissions due to both energy use by the energy industry and emissions due to methane flaring and

leakages. Differences across regions increase with the degree of transformation of energy products: for crude oil, natural gas, and coking coal, differences are hardly noticeable, while they are striking in the case of heat and electricity. Indeed, such differences in the case of electricity and heat are mostly due to the differences in the composition of the primary energy of heat and electricity, which are shown in Fig. 8 (Eq. (14)), for the same four regions.

The differences in the composition of embodied primary energy explains the differences in the energy-related CO₂ emissions intensities observed in Fig. 7. A large share of the EU electricity comes from nuclear fuels and renewable energy, leading to a relatively low energy-related CO₂ emissions intensity observed in Fig. 7. In the Russian case, the energy-related CO₂ emissions intensity of electricity is lower than in the US and China due mostly to a higher use of natural gas and lower use of coal products for electricity generation. Important changes can be observed in the period 2000–2017 for particular products, for instance the coal products embodied in electricity has significantly decreased in China and in the US, leading to an improvement in CO₂ emissions intensity of electricity (Fig. 7). The embodied primary energy in heat has also been significantly reduced in the US, mainly because of reduced consumption of embodied coal products, which has led to a reduced CO₂ intensity. Evolutions over time are particularly noticeable for electricity and heat, which may come from decarbonised energy sources, while fossil fuels are inherently carbonised.

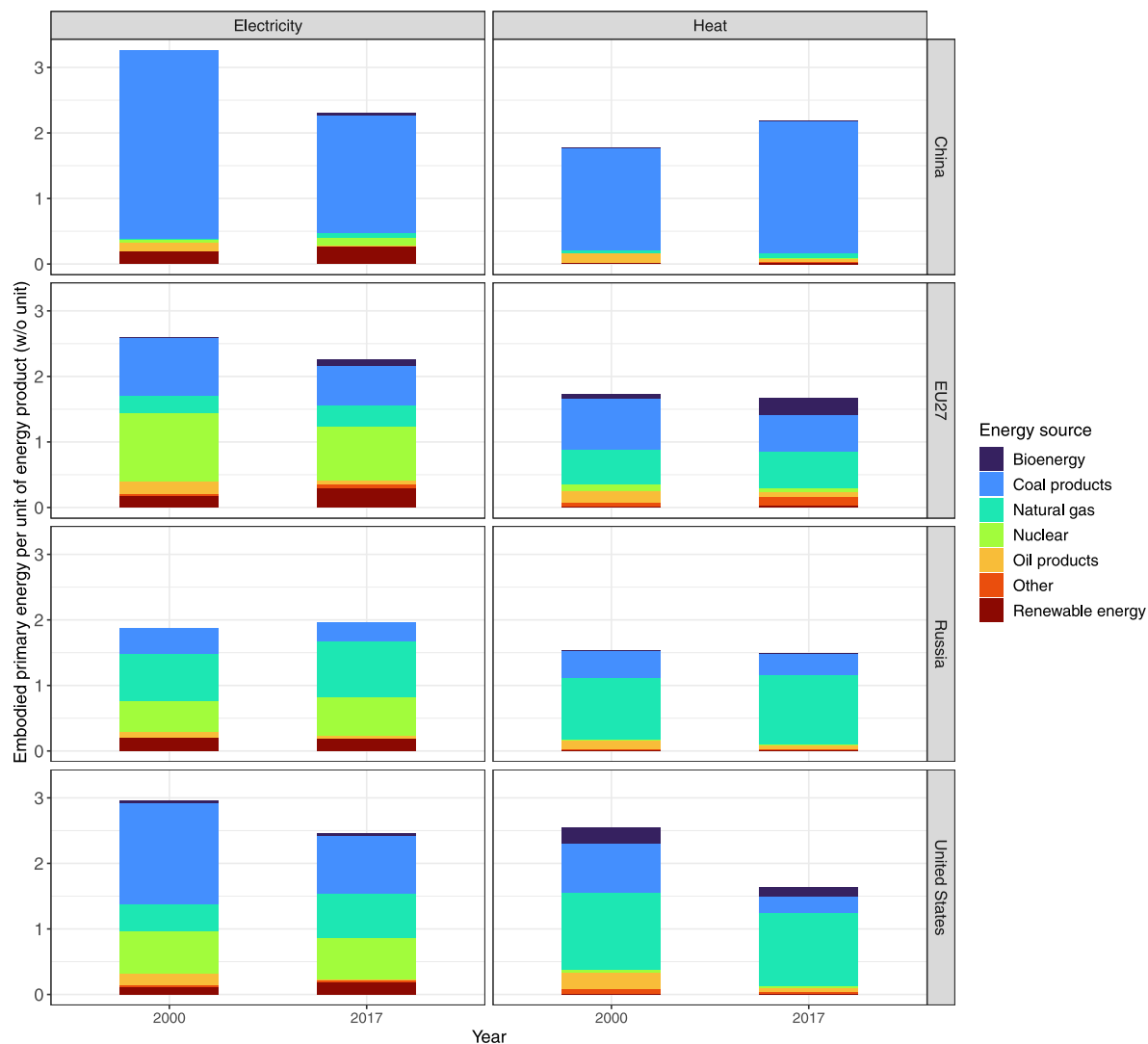


Fig. 8. Embodied primary energy by primary energy source, for one unit of provided final energy, in the case of electricity and heat. Without unit (energy per energy).

4.2.2. Determination of energy-related greenhouse gas emissions by final demand sector

Fig. 9 shows the greenhouse gas emissions by sector (Eq. (15), (16), (17)) for the EU27, the US, India and China, using the chemical and petrochemical, iron and steel, and road transportation final demand sectors as examples. The road transportation sector is responsible for considerably more emissions than the chemical and petrochemical and iron and steel sectors in the EU27 and the US, which shows the large scale of the road transportation sector in such industrialised regions. Emissions of the road transportation sector are unsurprisingly mostly due to oil products, while most emissions of the iron and steel sector come from coal products, due to the large use of coke to reduce iron ore in the sector. Emissions from the chemical and petrochemical and iron and steel sectors have decreased over years in the EU27 and in the US as a combination of increasing efficiencies and moving industrial activities to developing countries — a deeper study would be needed to untangle these effects (see [20] for an example) — while emissions of these sectors have increased in China and India (particularly for the iron and steel sector) as the regions are increasing industrial output.

4.3. Implications, limitations, and recommendations

Quantification of greenhouse gas emissions. We have shown (in Figs. 7 and 9) how energy-related greenhouse gas emissions can be quantified

and disaggregated by type of emissions (due to energy use by the energy industry, downstream energy use by final demand sectors, and fugitive emissions due to methane flaring and leakages) using the MR-PSUT framework. Emissions may be accounted for by energy product, or by final demand sector, and the framework also allows analysts to monitor evolutions over time and their causes, for instance looking into the composition of the embodied primary energy, be it by energy product or final demand sector. While we have demonstrated the framework focusing on fossil fuel emissions only, the framework can also be used to quantify the greenhouse gas emissions of bioenergy, which may become crucial in the near future. Indeed, while recent EU and US legislation favours the development and the consumption of bioenergy and biofuels (see pieces of legislation [65–67]), recent studies have questioned the environmental benefits of principally biofuels, most notably because of the possible induced indirect land use change [68,69]. By tracking energy flows across borders, the framework allows analysts to identify the region of primary production of such fuels, and to ascribe greenhouse gas emissions due to deforestation to the final consumer region.

In addition to the limitations already raised in Section 3.3, an important limitation is that the MR-PSUT framework only allows analysts to account for greenhouse gas emissions related to the energy industry, either because of energy production or because of downstream energy combustion. But other greenhouse gas emissions, coming for instance

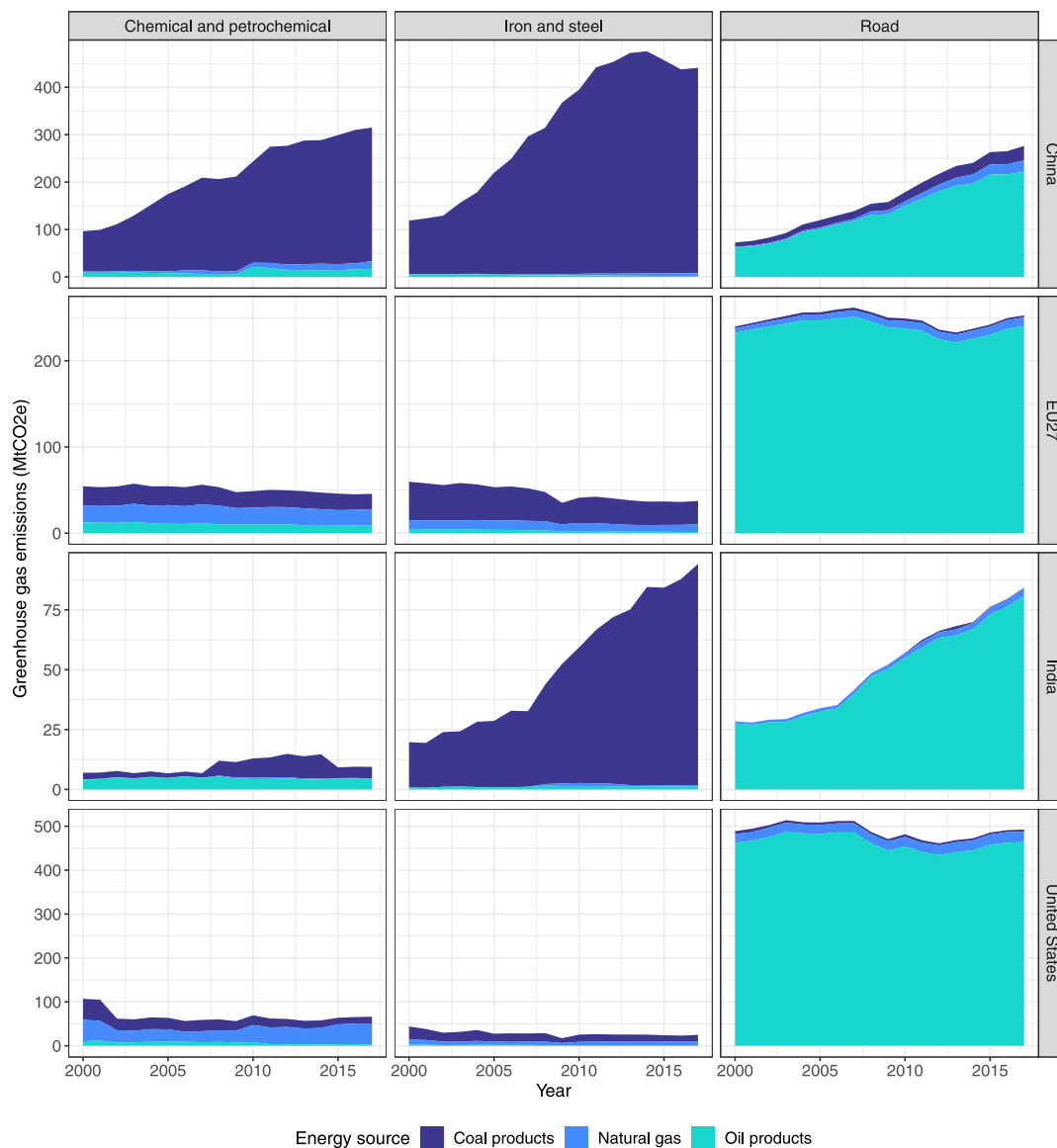


Fig. 9. Greenhouse gas emissions by sector and energy source. Values in MtCO₂e (1e6 tons of CO₂ equivalent).

from cement production, or from the reduction of metallic ores, cannot be captured with the framework. Likewise, greenhouse gas emissions due to the manufacture of the energy industry infrastructure (oil fields, refineries, solar panels, wind turbines...) cannot be estimated with the MR-PSUT framework. Other techniques such as Life Cycle Analysis need to be adopted to assess such emissions [70].

Further application: accounting for resources extraction. We have also shown that the framework allows analysts to quantify the primary energy embodied in energy products, and hence in each final demand sector, by final energy product. More generally, a key feature of the MR-PSUT framework is that it explicitly describes primary energy resources extraction through the resource matrix, and hence consistently binds energy products supplied to society to the level of primary energy resources extraction. Such an explicit representation makes the framework useful for energy-economy modelling, as energy products required for the functioning of the economy may be linked to the primary energy resources extraction, thereby facilitating the dynamic representation of primary energy resources stocks in broader models.

5. Conclusion

In this paper, we have introduced a Multi-Regional Physical Supply Use Table framework that builds on recent work. The new framework enables analysts to track energy flows across countries and to analyse the global trade of energy products using Input Output techniques. In doing so, it overcomes limitations of single region Physical Supply Use Table frameworks, which represent imports as a supplying industry and exports as a final demand sector. The adoption of a physical description of energy flows rigorously binds energy products supplied to the economy to a given Energy Conversion Chain, thereby overcoming some of the key limitations of traditional Energy Extended Input Output analysis. In addition, the expansion of the existing Physical Supply Use Table framework with a new resource matrix provides the framework with symmetry, binding energy products supplied to the economy to extracted primary energy resources and to the location of extraction. The symmetry of the framework enables analysts to reverse Input Output calculations, and to determine the downstream consequences of the extraction of primary energy in a given location. The practical process to construct the Multi-Regional Physical Supply Use Table framework using data from the International Energy Agency has been described,

and we have introduced open source R packages (**IEATools**, **ECCTools**, and **Recca**) that allow for a straightforward adaptation of the present work.

The framework is of particular value for linking the origin of primary energy extraction to the final demand region and sector for final energy products that are traded multiple times throughout their processing; for instance oil products that are extracted, refined, and finally consumed, in different regions. The framework is flexible, so that it may be used as a screening tool using an approximative assumption such as the global market assumption in the trade linking process. It may also be used as a tool to study in-depth the supply chain of a given energy product and region, in which case the relevant trade links can be built more precisely, while keeping as background a simplifying assumption for those flows less relevant to the question investigated.

The MR-PSUT framework is versatile, and may be useful for a wide range of energy analysis subfields. In addition to the applications demonstrated in this article (i.e. the analysis of a region's energy security and the accounting of greenhouse gas emissions) historical and energy transition studies may benefit from coupling the framework with the long time series of the International Energy Agency's World Energy Extended Balances. The framework can be of particular relevance to the Societal Exergy Analysis community, for it enables analysis both in energy and exergy terms, as well as at the useful stage of the Energy Conversion Chain. A wide range of environmental impacts related to the energy industry may be estimated and ascribed to the final demand region using the framework. For instance, biodiversity impacts and land use change induced by biofuel production could be estimated depending on the type of primary energy extracted and the location of extraction. The explicit representation of primary energy resources extraction allows the framework to be coupled with a stock-flow consistent structure, and thereby to account dynamically for energy resource stocks, which is crucial for energy-economy modelling in a resource-constrained future.

Data statement

The IEA data used to construct the MR-PSUT framework (World Energy Extended Balances 2019) is not publicly available; the user needs to access IEA data through a valid license. However, the R code that we used to construct the MR-PSUT framework from the raw IEA data and the concordance matrix for the regional aggregation are available under a CC-BY-4.0 license at the University of Leeds Data Repository: <https://doi.org/10.5518/1091>.

CRediT authorship contribution statement

Emmanuel Aramendia: Conceptualisation, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Matthew K. Heun:** Conceptualisation, Methodology, Software, Writing – original draft, Writing – review & editing. **Paul E. Brockway:** Conceptualisation, Methodology, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Peter G. Taylor:** Conceptualisation, Methodology, Writing – original draft, Writing – review & editing, Supervision.

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. Nomenclature

The paper adopts the following conventions: boldface capital letters (e.g., \mathbf{U}) represent matrices, while boldface lowercase letters (e.g., \mathbf{g}) identify column vectors. Where possible, symbols for matrices and vectors follow the Eurostat naming convention [43]. Table A.1 lists the nomenclature for this paper.

Appendix B. Additional example: downstream effects analysis

To showcase how the framework also enables analysts to assess downstream consequences (i.e. induced final demand) of a given quantity of extracted resources, we track down the final uses of the primary extraction of oil products in different regions. Thus, for each supplying region s , we define a new matrix \mathbf{R}_s in which only oil products extracted in region s are kept. We calculate the corresponding \mathbf{Y}_s matrix of induced final demand, no matter the region of final demand, following Table 7. Then, we adapt Eqs. (4) and (5), so that the induced final energy consumption in region τ , and noted $F_{\tau,s}$, is calculated as:

$$F_{\tau,s} = \hat{\mathbf{k}}_{\tau} \mathbf{Y}_s \mathbf{i}, \quad (\text{B.1})$$

where \mathbf{k}_{τ} selects final demand sectors corresponding to region τ . Then, the induced final energy by final demand sector u , independently of the region τ of end-use, is calculated as:

$$F_{\tau,u} = \hat{\mathbf{k}}_u \mathbf{Y}_s \mathbf{i}, \quad (\text{B.2})$$

where \mathbf{k}_u selects final demand sectors u , no matter the end-use region τ .

Fig. B.1 shows the destination regions of extracted oil products. For countries that are net importers of most oil products, for instance the EU, Brazil, or China, almost all domestically extracted oil products are consumed domestically. Conversely, for regions such as Mexico and the Russian Federation, most of the domestic extraction is exported. The US has evolved from being a net importer of oil products (exporting only some particular oil products in small quantities) to being a net exporter of oil products, which exports roughly 15% of its oil products extraction, due to the recent tight oil boom.

Appendix C. Description of Eurostat Input–Output models

Table C.1 presents the different Eurostat models [43], and discusses their validity in relation to the energy PSUT developed in this paper.

Of these models, all industry-by-industry models can first be dismissed, as the unit of interest is here the energy product. Indeed, the final energy demand by sector (e.g. Transport, Residential, Iron and steel...) is formulated in terms of energy products, and not in terms of industry output. Of the remaining models, the one that describes best the energy industry is the Industry Technology Assumption, which considers that “all products produced by an industry are produced by the same input structure”, and which is most appropriate when dealing with numerous cases of joint and by-products [43].

Appendix D. Specification of \mathbf{U} and \mathbf{Y} with the Global Market Assumption

To specify the \mathbf{U} and \mathbf{Y} matrices following the global market assumption and the imports proportionality assumption, we follow the four following steps:

1. We determine, for each product p and each region τ , the share of imported products compared to domestically consumed products (i.e. consumed in either \mathbf{U} or \mathbf{Y} , excluding exports). With that share, we ascribe a portion of used product p to domestically produced products following the imports proportionality assumption. The remaining portion of used products are ascribed to imported products.

Table A.1
Nomenclature.

Symbol	Description
<i>Letters</i>	
E	Refers to primary energy. Subscripts denote the demanding region, supplying region, and energy source type.
F	Refers to final energy. Subscripts denote the demanding region, supplying region, and final end-use sector.
c	Refers to the share of exports. Subscripts denote the region and product it refers to.
k	Refers to the line k of a matrix.
i	Refers to a given industry.
l	Refers to the column l of a matrix.
n	Refers to the number of regions considered.
p	Refers to a given product.
s	Refers to a given supplying region.
r	Refers to a given resource stock.
t	Refers to a given energy source type.
u	Refers to a given end-use sector.
x	Refers to exports. Subscripts denote the region and product if refers to.
<i>Greek letters</i>	
λ	Downscaling or upscaling factor for modifying the supply mix. See Table 2 .
τ	Refers to a given demanding region.
<i>Acronyms/abbreviations</i>	
EIO	Energy Input Output
EU27, or EU	European Union
GDP	Gross Domestic Product
IEA	International Energy Agency
MIOT	Monetary Input Output Table
MR-PSUT	Multi-Regional Physical Supply Use Table
PIOT	Physical Input Output Table
PSUT	Physical Supply Use Table
TES	Total Energy Supply
TPES	Total Primary Energy Supply
US	United States
<i>Subscripts</i>	
p	Refers to a given product.
s	Refers to a given supplying region.
t	Refers to a given energy source type.
τ	Refers to a given demanding region.
u	Refers to a given end-use sector.
feed	Refers to feedstock share of a matrix.
eiou	Refers to the EIOU share of a matrix.
<i>Superscripts</i>	
-1	Denotes square matrix inverse.
T	Denotes transpose of a vector or matrix.
'	Denotes a new version of a vector or matrix induced by a new final demand \mathbf{Y}' .
"	Denotes a new version of a vector or matrix induced by a new resources matrix \mathbf{R}'' .
<i>Superannotations</i>	
$\hat{\mathbf{v}}$	Denotes a square diagonal matrix formed by placing the elements of \mathbf{v} on the diagonal of \mathbf{I} .
\mathbf{Z}^*	Denotes the symmetric \mathbf{Z} matrix used to reverse the Input Output structure. See Table 6 .
<i>Column vectors</i>	
\mathbf{e}_c	Vector of CO_2 emissions by resource-product, due to its combustion ($p \times 1$).
\mathbf{e}_f	Vector of CO_2 emissions by resource-product, due to methane flaring and leakages ($p \times 1$).
\mathbf{f}	Total input by industry ($i \times 1$).
\mathbf{f}_c	Induced CO_2 emissions by final demand sector due to the combustion of fuels ($s \times 1$).
\mathbf{f}_f	Induced CO_2 emissions by final demand sector due to methane flaring and leakages ($s \times 1$).
\mathbf{f}_{CO_2}	Total induced CO_2 emissions by final demand sector. ($s \times 1$).
\mathbf{g}	Total industry output vector ($i \times 1$).
\mathbf{h}	Total output by resource-products vector ($p \times 1$).
\mathbf{i}	Identity column vector (flexible numbers of rows, one column).
\mathbf{k}_p	Vector selecting resource-products. ($p \times 1$).
\mathbf{k}_s	Vector selecting resource-stocks located in region s ($r \times 1$).
\mathbf{k}_t	Vector selecting resource-stocks of type t ($r \times 1$).

(continued on next page)

Table A.1 (continued).

Symbol	Description
m_e	Vector of primary energy multipliers ($p \times 1$).
m_{CO_2}	Vector of total CO ₂ emissions multipliers ($p \times 1$).
m_c	Vector of CO ₂ emissions multipliers due to combustion ($p \times 1$).
m_d	Vector of CO ₂ emissions multipliers due to downstream energy use ($p \times 1$).
m_{eiou}	Vector of CO ₂ emissions multipliers due to energy industry energy use ($p \times 1$).
q	Total output by product vector ($p \times 1$).
q_c	Total output by product vector, calculated with a consumption perspective ($p \times 1$).
q_s	Total output by product vector, calculated with a supply perspective ($p \times 1$).
r	Total output by resource-stocks vector ($r \times 1$).
y	Final demand vector ($p \times 1$).
Matrices	
A	Direct requirements matrix ($p \times p$).
B	Balancing matrix (flexible column size, product row size).
C	Product shares matrix ($p \times i$).
D	Market shares matrix ($i \times p$).
I	Identity matrix.
$L_{p \times p}$	Total requirements matrix ($p \times p$).
$L_{i \times p}$	Total requirements matrix ($i \times p$).
M_r	Matrix of embodied resource-products by demanded product ($p \times p$).
O	Resource shares matrix ($r \times p$).
R	Resources extraction matrix ($r \times p$).
R_r	Corresponding resources matrix for demanding country r ($r \times p$).
R_s	Resources extraction matrix for supplying country s ($p \times s$).
U	Use matrix. ($p \times i$).
U_{eiou}	Part of U that is used for energy purposes ($p \times i$).
U_{feed}	Part of U that is used as feedstock, i.e. for transformation purposes ($p \times i$).
V	Make matrix. ($i \times p$).
W	Value added matrix ($p \times i$).
Y	Final demand matrix ($p \times s$).
Y_r	Final demand matrix for demanding country r ($p \times s$).
Y_s	Induced final demand matrix by supplying country s ($p \times s$).
Z	Direct requirements matrix ($p \times i$).
Z_{eiou}	Direct requirements matrix for energy industry own use ($p \times i$).

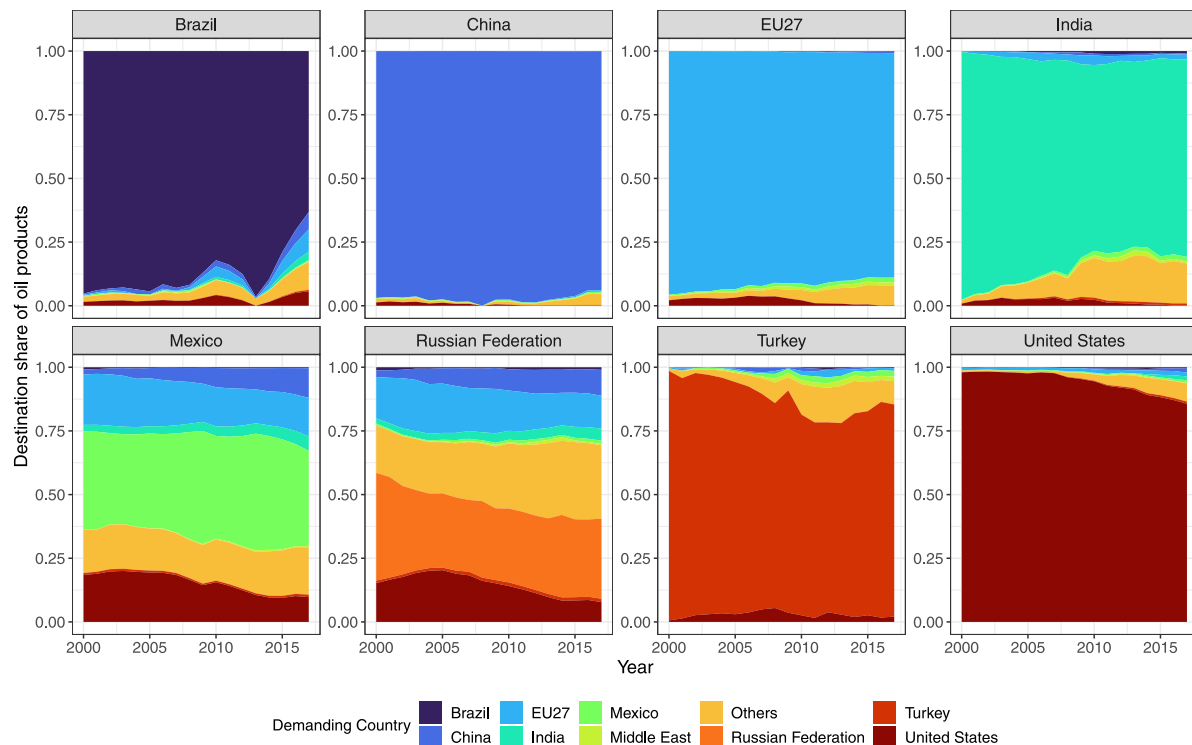


Fig. B.1. Destination region shares of domestically produced oil products.

Table C.1

List of different Eurostat models. Reasoning, arguments, and quotes from Eurostat [43, Chapter 11].

Eurostat Model	IO-structure	Assumption	Validity for PSUT
Model A	Product-by-product	Product Technology Assumption: “each product is produced in its own specific way, irrespective of the industry where it is produced,” equivalent to “a product has the same input structure in whichever industry it is produced.”	This assumption is adapted for cases of subsidiary production, i.e. where products produced by a same industry can be independently produced, and one of them can be defined as a primary product. In addition, a primary procedure industry needs to be defined for each product. Considering the numerous cases of joint production in the energy industry (e.g. oil refineries, blast furnaces, etc.), the assumption is not appropriate.
Model B	Product-by-product	Industry Technology Assumption: “each industry has its own specific way of production, irrespective of its product mix,” equivalent to “all products produced by an industry are produced by the same input structure.”	The assumption is particularly relevant for cases of joint and by-production, where different outputs products from a given industry are produced indistinctly from a given structure of inputs. The assumption is appropriate for describing the energy industry.
Model C	Industry-by-industry	Industry Sales Structure Assumption: “each industry has its own specific sales structure, irrespective of its product mix.”	The assumption does not seem appropriate, as joint products are used for different purposes; for instance, oil and gas extraction produces natural gas, crude oil, natural gas liquids, each of which will have a different use. In addition, the assumption leads to an industry-by-industry structure, which is not consistent with a final demand in terms of energy carriers.
Model D	Industry-by-industry	Industry Product Sales Structure Assumption: “each product has its own specific sales structure, irrespective of the industry where it is produced.”	The assumption may be consistent with the energy industry structure, but it leads to an industry-by-industry structure, which is not consistent with a final demand in terms of energy carriers.
Model E	Product-by-product	Hybrid Technology Assumption: “combines the product technology assumption and the industry technology assumption to avoid negatives in product-by-product input–output tables.”	As the Product Technology Assumption is not appropriate, neither is the Hybrid Technology Assumption.
Model F	Product-by-product	Almon procedure: “mathematical algorithm designed for compiling product-by-product input–output tables which are based in essence on the product technology assumption but avoids by step-by-step procedure negatives in the derives input–output tables.”	As the Product Technology Assumption is not appropriate, neither is the Almon procedure.

- We determine the global market suppliers for a product p ; i.e. we determine the contribution of each region $s \neq \tau$ to the global exports of product p , noted $c_{s,p}$, and defined as:

$$c_{s,p} = \frac{x_{s,p}}{x_p}, \quad (\text{D.1})$$

where $x_{s,p}$ and x_p stand respectively for exports of product p by region s , and for global exports of product p . (Hence $\sum_s x_{s,p} = x_p$.) Then, we use the determined global market shares $c_{s,p}$ to ascribe, for each product p in each region τ , the imported products to their region of production.

- The columns corresponding to exports are removed from the regional final demand \mathbf{Y} matrices.
- The regional \mathbf{U} and \mathbf{Y} matrices with specified product, industry, and sector names are combined in respectively a multi-regional \mathbf{U} and \mathbf{Y} , filling coefficients that do not belong to any regional matrix with zeros.

Table F.1

Values of energy-related CO₂ emissions by resource product (CO₂ equivalent), both for the combustion and extraction processes. Values for combustion emissions are taken from the IEA [71, page 1.24], and values for extraction emissions are deduced from the IEA [1, pp. 490–491]. Units: kgCO₂e/GJ.

Resource product	Combustion emissions	Extraction emissions
Anthracite	26.8	0
Coking coal	25.8	0
Crude oil	20	1.7
Lignite	27.6	0
Natural gas	15.3	2.3
Natural gas liquids	17.5	2.7
Other bituminous coal	25.8	0
Sub-bituminous coal	26.2	0
Other hydrocarbons	20	1.7
Oil shale and oil sands	29.1	2.5
Peat	28.9	0
All other products	0	0

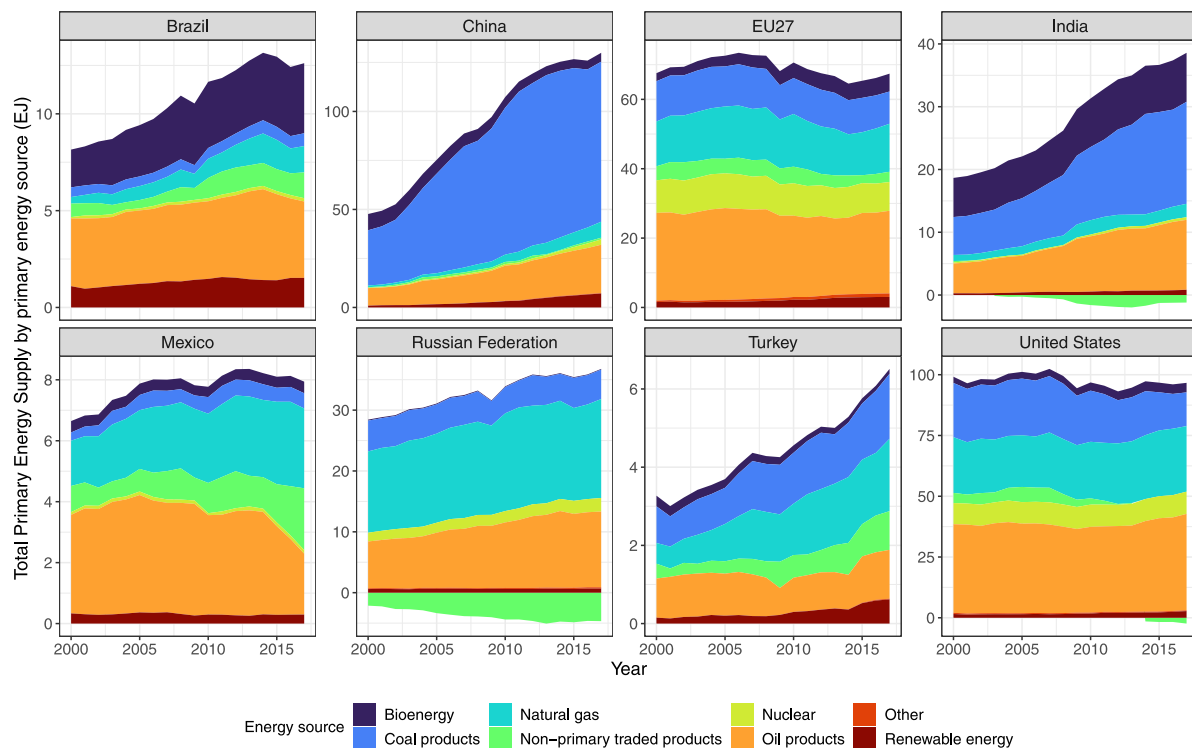


Fig. E.1. Total Energy Supply according to the International Energy Agency World Energy Extended Balances [45] for different regions, broken down by primary energy source, when possible.

Appendix E. Comparison of Total Primary Energy Supply (own calculations) with Total Energy Supply (IEA data)

Fig. E.1 shows the TES for each region according to the IEA World Energy Extended Balances, i.e. without treatment. A few remarks can be drawn from the figure. First, a share of the TES is composed by non primary energy products, such as electricity, heat, gasoline, coke oven coke, which means that the energy accounted for is not fully primary energy. The share of non-primary energy is significant in the case of for instance Brazil, Mexico, and Russia. Second, the fact that some of the products are non-primary products does not always enable identification of the type of energy source. For some traded products, such as coke oven coke, the energy source, namely coal, is obvious. But in the case of imported electricity or heat, such identification is not possible. Third, in the case of regions that are net exporters of energy products, there is a negative component for exported energy products that should be subtracted from the total TES. Each of these issues are solved when adopting the TPES calculation shown in Section 3.2. We note, however, that once subtracting exported energy products, the TES of each region is of similar magnitude than the TPES reported in Fig. 4.

Appendix F. Vector of energy-related CO₂ emissions

Table F.1 presents the combustion and extraction emissions used to construct the e_c and e_f extension vectors.

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