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Method Article

An extended hybrid input-output model applied to fossil- and bio-based plastics

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A B S T R A C T

Matrix augmentation method is developed further and described transparently for enabling more specific input-output analyses of bio- vs. fossil-based sectors. A number of economic and environmental effects of substitution can be estimated, compared, and managed. While the model was applied for the first time to the German plastics industry, it can be well integrated into existing bioeconomy monitorings to represent substitution in sectors and countries.

• Original matrix augmentation method is described in much detail for the first time considering available data for bio- and fossil-based industries.

• Particular attention is paid to balancing cost and benefit in model building so that indicators can be integrated in a continuous monitoring of the bioeconomy. Hence, industry data is prefered to process data whenever possible.

• Input structures of bio-based imports are considered in single-region input-output analysis.

A R T I C L E   I N F O

Method name: Matrix augmentation of supply and use tables to represent bio-based value chains
Keywords: Bioeconomy monitoring, Bioplastics, Matrix augmentation, Domestic technology assumption
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Specifications table

Subject Area	Economics and Finance
More specific subject area	Industrial Ecology
Method name	Matrix augmentation of supply and use tables to represent bio-based value chains
Name and reference of original method	Model III: Disaggregating an Existing Industry Sector (Joshi, 1999, see [1]) based on Input-Output Analysis (Leontief, 1936, see [2]) and Environmental Input-Output Analysis (Leontief, 1970, see [3])
Resource availability	Supply and use table, Source: Destatis [4] Energy use by production sector, Source: Destatis [5] Material- und Wareneingangserhebung (MWE), Source: Destatis [6] Life cycle inventory database, Source: Ecoinvent 3.4 [7]

Motivation

Considerable efforts are currently under way to establish bioeconomy monitorings to advice policy-makers on potential economic, social, and environmental trade-offs, especially in the EU [8–11]. Approaches partially rely on input-output data with a resolution of 65–200 sectors and on methods for estimating bio-based shares of these sectors [12]. Although research on net effects comparing bio-based sectors to the rest of the economy has begun [13,14], a significant challenge is to adequately represent bio-based sectors and to clearly distinguish them from other sectors in input-output modelling. Because national input-output data refers to broad sectors, such as chemicals and chemical products, different inputs and processes can only be analyzed if uncertainties of aggregation are accepted. This leads to rather broad overviews as in [14] rather than to analyses relevant for practical policy-making.

Hybrid input-output models have been proposed to reduce the aggregation error in input-output analyses. Joshi (1999) suggests 'Model III' to analyze environmental effects of product groups that are already included in existing sectors of input-output tables. Model III consists of a disaggregation of one sector into two sectors. Input structures of the more detailed sectors may be derived from cost sheets of representative products [1]. Input shares that are known can be added manually to the new use table columns while unknown input shares require an allocation method [15]. In literature, values are often allocated analogous to the original (aggregate) sector (see Supplementary Information p.16ff. in [15] or p.4ff. in [16]).

Although hybrid models have been created for some bioeconomy sectors, such as the biotechnology [17], biofuels [16,18–20], and wood [21] sectors, different methods have been applied making it difficult to compare their strengths and weaknesses and study results [22]. More specifically, it is rarely reported (1) how process data, detailed industry data, or input data of the aggregate sector are combined to create new sectors in input-output tables and (2) how to deal with non-competitive imports of inputs. These questions are addressed against the background that there should be a balance between cost of model building/data collection and benefits in terms of meaningful results. Concering question 1, using industry data is most preferable because process data introduces a new source of uncertainty while the proportionality assumption inherent in aggregate data may imply large errors as well. The existing sector, in this case chemicals and chemical products, contains a large variety of basic and processed products that are dissimilar to plastics. Hence, the model builds on plastics industry data from Destatis [6] for modelling the (new) fossil-based plastics industry, for bioplastics process data from Ecoinvent [7] for modelling parts of the (new) bio-based plastics industry, and on aggregate sector data from Destatis [4] for all remaining inputs. In a first step, a fossil- and bio-based plastics sector is extracted from the aggregate chemicals sector included in input-output tables. Information on the plastics sector is used to model the fossil-based part of the bio-based industry because bioplastics are at present based on biopolymers and fossil-based polymers to achieve certain product functionalities [23]. It can be assumed that the input structure of fossil-based polymer inputs is similar to that of the plastics industry as long as bio-based production is very low. Concerning question 2), the domestic technology assumption (DTA) may be applied or the input-output model can be extended to further regions that are relevant trading partners [24]. DTA holds for imports that are produced in a similar way as domestic products. Errors may be large in the case

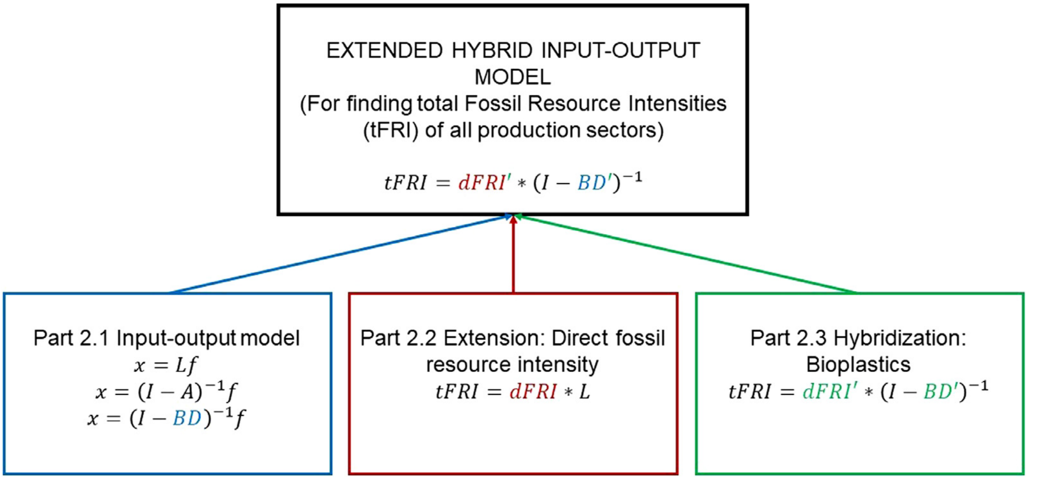

Fig. 1. Approach to building an extended hybrid input-output model in three steps. Source: own illustration.

of bioplastics because many biopolymers are imported without being produced in Germany. Setting up a multi-regional input-output (MRIO) model requires much effort because input-output data for biopolymers in other countries is hardly available. In this model, biopolymer input information draws on process data for domestically produced and imported biopolymers in order to represent non-competitive biopolymer imports that are used in bioplastics production. However, pretending that all biopolymers are produced domestically using foreign input structures is only plausible for small amounts as in the bioplastics case. If the bio-based industry because more significant, a MRIO model is more appropriate but has higher modelling demands.

This article presents a transparent method for augmenting supply and use matrices with a bioeconomy sector by integrating available process and alternative economic data, called hybridization. Special attention is paid to the challenges explained above in section 2.3.2.2. One central aim is to contribute to normalization of the matrix augmentation method while recognizing that exact procedures depend on data availability. The case chosen here, fossil resource intensity of bioplastics in Germany, relies on relatively few information and data, which makes it more complex to account for missing values. Thus, the method proposed here specifically relates to novel bio-based value chains in countries having a low resolution of their input-output data. A better representation of other value chains in input-output models or analyses for countries with high-resolution input-output tables may require different/fewer steps.

The extended hybrid input-output model starts with a basic input-output model (Part 2.1, see Fig. 1) explaining methodological choices and alternatives and continues with the environmental extension to account for fossil resource use (Part 2.2) before showing the hybridization process (Part 2.3). The method is validated for the case of bioplastics in Part 3.

Method details

Building a basic input-output model

Leontief quantity models measure the effects on the output supplied by each sector due to a change in final demand [25]. Through multiplication of a Leontief inverse matrix L with a final demand vector f, changes in sectors' outputs x can be obtained (Eq. (1)). Leontief inverse matrix L is derived from an identity matrix I and a technology coefficients matrix A.

$$x = Lf = (I - A)^{-1} f \quad (1)$$

Table 1
Scheme of notations and relationships between matrices and vectors. Dark grey – information derived from supply table V (q^{do}, x^{do}, q', x) and additional information (q^m, (T – S), tt). Light grey – information derived from use table U (x^{di}, q^{di}, x', q) and additional information (va, f_{hh}, f_{gov}, f_{po}, I, Δs, q^x).

	Industries (i)	Commodities (j)	Total input of j to all i	Total output of i of all j	Final demand	Invest-ments	Stock change	Exports	Total input of j
Industries (i)		V		$x^{do} = x$					
Commodities (j)	U		q^{di}		f_{hh}, f_{gov}, f_{po}	I	Δs	q^x	q
Total output of j by all i		q^{do}							
Total input to i of all j	x^{di}								
Imports		q^m							
Taxes minus subsidies		(T – S)							
Trade and transport margin		tt							
Total output of j		q'							
Value added	va								
Total input to i	x'								

V – supply table (commodity output produced by an industry)

x^{do}, x – total output of commodities by an industry
x – total output of commodities by an industry

q^{do} – total output of a commodity by domestic industries
q^m – imports of a commodity
(T – S) – taxes minus subsidies of a commodity
tt – trade and transport margins of a commodity
q' – total output of a commodity including imports

U – use table (commodity input used by an industry)

x^{di} – total intermediate input of commodities to an industry
va – value added by an industry
x' – total input of commodities and value added to an industry

q^{di} – total input of a commodity by all domestic industries
f_{hh}, f_{gov}, f_{po} – final demand for a commodity by households, government, and private organizations
I – investments in buildings and equipment for the production of a commodity
Δs – stock change of a commodity
q^x – exports of a commodity
q – total input of a commodity to domestic industries, final demand, and exports (and investments and stock change)

Matrix A, showing input structures, is based on an input-output table (IOT) or on supply and use tables (SUT), which are commonly provided by national statistical offices. An IOT is a model of interrelations between sectors of an economy and is derived from SUT. Four main types of IO models have been identified that are based on (strong) assumptions about input structures or (weak) assumptions about sales structures of secondary products [26]. To allow for greater flexibility regarding the way multiproduct processes are represented, the bioplastics model starts from SUT for integrating data [15,25–27]. While statistical offices prefer to use a model with weak assumptions because they are closer to observed data [26], these result in industry-by-industry IO models. For the purpose of this research, however, the IO model chosen is in the form product-by-product because, first, changes in products rather than industries are of interest, and, second, data for environmental extensions refer to production sectors rather than industries [28,29]. There are two ways for building a product-by-product IO model relying on either product technology or industry technology assumption. The former is better suited for subsidiary production, while the latter applies better to by-production [26]. In the bioeconomy, both forms of production are relevant but it was decided that a good representation of by-production is advantageous with regard to future bioeconomy analyses that will increasingly consider input of residues and by-products. Eq. (2) implies that all commodities produced by an industry have the same input structure [25]. Matrix *B* is called a technology matrix, which is values in a use table *U* divided by respective industry output *x'*. *D* is a market shares matrix, calculated by dividing values in a supply table *V* by the value of commodity inputs *q* [4].

$$A = BD = [U/x\prime][V/q\prime] \tag{2}$$

Table 1 gives an overview of matrices and vectors that are available from national statistical offices and serve as a basis for the hybridization process. Prior to a description of changes to industries *i* and commodities *j* in Part 2.3, I shortly recapitulate how to estimate total environmental effects triggered by a change in final demand through environmentally extended input-output models and show how direct intensities were split for disaggregated sectors.

Extending the basic model with direct fossil resource use data

The basic input-output model is extended with a vector for direct fossil resource intensities (*dFRI*) in order to find out how much more or less fossil energy is necessary if changes in demand occur. In my research, I wanted to calculate net fossil energy use due to substitution, i.e. reduced demand for fossil-based plastics and increased demand for bio-based plastics.

$$tFRI = dFRI*L \tag{3}$$

Calculation of total fossil resource intensities (*tFRI*) follows the established method of extending the basic IO model by environmental information to obtain so-called multipliers [25]. Thus, further effects of substitution can be measured using sector-specific data. Relating to bioeconomy objectives as stated in bioeconomy strategies [30,31] and having a reliable data base, value added, employer compensation, greenhouse gas emissions and water use were selected to exemplify trade-offs with fossil resource substitution [23]. As value added and employment multipliers rely on economic data collected from firms and refering to economic sectors (industries) rather than production sectors, the assumption that value added and employment data is similar for production and economic sectors for the selected case must be plausible to use this data in a product-by-product model [29]. Production sectors refer to homogenous products that are not empirically observable while economic sectors refer to a mixed bundle of goods produced by a certain industry, which is classified by its main activity [32].

Data for direct Fossil Resources Consumption (*dFRC*) in Joule (coal, lignite, crude oil, natural gas) by German production sectors is part of Environmental Accounting [5,33]. Intensity is *dFRC* divided by total output value of a commodity by domestic industries q^{do} (Eq. (4)). As data is available for fewer production sectors than in the IO model (48 compared to 85), it was split based on output value of the production sector *j* and the aggregate sector *agg* for which data is available (Eq. (5)). More detailed information is available for splitting aggregate *dFRC* of coke and petroleum products as well as of electricity and gases [34].

$$dFRI = dFRC/q^{do} \tag{4}$$

$$dFRC = dFRC_{agg} * \left(\frac{q_j^{do}}{q_{agg}^{do}} \right) \tag{5}$$

In the absence of data for the disaggregated sectors, it was assumed that no direct fossil resource consumption is required in bio-based plastics production and that fossil-based plastics production only sources natural gas directly (no crude oil, coal or lignite). Natural gas use was estimated based on output values of the fossil-based plastics sector and the (aggregate) chemicals sector.

Hybrid model using matrix augmentation

Disaggregation is performed for the commodity group *j* “chemicals and chemical products” and the industry *i* “manufacturing of chemicals and chemical products” (C20 according to CPA - Statistical Classification of Products by Activity, Version 2.1), resulting in fossil- and bio-based primary plastics sectors ($C20.16_f$ and $C20.16_b$) and an other chemicals and chemical products sector (C20*).

The following sections show adjustments to the supply table first and then to the use table. Factors that are marked in bold indicate the use of primary or secondary data. All factors not explained here are part of the basic model and described above in Table 1.

Supply table

Industry output. This section shows how information is added to supply table rows so that total output of bio-based, fossil-based and other chemicals industries (x_b, x_f, x_o) of all commodities, main and by-products, can be estimated (Eq. (6), Table 2).

$$x = \sum_{j=1}^{n} v_{ij} \tag{6}$$

Table 2
Augmentation of supply table rows, in relation to Table 1.

	V		$x^{do} = x$					
U		q^{di}		f	I	Δs	q^x	q
	q^{do}							
x^{di}								
	q^m							
	T – S							
	tt							
	q‘							
va								
x‘								

Table 3
Augmentation of supply table columns, in relation to Table 1.

	V		$x^{do} = x$					
U		q^{di}		f	I	Δs	q^x	q
	q^{do}							
x^{di}								
	q^m							
	T – S							
	tt							
	q‘							
va								
x‘								

Information on the kinds of commodities produced by new bio- and fossil-based economic sectors is required. For the case of bio- and fossil-based plastics, it is assumed that the respective industry only produces its main products that are classified as plastics and does not engage in other economic activity because information was not available. This is a reasonable assumption considering that, in the aggregate chemicals sector, more than 80% of its activity was related to chemicals products in Germany in 2016. Thus, commodities other than chemicals produced by the chemicals sector were fully assigned to the other chemicals and chemical products sector. Supply of bio- and fossil-based plastics and other chemicals (v_{oo}, v_{bb}, v_{ff}) is derived in the next section 2.3.1.2.

Commodity output. This section shows how information is added to supply table columns so that total output of bio-based, fossil-based and other chemical commodities (q_b', q_f', q_o') by all domestic and foreign industries, i.e. including imports, can be estimated (Eq. (7), Table 3).

$$q\prime = q^{do} + q^m + (T - S) + tt \quad (7)$$

For the bio-based sector, factors are determined in the following way:

$$q_b^{do} = \sum_{c=1}^{n} (\boldsymbol{q_c} * \boldsymbol{p_c}) = v_{bb} \quad (8)$$

q_c – production quantity of a bio-based product c (in tons) p_c – price of a bio-based product c (in €/ton)

An underlying assumption in Eq. (8) is that bio-based plastics are only produced by the bio-based plastics industry and not by other industries. If they were also produced by other industries, $q^{do}{}_b$ would also have to equal the sum of supply table column values (v_{ib}).

Information on imports of bio-based plastic are not available. Based on expert interviews, imports of bioploymers were estimated but not considered in modelling because the focus was on building a bio-based plastic sector, i.e. processed biopolymers (for further information see [23]). Nevertheless, the input structure of imported biopolymers is considered in section 2.3.2.2.

$$q_b^m = \sum_{c=1}^{n} (\boldsymbol{m_c} * \boldsymbol{p_c}) \tag{9}$$

m_c – imports of a bio-based product c (in tons)

$$(T-S)_b = (\boldsymbol{T}-\boldsymbol{S})_{\boldsymbol{agg}} / \boldsymbol{q_{agg}^{do}} * q_b^{do} \tag{10}$$

$(T-S)_{agg}$ – taxes minus subsidies of commodities in aggregate production sector $q^{do}{}_{agg}$ – total output of commodities in aggregate production sector by domestic industries, basic price

$$tt_b = \boldsymbol{tt_{agg}} / \boldsymbol{q_{agg}^{m}} * q_b^m \tag{11}$$

tt_{agg} – trade and transport margin of aggregate commodities $q^m{}_{agg}$ – imports of aggregate commodities

For the fossil-based sector, factors *(T – S)* and *tt* are determined in the same way by multiplying specific commodity output with aggregate sector shares as in Eqs. (10) and (11). Fossil-based imports $q^m{}_f$ are calculated by subtracting bio-based imports from known plastics imports (Eq. (11)). Output of fossil-based commodities by domestic industries $q^{do}{}_f$ depends on values in the respective use table column (u_{fj}), which are described in section 2.3.2.2. Here, again, it is assumed that fossil-based plastics are only produced by the fossil-based plastics industry ($q^{do}{}_f = v_{ff}$).

$$q_f^m = \boldsymbol{q_{f+b}^m} - q_b^m \tag{12}$$

$q^m{}_{f+b}$ – imports of fossil- and bio-based commodities

For the other chemicals and chemical products sector, factors *(T – S)* and *tt* are determined in the same way by multiplying specific commodity output with aggregate sector shares as in Eqs. (10) and (11). Other imports $q^m{}_o$ are calculated by subtracting known bio- and fossil-based plastics imports from known aggregate sector imports $q^m{}_{agg}$ (Eq. (13)). Output of other commodities by domestic industries $q^{do}{}_o$ is aggregate sector supply $q^{do}{}_{agg}$ minus the supply of fossil- and bio-based commodities (Eq. (14)). Entries in supply table columns for this sector, i.e. v_{io}, are assumed to be the same as for the aggregate sector, except for v_{oo}, which is calculated with Eq. (15) (v_{aggagg} is the intersection of the aggregate sector in the supply table).

$$q_o^m = \boldsymbol{q_{agg}^m} - \boldsymbol{q_{f+b}^m} \tag{13}$$

$$q_o^{do} = \boldsymbol{q_{agg}^{do}} - q_b^{do} - q_f^{do} \tag{14}$$

$$v_{oo} = \boldsymbol{v_{aggagg}} - v_{bb} - v_{ff} \tag{15}$$

Use table

Commodity input. This section shows how information is added to use table rows so that total input of bio-based, fossil-based and other chemicals commodities (q_b, q_f, q_o) to all industries (q^{di}), final demand (f), and exports (q^x) as well as investemnts (I) and stock change (Δs) can be estimated (Eq. (16), Table 4).

$$q = q^{di} + f + I + \Delta s + q^x \tag{16}$$

Information on bio-based export quantities is based on expert interviews and calculated with Eq. (17). As total exports of fossil- and bio-based plastics is known, fossil-based exports can be easily

Table 4
Augmentation of use table rows, in relation to Table 1.

	V		$x^{do} = x$					
U		q^{di}		f	I	Δs	q^{x}	q
	q^{do}							
x^{di}								
	q^{m}							
	T – S							
	tt							
	q‘							
va								
x‘								

calculated with Eq. (18).

$$q_b^x = \sum_{c=1}^{n} (\boldsymbol{q_c^x} * \boldsymbol{p_c}) \tag{17}$$

$q^x{}_c$ – export quantity of bio-based product c (in tons) p_c – price of a bio-based product c (in €/ton)

$$q_f^x = \boldsymbol{q_{f+b}^x} - q_b^x \tag{18}$$

In the absence of more detailed information, values for *f, I*, and Δs for bio- and fossil-based commodities are proprtional to aggregate sector values Eqs. (19)–((23)).

$$\Delta s_{b,f} = \left(q_{b,f} - q_{b,f}^x\right) * \left(\boldsymbol{\Delta s_{agg}} / \left(\boldsymbol{q_{agg}} - \boldsymbol{q_{agg}^x}\right)\right. \tag{19}$$

$$I_{b,f} = \left(q_{b,f} - q_{b,f}^x\right) * \left(\boldsymbol{I_{agg}} / \left(\boldsymbol{q_{agg}} - \boldsymbol{q_{agg}^x}\right)\right. \tag{20}$$

$$f_{b,f}^{hh} = \left(q_{b,f} - q_{b,f}^x\right) * \left(\boldsymbol{f_{hh,agg}} / \left(\boldsymbol{q_{agg}} - \boldsymbol{q_{agg}^x}\right)\right. \tag{21}$$

$$f_{b,f}^{po} = \left(q_{b,f} - q_{b,f}^x\right) * \left(\boldsymbol{f_{po,agg}} / \left(\boldsymbol{q_{agg}} - \boldsymbol{q_{agg}^x}\right)\right. \tag{22}$$

$$f_{b,f}^{gov} = \left(q_{b,f} - q_{b,f}^x\right) * \left(\boldsymbol{f_{gov,agg}} / \left(\boldsymbol{q_{agg}} - \boldsymbol{q_{agg}^x}\right)\right. \tag{23}$$

f^{hh} – final demand of households f^{po} – final demand of private organizations f^{gov} – final demand of government

Values for other chemicals and chemical commodities in use table rows are found by subtracting values for bio- and fossil-based sectors from aggregate sector values.

Because *q* is equal to *q’*, which is known from section 2.3.1.2, and all other factors are derived above, q^{di} can be calculated as shown in Eq. (24). It is the sum of sales of a commodity group to all industries.

$$q^{di} = q - f - I - \Delta s - q^x \tag{24}$$

Values in the use table (u_{ji}) can be estimated with q^{di} (Eq. (25)). Bio-based plastics (sector 20.16b) are sold to the rubber and plastics industry (sector 22) only so that $q^{di}{}_{20.16b} = u_{20.16b,22}$. This assumption holds because only biopolymers that are processed into plastics products, including plates, sheets, foils, packaging, plastic parts for vehicles, and household goods were included while biopolymers that are used in other sectors (e.g. polyurethane in mattress production) were excluded. Fossil-based plastics are sold to the fossil-based plastics, bio-based plastics, and other chemicals sectors (see section 2.3.2.2), as well as to the pharmaceutical industry (sector 21) and the rubber

Table 5
Augmentation of use table columns, in relation to Table 1.

	V		$x^{do} = x$					
U		q^{di}		f	I	Δs	q^x	q
	q^{do}							
x^{di}								
	q^m							
	T – S							
	tt							
	q‘							
va								
x‘								

and plastics industry (sector 22) according to official statistics [6]. Other chemicals are sold to other industries based on information for the aggregate chemicals sector, to sectors 21 and 22 based on aggregate chemicals sector values minus sales of fossil- and bio-based plastics, and to fossil-based plastics, bio-based plastics, and other chemicals sectors as described in section 2.3.2.2.

$$q^{di} = \sum_{i=1}^{n} u_{ji} \tag{25}$$

Industry input. This section shows how information is added to use table columns so that total input into bio-based, fossil-based and other chemicals industries (x'_b, x'_f, x'_o) can be estimated (Eq. (26), Table 5). Input consists of the sum of inputs from all industries (x^{di}) and value added (va).

$$x\prime = x^{di} + \boldsymbol{va} \tag{26}$$

Value added of bio-based plastics production (va_b) is not available and was estimated to be 25% of total input x'_b. It is a rough estimation and, thus, associated with high uncertainty. Value added of the aggregate chemicals sector (va_{agg}) was 36% of total inputs (x'_{agg}) in Germany in 2016 [4], which is assumed for the fossil-based plastics sector. Hence, value added of the other chemicals sector is aggregate value added minus value added by bio- and fossil-based sectors.

Information on commodity inputs to bio- and fossil-based industries (u_{jb}, u_{jf}), as well as to the adjusted aggregate sector (u_{jo}), has to be inserted in use table columns in order to build their sum (Eq. (27)). Estimating input structures for the three new sectors is the most complex step in the model and is illustrated in Fig. 2.

$$x^{di}_{b,f,o} = \sum_{j=1}^{n} u_{jb,f,o} \tag{27}$$

Bio-based plastic industry (C20.16b) uses biopolymers as well as fossil-based polymers in production, which requires splitting the bio-based industry again into a bio-based intermediate industry *bb* and a fossil-based intermediate industry *bf* to represent different input structures (Steps 1–3). These are then combined to build input structures of the bio-based industry (Eq. (28)). With information on the bio-based industry, the fossil- based and other chemicals industries can be modelled (Steps 4 and 5).

$$u_{jb} = u_{jbb} + u_{jbf} \tag{28}$$

u_{jbb} – input of commodity j into bio-based intermediate industry u_{jbf} – input of commodity j into fossil-based intermediate industry

Some of the inputs to the bio-based intermediate industry, i.e. to biopolymer production, are known from process data (u_{pbb}) while the majority of input relations was estimated based on

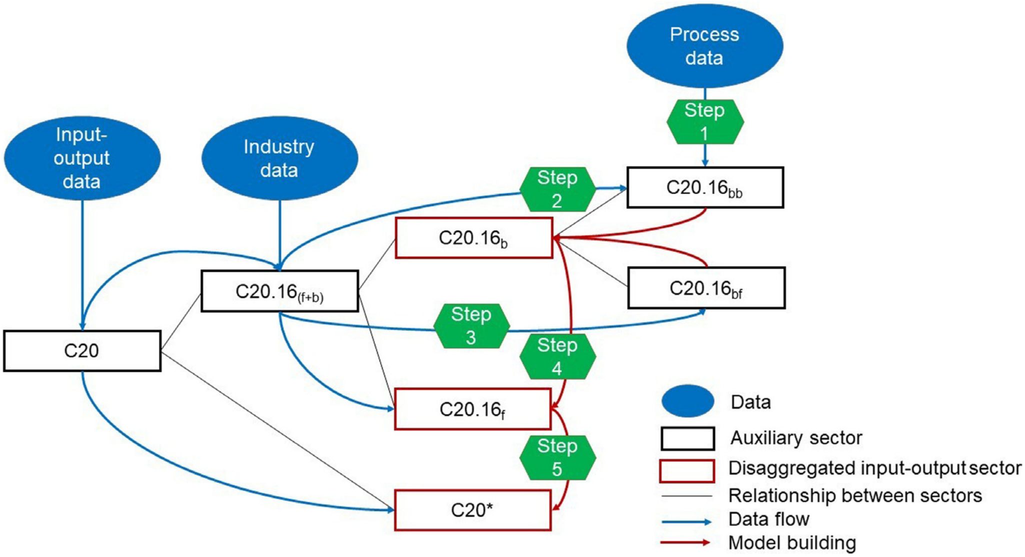

Fig. 2. Steps in estimating input structures of disaggregated sectors. Source: own illustration.

information of the combined bio- and fossil-based plastics industry (u_{rbb}) Eq. (29)). Eqs. (30)–((34) describe the procedure using process data and Eqs. (35)–(43) using plastics industry information. By using process data of imported and domestically produced biopolymers, the domestic technology assumption (DTA) is relaxed.

$$\sum_{j=1}^{n} u_{jbb} = \sum_{p=1}^{n} u_{pbb} + \sum_{r=1}^{n} u_{rbb} \tag{29}$$

u_{pbb} – input of commodity *p* into bio-based intermediate industry *bb* where information from technical literature is available; for the case of plastics, *p* refers to CPA 10, 17.2, 19.2, 20, 35.1, 35.3 u_{rbb} – input of residual commodity *r* into bio-based intermediate industry *bb* where no information from technical literature is available

Step 1

$$u_{pbb} = s_{pbb} * x_{bb}^{di} \tag{30}$$

s_{pbb} – share of commodity *p* in bio-based intermediate production *bb* where information from technical literature is available; for the case of plastics, p refers to CPA 10, 17.2, 19.2, 20, 35.1, 35.3 $x^{di}{}_{bb}$ – total input of commodities to bio-based intermediate industry

$$s_{pbb} = \sum_{c=1}^{n} \left(s_{pcbb} * s_{cbb}\right) \tag{31}$$

s_{pcbb} – share of commodity *p* in bio-based intermediate product *c* that is part of bio-based intermediate industry *bb* s_{cbb} – share of bio-based intermediate product *c* in production value of bio-based intermediate industry

$$s_{pcbb} = \left(\boldsymbol{q_p} * \boldsymbol{p_p}\right) * (\boldsymbol{q_{cb}} * \boldsymbol{p_{cb}}) / ((\boldsymbol{q_{cb}} * \boldsymbol{p_{cb}}) - \boldsymbol{va_{cb}}) \tag{32}$$

q_p – quantity of input commodity *p* into product *c*, in physical units per € p_p– price of input commodity *p*, in € per physical unit q_{cb} – quantity of bio-based intermediate product *cb*, in tons p_{cb} – price of bio-based intermediate product *cb*, in € per ton va_{cb} – value added of bio-based intermediate product *cb*

$$s_{cbb} = \left(\boldsymbol{q_{cb}} + \boldsymbol{q^{m}_{cb}}\right) * \boldsymbol{p_{cb}} \Big/ \sum_{cb=1}^{n} \left(\left(\boldsymbol{q_{cb}} + \boldsymbol{q^{m}_{cb}}\right) * \boldsymbol{p_{cb}}\right) \tag{33}$$

qmcb – import quantity of bio-based intermediate product cb, in tons

$$x^{di}_{bb} = \sum_{cb=1}^{n} (\boldsymbol{p_{cb}} * \boldsymbol{q_{cb}}) - \boldsymbol{va_{cb}} \tag{34}$$

Step 2

$$u_{rbb} = rs_{rbb} * R_{bb} \tag{35}$$

rs_{rbb} – share of residual commodity *r* according to industry information
R_{bb} – residual input value for bio-based intermediate industry *bb*

$$R_{bb} = x^{di}_{bb} - \sum_{p=1}^{n} u_{pbb} \tag{36}$$

$$rs_{rbb} = s_{(f+b)r} \Big/ \sum_{r=1}^{n} s_{(f+b)r} \tag{37}$$

$s_{(f+b)r}$ – share of input commodities *r* to the aggregate fossil- and bio-based industry *f*+*b* for which no process information on bio-based intermediate industry inputs is available

Information on the fossil- and bio-based industry *f*+*b* is available on a detailed basis for some input commodities *w* from Destatis [6] Eq. (38)) but not for others (residual shares *rs* of input commodities *z*). For the latter case, shares are estimated based on aggregate industry residual shares rs_{agg} (Eqs. (39)–((43).

$$s_{w(f+b)} = \boldsymbol{s_{wagg}} * \left(\boldsymbol{d_{w(f+b)}} \Big/ \sum_{w=1}^{n} \boldsymbol{d_{w(f+b)}}\right) \Big/ \left(\boldsymbol{d_{wagg}} \Big/ \sum_{w=1}^{n} \boldsymbol{d_{wagg}}\right) \tag{38}$$

$s_{w(f+b)}$ – share of input of commodity *w* into fossil- and bio-based industry *f*+*b*, from detailed industry data s_{wagg} – share of input of commodity *w* into aggregate industry *agg* $d_{w(f+b)}$ – input of commodity *w* into fossil- and bio-based industry *f*+*b* d_{wagg} – input of commodity *w* into aggregate industry *agg*

$$rs_{z(f+b)} = u_{z(f+b)} \Big/ \boldsymbol{x^{di}_{(f+b)}} \tag{39}$$

$rs_{z(f+b)}$ – residual share of input of residual commodity *z* into fossil- and bio-based industry *f*+*b* $u_{z(f+b)}$ – input of residual commodity *z* into fossil- and bio-based industry *f*+*b* $x^{di}_{(f+b)}$ – total input value of fossil- and bio-based industry *f*+*b*

$$u_{z(f+b)} = rs_{zagg}/R_{(f+b)} \tag{40}$$

rs_{zagg} – residual share of input of residual commodity *z* into aggregate industry *agg*
$R_{(f+b)}$ – residual input value for fossil- and bio-based industry

$$rs_{zagg} = \boldsymbol{s_{zagg}} \Big/ \sum_{z=1}^{n} \boldsymbol{s_{zagg}} \tag{41}$$

s_{zagg} – share of input of residual commodity *z* into aggregate industry *agg*

$$R_{(f+b)} = \boldsymbol{x^{di}_{(f+b)}} - \sum_{w=1}^{n} u_{w(f+b)} \tag{42}$$

$x^{di}_{(f+b)}$ – total input of fossil- and bio-based commodities by all domestic industries $u_{w(f+b)}$ – input of commodity *w* into fossil- and bio-based industry *f*+*b*

$$u_{w(f+b)} = s_{w(f+b)} \Big/ \boldsymbol{x^{di}_{(f+b)}} \tag{43}$$

Step 3

Recalling from Eq. (28) that the bio-based industry has fossil-based intermediate inputs, Eq. (45) shows that this aspect is accounted for by using input values from the fossil- and bio-based industry *f*+*b*. How input shares of this aggregate industry $s_{j(f+b)}$ were modelled is described in Eqs. (37)–(42).

$$u_{jbf} = s_{jbf} * x^{di}_{bf} \tag{44}$$

u_{jbf} – input of commodity j into fossil-based intermediate industry s_{jbf} – share of commodity *j* in total fossil-based intermediate industry *bf* inputs x^{di}_{bf} – total input of commodities to fossil-based intermediate industry

$$s_{jbf} = s_{j(f+b)} \tag{45}$$

$$\sum_{j=1}^{n} s_{j(f+b)} = \sum_{w=1}^{n} s_{w(f+b)} + \sum_{r=1}^{n} rs_{r(f+b)} \tag{46}$$

$$x^{di}_{bf} = \sum_{cf=1}^{n} \left(\boldsymbol{p_{cf}} * \boldsymbol{q_{cf}}\right) - \boldsymbol{va_{cf}} \tag{47}$$

q_{cf} – quantity of fossil-based intermediate product *cf*, in tons p_{cf} – price of fossil-based intermediate product *cf*, in € per ton va_{cf} – value added of fossil-based intermediate product *cf*

Step 4

Having built the bio-based industry, based on process data and plastics industry data, inputs to the fossil-based industry are aggregate fossil- and bio-based industry inputs corrected for bio-based industry inputs (Eq. (48)).

$$u_{jf} = u_{j(f+b)} - u_{jb} \tag{48}$$

u_{fj} – input of commodities into fossil-based industry $u_{(f+b)j}$ – input of commodities into fossil-and bio-based industry u_{bj} – input of commodities into bio-based industry

Step 5

Other chemicals industry inputs, in turn, are modelled based on inputs to the aggregate sector u_{jagg} and to the fossil- and bio-based industry $u_{j(f+b)}$ (Eq. (49)).

$$u_{jo} = u_{jagg} - u_{j(f+b)} \tag{49}$$

Method validation

Net effects on fossil resource use of substituting disaggregated product groups can be derived from the model described above. These net effects indicate a transition from a fossil-based to a bio-based economy, which is one of the main objectives in current bioeconomy strategies [30,31] and should be measured with an indicator in order to make visible trade-offs with other objectives [13]. The plastics sector is currently transitioning towards a bioeconomy at a relatively low rate of 0.1% [23]. Apart from the fact that bio-based plastics production is low and prices are high compared to fossil-based plastics production, total Fossil Resource Intensities of bio-based ($tFRI_b$) and fossil-based plastics ($tFRI_f$) are similar (14.8 MJ/$€_f$ and 13.6 MJ/$€_b$). One Euro more of bio-based plastics production and one Euro less of fossil-based plastics production saves only 8% of fossil energy [23].

Intensity of bio-based plastics is high because 40% of bio-based plastics inputs are fossil-based intermediate products [23]. Thus, for most inputs, shares do not differ much between bio- and fossil-based industries, especially for fossil resource intensive sectors including coke oven and refined petroleum products, basic iron and metals, gas, and transport services (see Table 6, columns 5 and 6). Although much less fossil-based plastics and other chemicals that also have above average fossil resource intensities are used in the bio-based industry, higher electricity input increases the bio-based industry's production intensity.

Table 6
Modelling results: Share of input commodities j (columns 1 – 2) in bio- and fossil-based industry output (columns 3 – 5) and total fossil resource intensities (column 6) for Germany in 2016.

Commodities j	*CPA 2008*	*Input share bio-based plastics industry* s_{jb}	*Input share fossil-based plastics industry* s_{jf}	*Difference in input shares* $s_{jb} - s_{jf}$	*Total fossil resource intensity (MJ/€)* *tFRI*
Products of agriculture, hunting (…)	01	0.02%	0.02%	0.00%	11.46
Products of forestry, logging (…)	02	0.02%	0.02%	0.00%	7.27
Fish and other fishing products	03	0.00%	0.00%	0.00%	8.60
Hard coal	5.1	0.02%	0.02%	0.00%	9.97
Lignite	5.2	0.01%	0.01%	0.00%	10.33
Crude petroleum and natural gas	06	2.06%	1.91%	0.15%	14.25
Metal ores	07	0.00%	0.00%	0.00%	0.00
Stone, sand and clay	08,09	0.29%	0.27%	0.02%	10.43
Food products	10	20.86%	0.00%	**20.86%**	7.49
Beverages	11	0.02%	0.02%	0.00%	7.75
Tobacco products	12	0.00%	0.00%	0.00%	7.49
Textiles	13	0.02%	0.02%	0.00%	6.72
Wearing apparel	14	0.00%	0.00%	0.00%	6.62
Leather and related products	15	0.00%	0.00%	0.00%	6.60
Wood and of products of wood	16	0.32%	0.30%	0.02%	6.54
Pulp, paper and paperboard	17.1	0.00%	0.00%	0.00%	6.96
Articles of paper and paperboard	17.2	1.61%	2.29%	-0.67%	11.41
Printing and recording services	18	0.12%	0.11%	0.01%	4.81
Coke oven products	19.1	0.15%	0.14%	0.01%	**532.41**
Refined petroleum products	19.2	3.23%	4.23%	-1.00%	**117.02**
Other chemicals and chemical products	20*	15.75%	34.92%	**-19.17%**	**15.59**
Fossil-based plastics	20.16f	7.70%	19.99%	**-12.29%**	**14.80**
Bio-based plastics	20.16b	0.00%	0.00%	0.00%	13.57
Basic pharmaceutical products (…)	21	0.02%	0.01%	0.00%	5.39
Rubber products	22.1	0.09%	0.08%	0.01%	7.13
Plastic products	22.2f	2.26%	2.09%	0.17%	7.23
Glass and glass products	23.1	0.04%	0.04%	0.00%	12.60
Clay building materials	23.2–23.9	0.50%	0.46%	0.04%	12.57
Basic iron and steel and ferro-alloys	24.1–24.3	0.01%	0.01%	0.00%	**29.31**
Basic precious and other non-ferrous metals	24.4	0.19%	0.17%	0.01%	**29.00**
Casting services of metals	24.5	0.00%	0.00%	0.00%	**29.02**
Fabricated metal products	25	0.76%	0.70%	0.06%	7.46
Computer, electronic and optical products	26	0.01%	0.01%	0.00%	3.96
Electrical equipment	27	0.19%	0.18%	0.01%	5.10
Machinery and equipment n.e.c.	28	0.45%	0.42%	0.03%	5.16
Motor vehicles, trailers and semi-trailers	29	0.05%	0.05%	0.00%	5.16
Other transport equipment	30	0.00%	0.00%	0.00%	4.67
Furniture	31	0.01%	0.01%	0.00%	4.28
Other manufactured goods	32	0.01%	0.01%	0.00%	4.38
Repair and installation of machinery (…)	33	1.55%	1.44%	0.12%	5.01
Electricity, transmission and distribution (…)	35.1, 35.3	13.36%	3.87%	**9.49%**	**46.59**
Manufactured gas	35.2	0.24%	0.22%	0.02%	**17.01**
Natural water	36	0.20%	0.19%	0.02%	8.50
Sewerage services	37	0.55%	0.51%	0.04%	5.04
Waste collection, treatment and disposal (…)	38	1.18%	1.09%	0.09%	4.67
Remediation services and waste (…)	39	0.12%	0.11%	0.01%	4.57
Buildings and building construction works	41	0.04%	0.04%	0.00%	5.57
Constructions (…) for civil engineering	42	0.00%	0.00%	0.00%	6.51
Specialised construction works	43	1.16%	1.07%	0.09%	5.60
Wholesale and retail trade: motor vehicles (…)	45	0.16%	0.15%	0.01%	3.50
Wholesale trade services	46	0.31%	0.29%	0.02%	5.32
Retail trade services	47	0.00%	0.00%	0.00%	3.96
Land transport services (…)	49	2.05%	1.90%	0.15%	9.43
Water transport services	50	0.10%	0.10%	0.01%	**18.49**
Air transport services	51	0.14%	0.13%	0.01%	**30.11**
Warehousing (…) for transportation	52	0.95%	0.88%	0.07%	9.21

(*continued on next page*)

Table 6 (*continued*)

Commodities j	*CPA 2008*	*Input share bio-based plastics industry* s_{jb}	*Input share fossil-based plastics industry* s_{jf}	*Difference in input shares* $s_{jb} - s_{jf}$	*Total fossil resource intensity (MJ/€)* *tFRI*
Postal and courier services	53	1.34%	1.24%	0.10%	7.05
Accommodation services (...)	55,56	0.35%	0.33%	0.03%	4.50
Publishing services	58	0.40%	0.37%	0.03%	2.04
Motion picture, video and television (...)	59,60	0.00%	0.00%	0.00%	2.33
Telecommunications services	61	0.31%	0.29%	0.02%	2.66
Computer programming (...)	62,63	1.72%	1.59%	0.13%	1.72
Financial services	64	0.92%	0.85%	0.07%	1.40
Insurance, reinsurance and pension (...)	65	0.81%	0.75%	0.06%	1.68
Services auxiliary to financial services (...)	66	0.02%	0.01%	0.00%	1.54
Real estate services	68	1.29%	1.19%	0.10%	1.25
Legal and accounting services (...)	69–70	2.39%	2.21%	0.18%	1.93
Architectural and engineering services	71	2.05%	1.89%	0.15%	2.19
Scientific research and development (...)	72	0.00%	0.00%	0.00%	3.93
Advertising and market research (...)	73	2.01%	1.86%	0.15%	1.91
Other professional, scientific and technical (...)	74	0.69%	0.64%	0.05%	3.26
Veterinary services	75	0.00%	0.00%	0.00%	3.19
Rental and leasing services	77	1.58%	1.46%	0.12%	1.97
Employment services	78	0.77%	0.71%	0.06%	0.86
Travel agency (...)	79	0.07%	0.06%	0.00%	9.16
Security and investigation services (...)	80–82	2.83%	2.62%	0.21%	3.36
Administration services of the State (...)	84.1,84.2	0.99%	0.92%	0.07%	2.95
Compulsory social security services	84.3	0.00%	0.00%	0.00%	2.95
Education services	85	0.19%	0.18%	0.01%	1.65
Human health services	86	0.03%	0.03%	0.00%	2.38
Residential care services (...)	87–88	0.00%	0.00%	0.00%	2.82
Creative, arts and entertainment services (...)	90–92	0.00%	0.00%	0.00%	2.48
Sporting services (...)	93	0.01%	0.01%	0.00%	2.95
Services (...) membership organisations	94	0.16%	0.15%	0.01%	2.18
Repair services of computers (...)	95	0.06%	0.05%	0.00%	2.43
Other personal services	96	0.12%	0.11%	0.01%	3.59
Services of households as employers (...)	97,98	0.00%	0.00%	0.00%	0.17

Summary

This extended hybrid input-output model was developed based on prior conceptual work addressing bioeconomy monitoring challenges [13,35]. Substitution of bio-based for fossil-based products can be analyzed by comparing net effects of two matching sectors. This requires hybridization of national input-output tables. In the article, a method for augmenting tables with bio-based, fossil-based, and other products industries using process, industry, and input-output data was described. During model building, the aim of a detailed representation of domestic and imported processes and products that enables specific analyses was carefully weighed against the effort of collecting and integrating data that is not available in official statistics. Reproduction of the method to other sectors and countries in bioeconomy monitorings that seek to show substitution of bio-based for fossil-based products and its effects is thereby facilitated. Results for the case of bio- and fossil-based plastics are discussed intensely in [23].

Declaration of Competing Interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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