

Titre: Coupling input-output tables with macro-life cycle assessment to assess worldwide impacts of biofuels transport policies. Supplément

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Date: 2018

Type: Article de revue / Article

Référence: Some, A., Dandres, T., Gaudreault, C., Majeau-Bettez, G., Wood, R., & Samson, R. (2018). Coupling input-output tables with macro-life cycle assessment to assess worldwide impacts of biofuels transport policies. *Journal of Industrial Ecology*, 22(4), 643-655. <https://doi.org/10.1111/jiec.12640>

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Version: Matériel supplémentaire / Supplementary material
Révisé par les pairs / Refereed

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Document publié chez l'éditeur officiel

Document issued by the official publisher

Titre de la revue: Journal of Industrial Ecology (vol. 22, no. 4)

Maison d'édition: Wiley & Yale University

URL officiel: <https://doi.org/10.1111/jiec.12640>

Mention légale: This is the peer reviewed version of the following article: Some, A., Dandres, T., Gaudreault, C., Majeau-Bettez, G., Wood, R., & Samson, R. (2018). Coupling input-output tables with macro-life cycle assessment to assess worldwide impacts of biofuels transport policies. *Journal of Industrial Ecology*, 22(4), 643-655. <https://doi.org/10.1111/jiec.12640>, which has been published in final form at <https://doi.org/10.1111/jiec.12640>. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions. This article may not be enhanced, enriched or otherwise transformed into a derivative work, without express permission from Wiley or by statutory rights under applicable legislation. Copyright notices must not be removed, obscured or modified. The article must be linked to Wiley's version of record on Wiley Online Library and any embedding, framing or otherwise making available the article or pages thereof by third parties from platforms, services and websites other than Wiley Online Library must be prohibited.

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Appendix – Supplementary material

Life cycle assessment description

The life cycle assessment (LCA) is a methodology defined in ISO standards 14040-44. The principle of LCA is to evaluate a product (or a service) based on the environmental impacts caused by emissions and natural resource consumptions occurring at each stage of the product life cycle. The methodology is iterative and stands on four steps. The first step is the goal and scope and consists in defining the system to be studied. The second step is the life cycle inventory (LCI) and aims to list all emissions and natural resources depletion occurring at each stage of the product life cycle. The third step is the impacts assessment which relates the LCI into impacts on several environmental indicators. The fourth step is the interpretation of the LCA results. Thus, LCA allows drawing a global picture of the environmental impacts of a product. A broader description of LCA methodology can be found in the literature (Rebitzer et al. (2004) and Pennington et al.(2004)).

Method

Goal and scope of the case study

The functional unit of this LCA is to fulfill with biofuels by 2020 either: a) 3.36% of US and 1.68% of European transportation (volume) or b) 12.1% of US and 10.0% of European transportation (volume) in the context of global demographic and economic growths (as defined in Table 3 in supplementary material). The system boundary includes the entire economy (as modeled in GTAP-BYP). Each scenario a) or b) is used separately to set up a simulation of the GTAP-BYP model (this model is described in the following section).

Ecoinvent database

The ecoinvent database (Frischknecht et al. 2005) represents the technological activities as a network of processes based on the physical flows of commodities involved in each process life cycle. All emissions and natural resources consumptions are directly linked to each technological process (ideally the data have been monitored at the process level). This database is a bottom-up environmental model of economic activities (such databases are also referred to as process databases within LCA community).

GTAP-BYP description

Since 2005, developments of the GTAP model have lead to GTAP-BYP, a new version of the GTAP model that enables the specific study of the economic consequences of the first generation biofuels (Taheripour et al. 2007; Taheripour et al. 2010). GTAP-BYP integrates the production of biofuels from corn, sugarcane and vegetable oils (including the biofuel by-products) and makes it possible to study the impacts of these biofuels and their by-products among the economy (Tyner et al. 2010). Each scenario is implemented in GTAP-BYP which provides a technological matrix (A) presenting monetary transaction between every economic sector (in \$/Sector), as presented in Equation {1}:

$$A = f(\Delta Pop, \Delta GDP, \Delta Cap, \Delta Lab1, \Delta Lab2, \Delta Eth1, \Delta Eth2, \Delta Bio, A0) \quad \{1\}$$

Where f is a non-linear function corresponding to the GTAP-BYP model and Δ is a regional variation over 2006 to 2020, and:

- Pop is the population;
- GDP is the gross domestic product;
- Cap is capital investment;
- $Lab1$ and $Lab2$ are respectively the skilled and unskilled labor forces;
- $Eth1$ and $Eth2$ are the biofuels made respectively from crops and sugar canes;
- Bio is the biofuel made from vegetal oil;
- $A0$ is the technology matrix of the year 2006.

Coupling of GTAP and EXIOBASE

Coupling of economic sectors and regions

The coupling of the environmental extension of EXIOBASE and GTAP-BYP is performed consistently with the principle of I/O analysis (Suh and Huppes 2005) as shown in Equation {2}:

$$Q = CB[(I - A)^{-1}y] \quad \{2\}$$

Where:

- Q: final characterized environmental impacts (in kg characterised emissions);
- C: characterization matrix (in kg characterised emissions/kg emissions);
- B: environmental matrix linking emissions and resources to economic sector (in kg emissions/\$);
- I: identity matrix (without unit);
- A: technological matrix presenting monetary transaction between every economic sector (in \$/\$);
- y: final demand (in \$).

In this study, the final demand, the creation of the technological matrix and the matrix inversion are calculated by GTAP-BYP for each scenario. GTAP-BYP calculates x , the total production vector, as defined hereafter:

$$x = (I - A)^{-1}y$$

Then, x is introduced in Equation {2}:

$$Q = CBx$$

In order to solve Equation {2}, the list of economic sectors and regions must be coupled between EXIOBASE and GTAP. Thus, the 129 economic sectors and 43 regions of EXIOBASE have been mapped with the 30 economic sectors and 19 regions of GTAP-BYP. It results in a new EXIOBASE/GTAP-BYP aggregation of 27 economic sectors and 14 regions (cf. Tables 4 and 5 in the supplementary material). When one sector (or region) in GTAP-BYP corresponds to several sectors (or regions) in EXIOBASE, a weighted average was made with EXIOBASE data to meet the level of aggregation in GTAP-BYP. Also, since consumed and emitted substances in EXIOBASE are expressed in mass per € of the year 2000 and GTAP results in \$ of the year 2006, an exchange rate must be applied to compute emissions. Equation {3} describes the EXIOBASE/GTAP-BYP coupling.

$$\bar{G} = \left(\hat{p} \times G_{exiobase,gtap} \times \left(p \times \widehat{G_{exiobase,gtap}} \right)^{-1} \right) \times \langle t \rangle \quad \{3\}$$

Where:

- \bar{G} : normalised correspondence matrix between GTAP and EXIOBASE (EXIOBASE (sectors+regions) \times GTAP (sectors+regions));
- $G_{exiobase,gtap}$: correspondence matrix between GTAP and EXIOBASE (EXIOBASE (sectors+regions) \times GTAP (sectors+regions));
- p : original production vector in M€ (1 \times EXIOBASE sectors);
- \hat{p} refers to a square matrix that has values of vector p on its diagonal and null values elsewhere;
- $(p \times \widehat{G_{exiobase,gtap}})$ refers to a square matrix that has values of vector $(p \times G_{exiobase,gtap})$ on its diagonal and null values elsewhere;
- $\langle t \rangle$: exchange rate in 2000 €/2006 \$.

Hence, Equation {2} becomes:

$$Q = CB_{exiobase} * \bar{G} * x_{GTAP}$$

Where \bar{G} shows the coupling of the environmental intensities, from EXIOBASE, to the economic output, from GTAP.

Adaptation of emission factors for motor transport

Environmental extension of EXIOBASE relies on GHG emissions factors for transportation that are based on the technological context in 2000. Thus, these emission factors are based on a negligible contribution of biofuels for transportation. Therefore, these emission factors cannot properly represent the 2020 fuel mix which involves a more important share of biofuels in the biofuel scenario. For that reason, the environmental matrix for the industries of EXIOBASE has been modified to represent the change in GHG emissions factors due to the increased share of biofuels in the economy. Several assumptions were made: (1) bioethanol would only replace motor gasoline and biodiesel, diesel; (2) other emissions than GHG emissions would not vary; and (3) biogenic carbon dioxide emissions would not contribute to potential climate change impacts. The computing is shown in Equation {4}:

$$\forall i \in \{industries\}: b_{i,modified} = b_{i,unmodified} - \sum_{j=1}^{type\ of\ fossil\ fuel} p_j * e_j * U_{j,i} \quad \{4\}$$

Where:

- b_i : environmental matrix coefficient for sector i (in kg CO₂/\\$);
- p_j : percentage of fossil fuel j replaced by biofuel ;
- e_j : emission factor of fossil fuel j (in kg CO₂/MJ);
- $U_{j,i}$: energy use of fossil fuel j in sector i (in MJ/\\$).

Emissions related to private household consumption

EXIOBASE not only gives environmental emission data for industries but also for private households.

The coupling between GTAP-BYP and the environmental extension of EXIOBASE described so far considered only the emissions from the direct requirements by industries by extracting the industrial output from GTAP (variable “qo” in GTAP). GTAP calculates the variations in private consumption expenditures (variable “yp” in GTAP), which can be coupled with the environmental extension of EXIOBASE's to represent the effects of the variation of the economy for the private households. Equation {5} represents this coupling:

$$H = V * \sigma_{yp} \quad \{5\}$$

With:

- H : final emission vector (in kg emissions);
- V : emissions vector intensity per unit of consumption expenditure (given by EXIOBASE in kg emissions/\\$);
- σ_{yp} : (scalar) total final consumption expenditure in \\$.

Contrary to industrial emissions, which can be traced to specific activities, direct household emissions are aggregated in EXIOBASE, such that it is not simple to distinguish emissions from transport, from heating, etc. (Equation {5}). To circumvent this issue, the biofuel used by households in transport was calculated as a residual: all biofuel production modelled in GTAP that was not ascribed to industries went for direct purchase by households for personal transport, and benefits in direct GHG emissions were calculated accordingly (see previous section “Adaptation of emission factors for motor transport”).

Equation {6} describes the calculation of the benefits of biofuels for private households using both global emissions and industrial emissions saved by biofuel policies:

$$H = V * \sigma_{yp} - \sum_{j=1}^{type\ of\ fuel} (G_j - I_j) * e_j \quad \{6\}$$

Where:

- H: final emission vector for private households (in kg emissions);
- V: emissions vector intensity per unit of consumption expenditure (in kg emissions/\$);
- σ_{yp} : final consumption expenditure in \$;
- G_j : global fossil fuel amount replaced by biofuel (in MJ) according to j (type of fuel);
- I_j : industrial fossil fuel amount replaced by biofuel (in MJ) according to j (type of fuel);
- e_j : emission factor for j (in kg CO₂/MJ).

The overall benefits from using biofuels are estimated by 1) calculating the total volumes of biodiesel and bioethanol required to fulfill the needs of the biofuels policies and 2) evaluating the total emissions avoided by the replacement of fossil fuels with the volume of biofuels previously calculated. The factors that have been used are presented in Table 6 in supplementary material.

Mapping GTAP-BYP land types with IPCC factors

The mapping between the GTAP-BYP and IPCC land data was performed using the SAGE land cover distribution data (Lee et al. 2005). Then, the GHG emissions related to LUC depends on the type of lands that are affected by the changes. Computing of global variations of carbon stocks is presented in Equation {7}:

$$\Delta Total\ carbon\ stocks = \sum_{ij} \Delta L_{ij} \times (B_{ij} + M_{ij}) \quad \{7\}$$

Where:

- ΔL_{ij} : variation of area of land type i used for activity j (in ha, given by GTAP);
- B_{ij} : carbon stock in biomass in land type i for activity j (in C/ha, given by the IPCC);
- M_{ij} : carbon stock in mineral soil in land i for activity j (in C/ha, given by the IPCC).

In this study, the variation of carbon in the organic soils is not considered because of the large uncertainties associated with them.

Limitations and uncertainty of the method

Limitation related to EXIOBASE

In theory, the coupling between GTAP and an environmental I/O database enables the modeling of worldwide emissions and resources among the world and is likely to improve the comprehensiveness of the factor considered when performing the M-LCA. The main limitation of the environmental I/O database EXIOBASE is the limited amount of substances for which information is available. Even if the air emissions are well considered, some other environmental impacts categories may be underestimated. A comparison of EXIOBASE with the ecoinvent database could help to evaluate the impacts of the missing substances in EXIOBASE (Majeau-Bettez et al. 2011). Then, a hybridization of these databases could eventually improve the impact assessment in M-LCA.

Limitation related to GTAP-BYP

It was shown in this study that the consideration of LUC GHG emissions when assessing the effects of biofuel policies significantly affect the results, to a point where it could change the overall conclusions if LUC are included or not in the scope of the study. The version of GTAP-BYP used in this study, however, does not consider every type of land use. For instance, natural ecosystems are not included within GTAP-BYP. Thus, conversion of natural ecosystems into land use for agriculture, livestock, and forestry is not considered in this study. This limit can lead to a potential underestimation of the GHG impacts given that natural ecosystems are generally rich in carbon and that their conversion could result in a loss of land-based carbon. Another limitation of GTAP-BYP is that it cannot predict unplanned events that may have a considerable effect on the structure of the economy, such as financial crises, wars, or natural disasters.

Limitation related to the coupling of EXIOBASE and GTAP

In the approach proposed, there are some limitations related to the coupling of GTAP and EXIOBASE regions. The regions represented in these two models are different and some aggregations were made. For instance, Australia in EXIOBASE was used to model the entire regions of Oceania that is available in GTAP. These aggregation choices may potentially be the cause for some errors as the technology employed in a single country is not necessarily representative of the average technology of the whole region.

Another limitation of this coupling stems from the fact that GTAP models changing technologies (in response to price effects) in each sector, whereas the emissions coefficients taken from EXIOBASE for these sectors are fixed and historical. One would expect that a change in technology could lead to changes in direct emissions, but this was not represented in our model. The only exception to this, as noted above, concerned the biogenic CO₂ emissions resulting from biofuel combustion, which were adapted in both industry and household emissions. Ideally, all EXIOBASE emission factors should be modified to reflect the new situation modeled by GTAP.

Limitation related to the modeling of land use changes

In the approach proposed, there are some limitations related to the calculation of direct and indirect land use change by GTAP and the IPCC factors. Indeed, GTAP-BYP does not allow conversion of natural ecosystems to land use for human activities: this exclusion can lead to an underestimation of impacts. Moreover, in this study, all the impacts triggered by land use change have been attributed to changes in the economy (and in particular the policy of biofuels in biofuels scenario). Once land has been converted to a new use, it can still be used for years for this purpose. Thus, the impact of changes in land use would be distributed over a number of years greater than the duration of the biofuel policy. Eventually, IPCC factors are determined with a level of definition that does not include regional specificities. But because types of cultures vary between different regions some impacts triggered by land use change may be under or over estimated. Thus, there is an important uncertainty about the modeling of land use change.

Limitation related to the exclusion of second and third generations of biofuels

This study excludes the second and third generations of biofuels, therefore it assumes the future demand for biofuel will be met by biofuels of the first generation. It is difficult to evaluate precisely how the results of the study are affected by this limitation. It can be anticipated that the inclusion of second and third generations of biofuels would reduce the demand for land use, and therefore GHG emissions from land use changes. Nevertheless, the method presented in this article is expected to remain valid for a coupling of EXIOBASE with a future version of the GTAP model that would include new generations of biofuels.

Uncertainty of the method

All the mentioned limitations lead to some uncertainty on the results. While the uncertainty in LCA may be evaluated and possibly managed thanks to Monte-Carlo simulations (attributing a density of probability to each variable and computing the LCA results a high number of times (typically five to ten thousand times) varying the value of each variable according to its density of probability), uncertainty management is more complex when economic models are involved in LCA. Indeed, Monte-Carlo simulations are not adapted to equilibrium models that typically have thousands of variables and may require hours to run a single simulation (unless significant computing resources are available). A possible approach to evaluate the uncertainty in this study would be to design alternative prospective reference scenarios (to explore possible futures where the economic and demographic backgrounds would be different), to evaluate the biofuel policies in the context of each of these alternative scenarios and then to run Monte-Carlo simulations on LCA inventory in each case (Dandres et al. 2014). This approach, however, would still not capture all sources of uncertainty since the number of variables studied and scenarios would be limited. Due to the lack of resources, it was not possible to conduct an extended uncertainty analysis. Nevertheless, Dandres et al. (2014) showed the comparison of different EU energy policies with GTAP coupled with LCA was rarely affected by variations in the economic, technological and demographic backgrounds. It can be expected it is also true for GTAP-BYP and so, despite the possibility that the numbers are not reliable, the tendencies observed in the results could be quite robust. Nevertheless, the stability of GTAP-BYP results in the context of various economic and demographic backgrounds still needs to be demonstrated rigorously.

Implementation of the economic growth and dietary preference in GTAP

Data have been collected from several sources to model the economic growth and the dietary preference change in GTAP simulations. Practically, the economic growth is taken into account in GTAP simulation by changing the values of the main macroeconomic variables for each region. The changes for these variables are expressed in percentage changes over the period 2006-2020 and are presented in Table 3.

	USA	UE 27	JAPAN	RUSSIA	INDIA	CHINA	BRAZIL	SOURCE
Population	12.53	3.66	-1.31	-1.73	19.87	5.57	11.96	Fouré et al. (2012)
GDP	22.83	17.42	15.59	71.09	157.99	209.61	65.46	Fouré et al. (2012)
Capital	26.13	16.13	6.60	35.08	128.27	201.30	54.69	Fouré et al. (2012)
Percentage of skilled workers	9.17	26.76	35.42	11.73	49.53	62.18	35.95	Kc et al. (2010)
Percentage of unskilled worker	-9.85	-6.64	-21.94	-12.89	-2.78	-3.93	-3.02	Kc et al. (2010)
Ruminants (beef and sheep)	1.12	-7.88	10.39	15.77	14.31	41.19	46.56	OECD/FAO (2011)
Non Ruminants (poultry and pork)	13.67	27.02	26.27	38.94	38.59	71.01	54.02	OECD/FAO (2011)

Table 1: Macroeconomic variable changes over 2006-2020 by region

Coupling tables between GTAP-BYP and EXIOBASE

GTAP-BYP and EXIOBASE represent the global economic activity using regions and economic sectors. A region can be a country or a group of countries. An economic sector usually regroups several economic activities. Since the level of aggregation for regions and economic sectors slightly differ between GTAP-BYP and EXIOBASE it was necessary to build coupling tables to match regions and economic sectors. Table 4 presents the geographic coupling and Table 5 present the coupling for economic sectors.

Regions in GTAP	Regions in EXIOBASE
USA	USA
European Union 27	Austria; Belgium; Bulgaria; Cyprus; Czech Republic; Germany; Denmark; Estonia; Finland; France; Greece; Hungary; Ireland; Italy; Lithuania; Luxembourg; Latvia; Malta; Netherlands; Poland; Portugal; Romania; Spain; Sweden; Slovenia; Slovakia; United Kingdom
Canada	Canada
Brazil	Brazil
Japan	Japan
China and Hong-Kong	China
Russia	Russia
India	India
East Asia	South Korea and Taiwan
Malaysia and Indonesia	Indonesia
Rest of Europe	Switzerland and Norway
Oceania	Australia
Central and Caribbean Americas	Mexico
South and Other Americas; Rest of South East Asia; Rest of South Asia; Other East Europe and Rest of former Soviet union; Middle Eastern and North Africa; Sub-Saharan Africa	Rest of World

Table 2: Coupling by region between GTAP and EXIOBASE

Industries in GTAP	Industries in EXIOBASE	Industries in GTAP	Industries in EXIOBASE
Paddy rice	Cultivation of paddy rice	Cr grains	Cultivation of cereal grains n.e.c.; Cultivation of vegetables, fruit and nuts
Wheat	Cultivation of wheat	Proc rice	Processed rice
Dairy farms	Raw milk	Proc food	Processing of food products n.e.c.
Sugar-crop	Cultivation of sugarcane, sugar beet	Proc feed	Manufacture of fish products
Oilseeds	Cultivation of oilseeds	Ruminant	Cattle farming; Pigs farming, Wool; Silkworm cocoons
Other agri	Cultivation of plant-based fibers; Cultivation of crops n.e.c. ¹	Non-ruminant	Poultry farming; Meat animal n.e.c.; Animal product n.e.c.
Processed dairy	Processing of dairy products	Soybean	Processing of vegetable oils and fats
Processed non ruminant	Processing of meat poultry; Processing of meat products n.e.c.	Processed ruminant	Processing of meat cattle; Processing of meat pigs
Forestry	Forestry, logging, and related service activities	Oil	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
Beverage sugar	Sugar refining; Manufacture of tobacco products; Manufacture of beverage	Coal	Mining of coal and lignite; Extraction of peat

¹ not elsewhere classified

Other primary sectors	Fishing, operating of fish hatcheries and fish farms; Service activities incidental to fishing; Mining of uranium and thorium ores; Mining of iron ores; Mining of copper ores and concentrates; Mining of nickel ores and concentrates; Mining of aluminum ores and concentrates; Mining of precious metal ores and concentrates; Mining of lead, zinc and tin ores and concentrates; Mining of other non-ferrous metal ores and concentrates; Quarrying of stone; Quarrying of sand and clay; Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.	Oil-products	Manufacture of coke oven products; Manufacture of motor spirit (gasoline); Manufacture of kerosene, including kerosene-type jet fuel; Manufacture of gas oils; Manufacture of fuel oils n.e.c.; Manufacture of petroleum gasses and other gaseous hydrocarbons, except natural gas; Manufacture of other petroleum products; Processing of nuclear fuel
Gas	Extraction of natural gas and services related to natural gas extraction, excluding surveying; Extraction, liquefaction, and regasification of other petroleum and gaseous materials; Manufacture of gas; distribution of gaseous fuels through mains	Electricity	Production of electricity by coal; Production of electricity by gas; Production of electricity by nuclear; Production of electricity by hydro; Production of electricity by wind; Production of electricity n.e.c., including biomass and waste; Transmission of electricity; Distribution and trade of electricity

Energy intensive industries	<p>Manufacture of other non-metallic mineral products n.e.c.; Manufacture of basic iron and steel and of ferro-alloys and first products thereof; Precious metals production; Aluminum production; Lead, zinc and tin production; Copper production; Other non-ferrous metal production; Casting of metals; Manufacture of chemicals and chemical products</p>	Other industries and services	<p>Manufacture of rubber and plastic products; Manufacture of glass and glass products; Manufacture of ceramic goods; Manufacture of bricks, tiles and construction products, in baked clay; Manufacture of cement, lime and plaster; Manufacture of fabricated metal products, except machinery and equipment; Manufacture of machinery and equipment n.e.c. ; Manufacture of office machinery and computers; Manufacture of electrical machinery and apparatus n.e.c.; Manufacture of radio, television and communication equipment and apparatus; Manufacture of medical, precision and optical instruments, watches and clocks; Manufacture of motor vehicles, trailers and semi-trailers; Manufacture of other transport equipment; Manufacture of furniture; Manufacturing n.e.c.; Recycling of metal waste and scrap; Recycling of non-metal waste and scrap; Construction; Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motorcycles parts and accessories; Retail sale of automotive fuel; Wholesale trade and commission trade, except of motor vehicles and motorcycles; Retail trade, except of motor vehicles and motorcycles; Repair of personal and household goods; Hotels and restaurants; Transport via railways; Other land transport; Transport via pipelines; Sea and coastal water transport; Inland water transport; Air transport; Supporting and auxiliary transport activities; Activities of travel agencies; Post and telecommunications; Financial intermediation, except insurance and pension funding; Insurance and pension funding, except compulsory social security; Activities auxiliary to financial intermediation; Real estate activities; Renting of machinery and equipment without operator and of personal and household goods; Computer and related activities; Research and development; Other business activities</p>
Non-tradable services	<p>Steam and hot water supply; Collection, purification and distribution of water; Public administration and defence; Compulsory social security; Education; Health and social work; Collection and treatment of sewage; Collection of waste; Incineration of waste; Landfill of waste; Sanitation, remediation and similar activities; Activities of membership organisation n.e.c.; Recreational, cultural and sporting activities; Other service activities; Private households with employed persons; Extra-territorial organizations and bodies</p>		

Table 3: Coupling by economic sector between GTAP and EXIOBASE

Emission factors for CO₂ for different types of fuel

In this study, it is considered petroleum fuels and related biofuels have same emissions per unit of energy. These emissions per terajoule (TJ) generated from petroleum fuels and biofuels and presented in Table 6.

Type of fuel	Unit	Emission factor	Source
Biodiesel/diesel	kg CO ₂ /TJ	74100	IPCC (2006)
Bioethanol/gasoline	kg CO ₂ /TJ	69300	

Table 4: Emissions factors for CO₂ according to the type of fuel

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