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Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints

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Abstract
After the publication of various multi-regional input–output (MRIO) databases over the past years and related environmental and socio-economic footprint analyses, the interest in these global value chain analyses is ever increasing. In order to provide forward-looking analysis of policy impacts, it is necessary to take MRIO data one step further, projecting them into the future. This paper introduces a simple approach to implementing existing climate change scenarios, such as the IEA energy technology perspective scenarios, in MRIO models. Rather than forecasting the world economy, the methodology is based on a mix of econometric estimations on the demand side and using specific information regarding technology development and its classical implementation in input–output tables. We apply this "what if" scenario approach to the most recent version of the MRIO system EXIOBASE. We compare the development of consumption- and production-based CO_2 emissions up to 2030. As an additional example, we show that the energy dependency of Europe is reduced in the 2-degree scenario compared to the 6-degree scenario, while the material dependency is higher. We discuss the major shortcoming of the model, the assumption of constant shares if no better information is available, and suggest that this actually is an advantage for deducing policy implications.

Keywords: Technological change, Climate change scenario, Multi-regional input–output analysis, Environmental footprints, Energy dependency, Material dependency, Europe

1 Background

In 2015, the world leaders agreed to combat climate change by taking efforts to keep the global temperature increase well below 2 degrees compared to pre-industrial levels, but the world leaders have not yet achieved a set of rules, regulations and processes that translate the Paris Agreement into specific country actions (Höhne et al. 2017). However, various sets of climate change scenarios exist, that suggest pathways of low-carbon technology deployment to reach the 2-degree target. The Intergovernmental Panel on Climate Change summarizes a number of global low-carbon scenarios that have been calculated with a variety of different Integrated Assessment Models (IPCC 2012). The International Energy Agency (IEA) has also developed two sets of scenarios, the World Energy Outlook and the Energy Technology Perspectives (ETP), that have been estimated using a computable general equilibrium model (IEA 2015). These models have a detailed representation of the energy system, while the rest of the economy is rather aggregated.

Models based on input–output tables (IOTs) and supply-and-use tables (SUTs) have a detailed representation of national economies by showing the interaction between different industries and sectors in the economy (Miller and Blair 2009). Therefore, these models provide a good basis for calculating economy-wide effects of climate change mitigation and other sustainable development scenarios (Duchin and Steenge 2007). Global multi-regional input–output (GMRIO) systems additionally represent the interlinkages between industries and final demand between different countries and give a complete picture of the global production network, something that Leontief envisioned in the 1970s already (Leontief et al. 1977). GMRIO databases have extensively been applied to calculate environmental footprints of nations (Hertwich and Peters 2009; Wiebe et al. 2012; Simas et al. 2015; Tukker et al. 2015, 2018; Wiedmann et al. 2015; Giljum et al. 2016; Ivanova et al. 2016; Wiedmann and Lenzen 2018). As constructing these databases is very time-consuming and depends on the availability of national IOTs and SUTs, footprint calculations are usually only available with a time lag of 3–6 or even more years. Efforts for now-casting global MRIOs are well underway (Miao and Fortanier 2018; Stadler et al. 2018) and some first estimations of projections of GMRIO or other life-cycle assessment data exist (Hertwich et al. 2015; Wiebe 2016).

This paper introduces a static, but scenario-based approach to implementing existing climate change scenarios, such as the IEA ETP scenarios, in GMRIO systems. The work here is distinct from other macroeconomic models, in that it is neither a forecasting tool for the world economy nor a way to investigate policy responses, rather it is a GMRIO system calibrated to meet the specifications of already existing scenarios. It adds industry and product detail to the scenarios and allows for the calculation of not only direct, but also indirect economic effects and environmental and socio-economic impacts of technological and structural change along global production chains. The aim of this exercise is to have a simple tool to estimate carbon and material footprints under different "what if" scenarios.

The paper is organized as follows: the next section shortly summarizes existing input–output-based economic scenario tools and motivates the use of the simple approach for certain types of analysis. Section 3 describes the approach in detail, using as an example the implementation of the IEA ETP 6-degree and 2-degree scenarios. Section 4 presents results regarding European consumption-based CO_2 emissions, energy and material use. Section 5 concludes and shows ways forward.

2 Input–output-based scenario tools

In order to provide insights into future scenarios of environmental footprints and emissions, energy and materials embodied in trade, it is necessary to take the GMRIOs one step further, projecting them into the future. Note that GMRIO databases in themselves are merely accounting systems and not dynamic models. We can distinguish three major types of approaches for input–output-(IO)-based scenario tools: static demand-driven IO, dynamic macroeconometric IO models and computable general equilibrium (CGE) models (West 1995; Rey 2000). Of course, various alternative formulations of these models exist, blending elements from these different types.

CGE models are widely applied in economic scenario modelling (West 1995; Rey 2000). These models are often used to model behavioural responses to policies; they are closer to neoclassical economic theory, assuming different forms of optimization behaviour, and do not make extensive use of empirical data (Duchin et al. 2016). According to Duchin et al. (2016), this often makes them "too constraining, ..., especially for analysing scenarios about resource use and environmental degradation". As an alternative, (Duchin 2005) developed the input–output World Trade Model that extends a dynamic IO model developed as the World Model (Leontief et al. 1977) by integrating international trade using comparative advantages. In such a model, global factor costs are minimized, subject to constraints given by regional consumption demand and regional factor endowments. As a result, production could be assigned to the lowest-cost producers available, leading to "corner solutions" with production being geographically located far away from consumption. In existing applications (Duchin 2005; Strømman and Duchin 2006; Duchin and Levine 2016b; Duchin et al. 2016), these corner solutions have not occurred and in the rare cases these would occur, additional constraints can be implemented. Bilateral trade has a substantial influence on the outcomes of national environmental footprints, and comparative advantages play a significant role in trade. In Duchin and Levine (2016a, b), the World Trade Model with Bilateral Trade, WTMBT (Strømman and Duchin 2006), is solved in a GMRIO framework with exogenous technological change and exogenous changes in final demand and factor endowment. This model could therefore be classified as being between a static and dynamic IO model, as parts of the system dynamically react to changing inputs, while others are kept constant or only changed exogenously.

Alternative approaches able to also simulate long-term scenarios and which cover more detailed sectorial interlinkages are dynamic econometric input–output models (Rey 2000; Eurostat 2008). They have been widely applied to scenario analysis, especially in the context of climate change and resource use. For example, the E3ME[1] model (Barker and Scrieciu 2010; Barker et al. 2010; Scrieciu et al. 2013; Mercure et al. 2015, 2018) covers more than 50 countries and differentiates between almost 70 sectors. Alternatively, the latest GINFORS[2] model (Distelkamp and Meyer 2017), following the philosophy of earlier versions (Lutz et al. 2010), is based on the GMRIO database WIOD (Timmer et al. 2015) and covers about 40 countries and industries. As the sector coverage does not capture individual energy/electricity technologies in either E3ME or GINFORS, both models have modules with additional information on the energy sector. Furthermore, the models consistently link IOTs/SUTs with the system of national accounts data. The individual country models are interconnected via international trade. The models therefore do not contain full-resolution GMRIOs, but most of the information that is necessary to estimate a full GMRIO system. Hence, GMRIO systems for future years could be estimated from the information available from those models in a similar manner that has been used to construct GMRIOs from historical data. These

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[1] http://www.camecon.com/how/e3me-model/.

[2] http://www.gws-os.com/de/index.php/global-developments-and-resources/models.html.

dynamic econometric (and CGE) models are different to our approach of exogenous "what if" scenarios in a GMRIO system, because dynamic models are designed to investigate shocks to an economy (e.g. a carbon tax, bioenergy competes with food for constrained resources, BREXIT, etc.).

The scenario tool developed by De Koning et al. (2016)—see Meyer and Ahlert (2016) for a detailed comparison of this with the GINFORS model—is closest to our approach (exogenously changing various parts of the GMRIO system), but still has some differences. Even though it is based on EXIOBASE [version 1—(Wood et al. 2014)], it does not make use of the detailed country availability, but aggregates the data to four world regions. A second difference (not related to the method, but which may affect the results) is the use of the year 2000 as a base year, which represents the world economy before (or only at the beginning of) the rise of China and other South-East Asian countries and before the economic crises of 2008. The third, and probably most important difference, is that the authors apply a balancing procedure to the SUT data after implementing the scenario information. By doing that, inter-industry and bilateral trade is adapted to the exogenously specified final demand, value added and production (De Koning et al. 2014). The impacts on value added and production are not endogenous outcomes resulting from technological change, but exogenously given in the scenarios. The model therefore foregoes the possibility of clearly showing the indirect effects on value added and production (which is one of the major advantages of using an input–output-based approach) that come about when implementing the exogenously specified direct changes in the model.

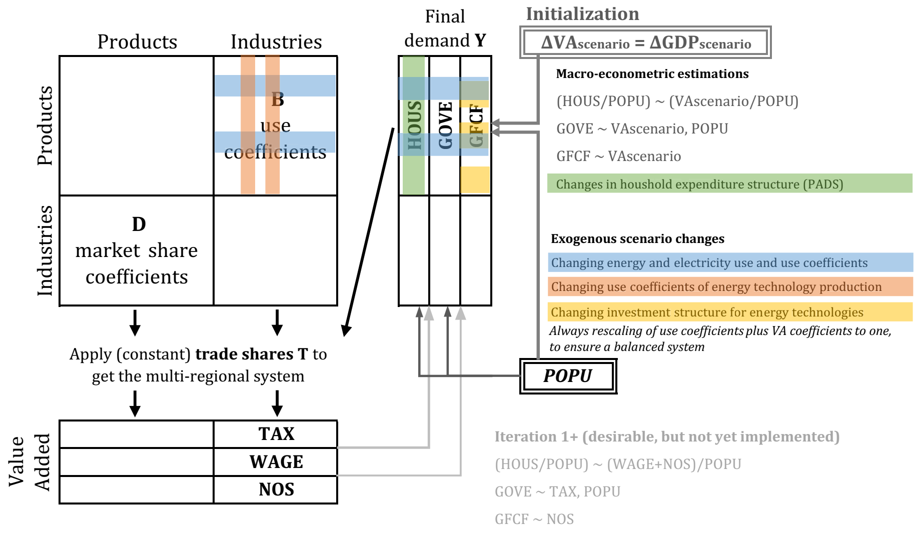
3 Methods: a multi-regional input–output-based scenario tool

In this section, we present an approach that uses the detailed outputs of either dynamic macroeconomic models or other more targeted partial equilibrium models as exogenous inputs to give the analyst full control over the implementation of changes due to scenario specifications in an GMRIO system. According to Duchin and Steenge (2007) "from an input–output point of view, use of expert knowledge in the form of exogenous assumptions about technological options is superior to relying on formal methods to represent behaviours that make technological change endogenous". In our approach, each individual change is implemented directly and as such, there is a higher dependency on the modeller to ensure that each exogenous change is modelled consistently. This results in a model that is a lot simpler (or less sophisticated) in its structure but demands rigorous consistency checks from the modeller. It can be classified as being somewhere between a static IO model and a model with simple dynamics, see Rey (2000) or West (1995). For now, the dynamics only relate to household demand (the structure changes with increasing spending) and investment into renewable energy technologies depends not only on capacity additions, but also on the lifespan of the technologies and required replacement investment.

By incorporating explicit exogenous technological and demand change, it is possible to model direct and indirect effects of demand in a scenario, but not model the dynamic response of an economy, such as macroeconomic price changes or systemic rebound effects (Gillingham et al. 2013). The system is closed using value added at the global level, i.e. global value added remains the same across the scenarios, given that demand is exogenous to the system. The distribution of value added across countries is endogenous, resulting in deviations from the exogenous information of less than 0.5% for most countries, see Additional file 1: Figure SI1. The results must be understood as a comparison between the status quo and a result in which the scenario, *ceteris paribus*, has been achieved. One strength of using a GMRIO table is that the study can consider all supply chains, so an intervention at the production or consumption end of a supply chain will be linked, globally, to the other end of that chain. One large drawback for this though is the lack of changing trade structures at the product level. Nonetheless, this limitation makes the interpretation of the results and deduction of policy implications very straight forward. Other virtues and shortcomings of an approach very similar to ours (lack of rebound effects and dynamic price effects) are very well summarized in Cooper et al. (2016). Given that we assume the GDP trajectory following the economic projection data underlying the IEA ETP scenarios (or possibly other scenarios), the lack of these feedback effects is not considered as a major drawback. Nonetheless, these limitations need to be kept in mind when analysing the results.

The model has been set up in the global multi-regional supply-and-use (GMRSUT) framework of EXIOBASE version 3 (Stadler et al. 2018). Everything explained in the remainder of the paper is equally valid for both an GMRSUT as well as an GMRIO system. Rather than independently forecasting the world economy, the GMRSUT system is changed according to exogenous scenario specifications. The methodologies for this are a mix of econometric estimations on the demand side, similar to the Inforum approach (Almon 1991; Lutz et al. 2010) and using specific information regarding technology development (from the exogenous scenarios) and its classical implementation in input–output tables (Rose 1984). The underlying philosophy of "keeping it simple" is based on observations from the data: economic structures and consumer behaviour change slowly, technological change has a significant influence on the environmental outcomes of economic development, the deployment of new technologies requires investment, and trade structures change quickly, sometimes just depending on policies. Given this, it is almost impossible to forecast bilateral trade at the product level and the baseline assumption applied in the model of structures being constant, if no better information is available, is applied to bilateral import shares of products as well. The constant trade shares reflect current comparative advantages. The results from the scenario analysis will clearly show which industrial and trade policies need to be implemented to change or enhance current comparative advantages.

The parts of the GMRSUT system that must be changed when modelling scenarios are the different final demand components, the intermediate (mostly the use, not so much the market share) and factor input (of value added) coefficients, and the environmental stressor matrix. Absolute levels of value added and output by industry are endogenous to the demand-driven system. The aggregate country level values of final household demand, government consumption and gross fixed capital formation depend on the exogenously given GDP growth rate, and the relationship has been estimated using ordinary least squares as displayed in Eq. (3) and Additional file 1: Sect. 1.2. Using income elasticities of demand, the composition of final household demand changes over time. The structure of government consumption and capital formation is changed exogenously based on assumptions deduced from scenarios. Industry technology, represented



Notation:
HOUS = Houshold final consumption expenditures, GOVE = Government final consumption expenditures, GFCF = Gross fixed capital formation, VA=Value added, GDP = Gross domestic product, POPU = Population, TAX = Taxes and subsidies, WAGE = Compensation of employees, NOS = Net operating surplus

Fig. 1 Model overview

by the coefficients in the use table, value added shares and environmental and socio-economic stressors are changed exogenously according to the scenario specifications. These changes are applied to the individual country SUTs, which are then disaggregated using bilateral import shares by product. That is, the energy use coefficients for example are changed with the relative development of energy use and GDP as given by the scenario. As the model in constant prices, the same relative change must be applied to the energy extensions, which are given in physical units per unit of industry output.

The model is based on data in constant prices, following the argumentation of De Koning et al. (2016). The main purpose of the model is to analyse environmental impacts along global production chains in different scenarios. There is a clear relation between emissions, energy and materials used and the monetary SUT system in constant prices. This makes it possible to change the model components in monetary terms, using growth rates of the physical data provided in the scenario specifications. In addition, technological change is better represented in volumes rather than prices.

Figure 1 sketches a demand-driven supply-and-use system. Note that the changes described below can as well be implemented in a system of symmetric input–output tables.

The modelling of climate change-related scenarios in a GMRIO/GMRSUT system is specified by the equations below and described in detail in the Additional file 1. The equations are presented in the order the model is solved. When doing the projections, the previous year's multi-regional table is taken as an initial estimate for the current year. The multi-regional table is first aggregated to national tables, then changes in intermediate and final demand are modelled, before the table is disaggregated into its multi-regional version using constant trade shares (as discussed above). Production by country and industry is calculated from the resulting multi-regional system.

The model can be summarized by,

$$\mathbf{x}_{t+1} = (\mathbf{I} - \mathbf{T}_t\mathbf{D}_t\mathbf{B}_{t+1})^{-1}\mathbf{T}_t\mathbf{D}_t\mathbf{y}_{t+1} \tag{1}$$

$$\mathbf{va}_{t+1} = \boldsymbol{\gamma}_{t+1}\mathbf{x}_{t+1} \tag{2}$$

where $\mathbf{va}_{t+1}$ is the vector of value added by country and industry in current year $t+1$, $\boldsymbol{\gamma}_{t+1}$ denotes the vector of value added per unit of output, $\mathbf{B}_{t+1}$ denotes the (block-diagonal) matrix technological coefficients (i.e. total intermediate demand for products of industries), $\mathbf{D}_t$ denotes the (block-diagonal matrix) of market shares of industries in the supply of products, $\mathbf{T}_t$ denotes the matrix of trade shares by product and country, and $\mathbf{y}_{t+1}$ denotes final demand. As mentioned above, the current year components are adjusted to the scenario specifications for each year, whereas the trade-share and the market-share matrices are kept constant here. However, in general the fixed components can also be adjusted by using, e.g. a trade model to adjust $\mathbf{T}$.

3.1 Changes in final demand

Aggregated development of the different final demand categories, household consumption (HOUS), government consumption (GOVE) and gross fixed capital formation (GFCF) depend on GDP or GDP growth from the exogenous scenarios. Let FD be the set of these macro values: FD = {HOUS, GOVE, GFCF}. The relation between these and GDP has been estimated for each country c using the ordinary least squares (OLS) method on the time series 1995–2014:

$$\mathrm{FD}_{tc} \sim \alpha_c + \beta_c \mathrm{GDP}_{tc} + \varepsilon_{tc} \tag{3}$$

More information on the data used is in the Additional file 1. The structure, that is the product shares in total demand per category, is assumed to be constant for GFCF and GOVE, but changing for HOUS. In order to determine the impact of changes in total household spending (HOUS) of country c on the shares of HOUS, y_{hhcp}, households spent on the different products denoted by p and q below, we estimate a perhaps adequate demand system model (Almon 2011) using maximum entropy (Golan et al. 2001) for each country c

$$y_{thhcp} \sim \left(\alpha_{cp}t + \beta_{cp}\left(\frac{\mathrm{HOUS}_{tc}}{\mathrm{PRICE}_{tc}}\right)\right)\prod_q (\mathrm{prices}_{tcq})^{\gamma_{cpq}} + \varepsilon_{tcp}\forall_{c,p}, \tag{4}$$

with $\mathrm{PRICE} = \sum_{i=1}^{n} p_k^{s^k}$ calculated from 21 product group prices_{cq}. As in this paper we do not consider changes in relative prices, the future shares only depend on total household expenditures (HOUS) determined from Eq. (1). If there is additional information available about future changes of prices (e.g. of crude oil) from the exogenous scenario or other expert knowledge, this is used to change the structure of final demand of households.

Furthermore, it is possible to adjust the shares of certain product in total final demand of households (HOUS) and governments (GOVE), as well as product shares in total gross fixed capital formation (GFCF) manually. This information can, for example, be the shares of the different electricity types. In most climate change-related scenarios, the share of coal electricity shrinks relative to the share of renewable electricity. The sum over all product shares needs to remain equal to one. This is ensured using two different approaches depending on the data available: first, if the reduction in the demand for one product goes hand in hand with the increase in the demand for another product, the value of the reduction in the first product is added to the demand for the second product. We follow this approach for modelling energy efficiency improvements of buildings,[3] which are only possible after some investments into construction. Note that we assume that the investments into upgrading the buildings are already visible in the energy consumption of the buildings in the same year. Second, if for example only the relative development of demand for one product compared to last year is known, the demand is changed accordingly, and the values of all other products are scaled so that the sum over all products remains equal to HOUS, GOVE or GFCF.

For any low-carbon pathway, an increased investment in new technologies is necessary, so that the structure of GFCF does not remain constant, not even in the baseline scenario. When investing in these technologies, it is not only the solar panel or the wind turbine that are necessary, but also other aspects of the projects need to be considered: planning, building the infrastructure and connecting the technologies to the grid. Thus, additional capital costs include investments in different products in the GMRIO system (ISIC Rev 3 codes in brackets), i.e. machinery and equipment n.e.c. (29), electrical machinery and apparatus n.e.c. (31), construction (45), insurance and pension funding, except compulsory social security (66) and other business activities (74) (MacDonald 2011) estimate the breakdown of capital costs for a range of renewable electricity generation technologies, see Additional file 1: Table SI1. These data are used to allocate the investment flows to the different final demand GFCF products.

3.2 Changes in the intermediate input structure

Investment in the new electricity technologies leads to an increased demand for the production of these technologies. If the full coefficient vector of the new technology is available, the input structure of the corresponding industry (technology industry) changes according to the share of the new technology in the output of the industry (Wiebe 2016). Equations (5) and (6) show the change for intermediate use coefficients b and value added v coefficients, respectively, for a known input coefficient vector of the new technology.

$$b_{.,\text{technologyindustry}} = (1-s)b_{.,\text{old\_technology}} + sb_{.,\text{new\_technology}} \tag{5}$$

$$v_{.,\text{technologyindustry}} = (1-s)v_{.,\text{old\_technology}} + sv_{.,\text{new\_technology}}. \tag{6}$$

Note that no rescaling of the coefficients is necessary when this approach is applied.[4] Renewable electricity technologies are produced within more general industries, mostly

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[3] This is part of the IEA EPT scenario specifications under the heading “Buildings, agriculture, fishing, non-specified other”.

[4] If $\sum_i b_{i,\text{old}} + \sum_i v_{i,\text{old}} = 1$ and $\sum_i b_{i,\text{new}} + \sum_i v_{i,\text{new}} = 1$, then $\sum_i (1-s)b_{i,\text{old}} + \sum_i (1-s)v_{i,\text{old}} + \sum_i sb_{i,\text{new}}$ $+ \sum_i sv_{i,\text{new}} = (1-s)\left[\sum_i b_{i,\text{old}} + \sum_i v_{i,\text{old}}\right] + s\left[\sum_i sb_{i,\text{new}} + \sum_i sv_{i,\text{new}}\right] = (1-s)[1] + s[1] = 1.$

machinery and equipment, M&E (for wind, hydro, geothermal, biomass and waste), and electrical machinery and apparatus, EMA (for solar photovoltaics and solar thermal). The input coefficient vectors, $b_{.\mathrm{WIND}}$, etc., are based on Lehr et al. (2011) and further broken down into the 200 EXIOBASE products.

3.3 Simultaneous changes in intermediate input structure and stressor matrix

Energy and material efficiency improvements are modelled in the intermediate use coefficient matrix **B** (the changes can also be applied to the intermediate input coefficient matrix **A** of a symmetric GMRIO system) and the environmental extensions S. Let E denote different energy or material inputs, then the corresponding intermediate use coefficient changes according to the growth rate of energy/material efficiency improvements in the scenario, here the IEA ETP scenarios described in IEA (2015), are given as:

$$\frac{\partial b_{Ej}}{\partial t} = \frac{\partial [E/\mathrm{GDP}]}{\partial t}_{(\text{scenario information for industry } j)} \tag{7}$$

Note that the sum over all input coefficients b and value added coefficients v of an industry still need to add up to one. This is achieved by rescaling. The combination of benchmarking, changing those coefficients where there exists information, and scaling has already been used by Leontief et al. (1977) to ensure that the sum of the scaled coefficients give the desired column sum, i.e. one for the sum over all intermediate input coefficients (domestic and imported) and the value added coefficients. This guarantees that the system is balanced, when industry output is calculated from the demand-driven system as specified in Eq. (1).

The same approach is used to change the physical extensions in the stressor matrix S, i.e. energy, materials, or emissions per unit of industry output.

$$\frac{\partial s_{Ej}}{\partial t} = \frac{\partial [E/\mathrm{GDP}]}{\partial t}_{(\text{scenario information for industry } j)} \tag{8}$$

While information on energy efficiency development as well as energy-related emissions is readily available from the IEA ETP scenarios, see Additional file 1: Table SI2, no information on material efficiency improvements is given in the scenario specifications. These could therefore be estimated from the historical data. These improvements should follow an *s*-curve over time (Rogers 1962). That is, efficiency improvements are slow in the beginning, speed up as improved technologies diffuse within industries and then slow down again as lower bounds of possible efficiencies are approached. Hence, the alternative for Eqs. (7) and (8) takes the form of an inverted logistic *s*-curve depending on time t (Eq. 9). It can be estimated based on the physical environmental extensions S and the resulting growth rates should then also be applied to the corresponding intermediate input coefficients b as well (Eq. 10).

$$s_{Ej}(t) = \frac{d_1}{1 + \mathrm{e}^{d_2(t-t_0)}} \tag{9}$$

$$\frac{\partial b_{Ej}}{\partial t} = \frac{\partial s_{Ej}}{\partial t}. \tag{10}$$

4 Results: Europe's fossil fuel and metal dependency

We apply this scenario implementation approach to the most recent version of the GMRSUT system EXIOBASE (Wood et al. 2015; Stadler et al. 2018). EXIOBASE is available as both a GMRIOT and a GMRSUT system, in current and constant prices as a times series from 1995 to 2014 and extrapolated to 2016. It differentiates between 200 product groups and 163 industries and covers 44 countries and five rest of the world regions by continents.

We implement the IEA ETP 6-degree and 2-degree scenarios following the methodology outlined above. Table 1 summarizes the changes implemented in the GMRSUT system. See the Additional file 1 for further information, also on how we deal with the limited information available for the transport scenario specifications.

Note that the results of a "what if" scenario analysis should be analysed in relation to each other, not in absolute terms. That is, we have to consider the differences in the environmental impacts between the scenarios, not at the actual level of the impacts, as there will be many changes in the structure of the world economy that we are not able to capture. However, for validating the model outcomes relative to the implemented scenarios, Fig. 2 also includes absolute numbers for the development of CO_2 emissions.

Figure 2 shows the development of global CO_2 emissions, as well as the EU's consumption- and production-based emissions in the 2-degree and 6-degree scenarios up to 2030 in Gt. Note that the absolute level of global emissions in EXIOBASE in the base year 2014 is significantly lower than in the IEA reported numbers for the same year. We have not rescaled emissions in order to match, but rather have taken growth rates from the IEA scenario to drive the development in our model. When comparing the development of global emissions in the IEA scenario and our model, we can see that even though the absolute numbers are the not the same, the trends are. This is one of the reasons, why we emphasize that the "what if" scenarios should always be compared relative to each other. For the EU, we see that consumption-based emissions in the 2-degree scenario decrease relatively faster than production-based emissions. While in the 6-degree scenario, most of the mitigation efforts are taken within the EU, in the 2-degree scenario, mitigation efforts are accelerated outside the EU as well.

The EU28 is a net-importer of natural resources, see Fig. 3. Net-imports are the difference between the total length of the consumption and the production bars. The darkest part of the bar shows the materials extracted within the EU that are eventually embodied in products and services consumed within the EU28. The lighter shaded parts of the production bars (negative) are what is extracted within the EU28 and exported from the EU28 to other world regions. The lighter shaded parts of the consumption bars are the total volume of material extraction in other countries that are embodied in the consumption of the EU28.

This dependence of the EU's consumption on imports is due to the limited abundance of fossil fuels and metal ores relative to its population and, more importantly, relative to its economic activity. The switch to a more renewables-based energy system is not only beneficial for climate change mitigation, but also reduces the EU's dependency on

Table 1 Implementation of IEA ETP scenarios in EXIOBASE

		IEA EPT 6 deg	**IEA EPT 2 deg**		
		Energy	**Energy**	**Transport**	**Construction**
1	Investment (GFCF)	Renewable energy technologies	Renewable energy technologies	No additional spending on electric vehicles	Investment = savings from decreased energy spending compared to BAU
2	Input coefficients of technology production	Machinery and equipment, electrical machinery and apparatus	Machinery and equipment, electrical machinery and apparatus	Motor vehicles own inputs replaced by electrical machinery	No structural change in construction industry
3	Input coefficients of technology use	Relative changes of electricity use	Relative changes of electricity use	No switch of intermediate transport	Energy savings according to IEA EPT 2 deg
1-3	Other intermediate and final demand	Shares of electricity types and energy saving according to IEA EPT 6 deg	Shares of electricity types according to IEA EPT 2 deg	Fuel use: additional electricity = 0.33 * (petroleum product savings)	
4A	Employment extension	Sectoral totals based on ILO (2017)	Based on labour productivity calculated from BAU		
4B	Emissions extension	According to relative GDP emission intensity changes in IEAEPT6 deg	According to relative GDP emission intensity changes in IEA EPT 2 deg		
5	Value added shares	Corresponding to changes in technology production and use	Corresponding to changes in technology production and use		

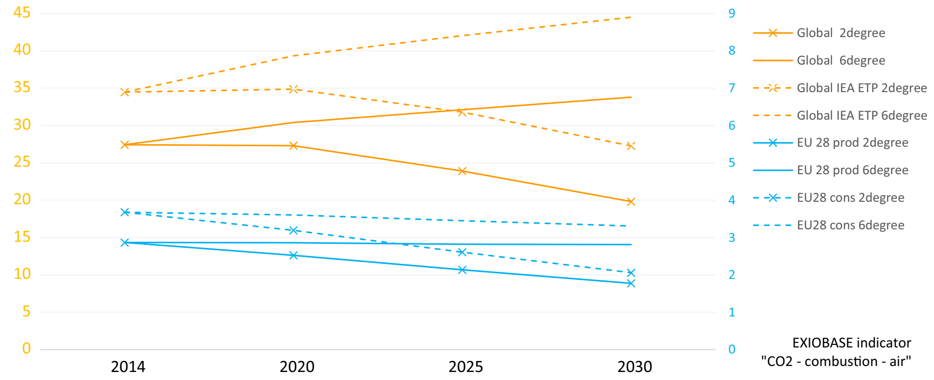

Fig. 2 Scenario results for EU's production- and consumption-based CO_2 emissions in Gt CO_2

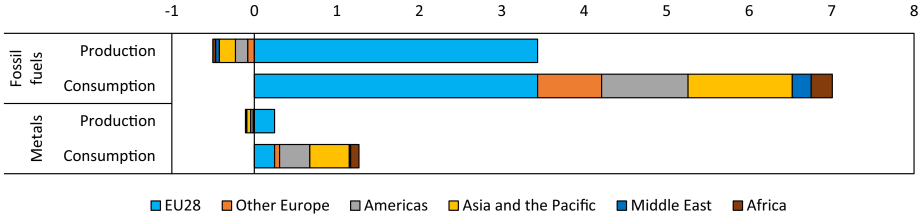

Fig. 3 EU28's production and consumption of fossil fuels and metal ores in 2014 in Gt, used extraction, EXIOBASE 3.4, negative values are reflecting EU28's exports with the regions being the destination of the exports, for consumption the regions are the regions of origin

energy carrier imports. About half of the fossil fuels consumed in the EU28 are extracted somewhere else. For materials, this share is more than 80%. Material flow and life-cycle analyses outcomes show that renewable energy technologies have higher metal requirements than conventional electricity technologies (Nansai et al. 2012; Hertwich et al. 2015; Nakajima et al. 2017).

One research question is whether the decreased energy dependency in a climate change mitigation scenario, such as the 2-degree scenario, implies a higher material, specifically metal ores dependency of the EU28. To answer this, we use the environmental stressors of used and unused domestic extraction of fossil fuels and metals, see Additional file 1: Table SI4 for a detailed list. The stressor data in EXIOBASE are based on data from materialflows.net as described in Stadler et al. (2018) which records the annual usage of twelve groups of metal ores: iron, bauxite, copper, lead, nickel, gold, other non-ferrous metal ores, platinum group metals (PGM), silver, tin, uranium and thorium, and zinc. EXIOBASE provides estimates of the ore quantities (rather than quantity of metal in the ore), in line with material flow accounting standards and conventions, and additionally provides estimates for the amount of "unused extraction" such as mining overburden. The metal ore stressors are directly linked to the extraction sectors in EXIOBASE, not the non-extracting manufacturing or service industries where a change in the energy or material intensity can be modelled with an *s*-curve. This implies that the resource extraction only changes with the changes in the intermediate demand that stem from the changes in the energy system. No additional material/resource productivity

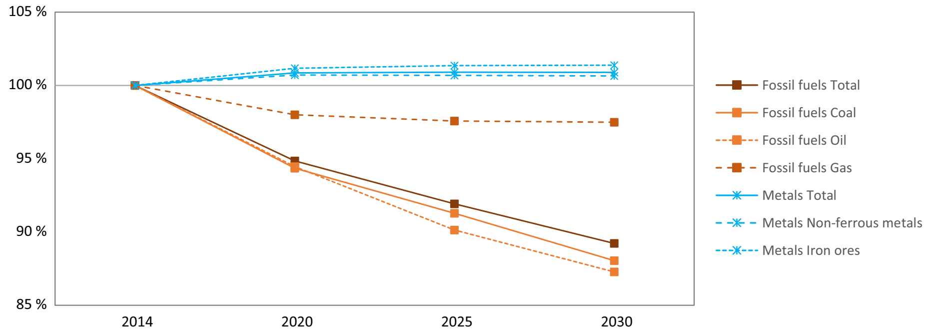

Fig. 4 Embodied materials net-imports of EU28 compared to baseline

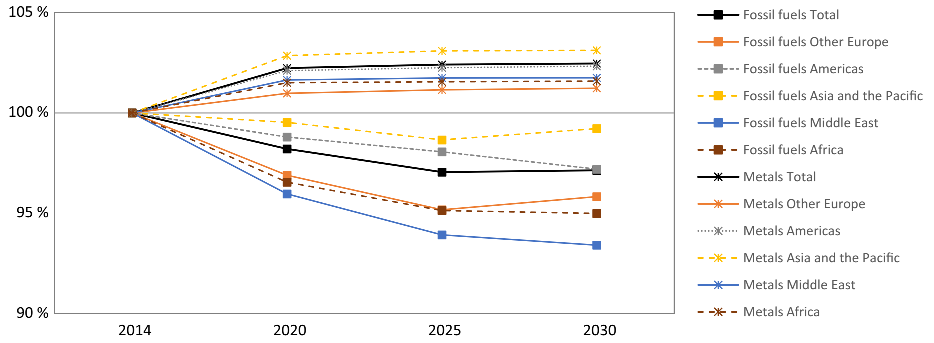

Fig. 5 EU28 imports of embodied materials for EU28 exports

enhancements, as for example those described in Aguilar-Hernandez et al. (2018), are modelled. We make the strong assumption that the amount of materials extracted per unit of output of the corresponding industries does not change over time (i.e. that ore quality does not change). Therefore, when analysing the results, we clearly see the indirect impacts on fossil fuel and metal extraction due to the change of the energy system implied by going from the 6-degree scenario to the 2-degree scenario. Questions about declining metal contents of ores can then be investigated separately.

Our results show that the energy import dependency of Europe is reduced in the 2-degree scenario compared to the 6-degree scenario, while the material import dependency is indeed slightly higher. This is shown in Figs. 4 and 5. Figure 4 shows the development of the EU28's net-imports of the different materials in the 2-degree scenario relative to the 6-degree scenario. Total fossil fuels net-imports are reduced by about 10% until 2030, with the reduction in oil being two- and fourfold the reduction in coal and gas, respectively. The change in net-embodied imports of metals is significantly smaller, but positive. In the 2-degree scenario, the EU28's net-imports of embodied metals are expected to be on average 1% higher per year than in the 6-degree scenario.

From a consumption-based point of view, decreasing net-imports would translate to a direct decrease in the fossil fuel footprint (consumption-based account) of Europe, if imports are not replaced by domestic production. Production of fossil fuels outside and inside Europe decreases at an approximately same pace in the 2-degree scenario, compared to the 6-degree scenario, so that the EU28's consumption-based fossil fuel footprint in the 2-degree scenario is 10% lower than in the 6-degree scenario. Comparing these relative numbers to the absolute values presented above shows that the absolute increase in metals footprint in the EU28 in Gt, which is already significantly lower in mass terms than fossil fuels, is more than offset by the reduction in fossil fuels in Gt. However, in monetary terms, this picture might be reversed, depending on a variety of factors, e.g. the scarcity of the metals and the technologies that are necessary to mine from scarcer sources.

It is not only the EU28's final demand that depends on imports of fossil fuels and metal ores, but also its production. The lower dependency of the EU's production on fossil fuel imports can be seen in Fig. 5. This graph shows the development of fossil fuels and metal ores that are embodied in imports into the EU28, further processed or used and then embodied in the EU28's exports. The reduction in fossil fuels here is lower than in the net-imports, but still significant. The increase in metal ore imports for exports, however, is higher than the respective increase in Fig. 4. This is due to the relative strong position of some EU countries in producing renewable energy technologies that are increasingly demanded around the world. Recall that the trade shares are left constant, projecting the current comparative advantages of the different countries out to 2030. If other countries start producing the technologies themselves, the flows of embodied metals may simply bypass the EU countries.

From Fig. 5, it also becomes clear that the global demand for products from countries in the Middle East with high embodied fossil fuels is significantly lower in the 2-degree than in the 6-degree scenario. Remember that these results are based on calculations with constant trade shares, i.e. assuming that the Middle East will continue to export fossil fuels, or products that depend on fossil fuel production and not switch to other products. From these results, a straightforward policy conclusion can be drawn: if those countries are not to loose out in a clean energy scenario, they need to start producing non-fossil fuel-based products.

5 Discussion of modelling approach and interpretation of modelling results

The approach presented here gives the modeller a maximum degree of freedom, but also the responsibility of ensuring that the changes implemented are consistent in both a mathematical and a contextual way. The changes implemented in the GMRIO system have mostly been described using the example of energy-related structural and technological change, but the principles are equally valid for other types of structural and technological change. However, some important considerations to keep in mind when implementing scenarios are first that technological or structural change is represented by changing input coefficients, be it in the intermediate input coefficient table in a symmetric IO system, or in the use coefficient table in a SUT table. Changes in the market-share table in a SUT system can also be modelled to represent further structural change. Second, when changing any input or value added coefficient, the modeller needs to ensure the corresponding column sum, i.e. the sum over the input and value added coefficients, remains equal to one, so that the system is balanced. Third, if new technologies are used, they need to have been produced. This can be reflected by modelling investments in gross fixed capital formation while considering changes in the production structure of the technology producing industry. Generally, the changes implemented need to be consistent from both the consumption and production side. Fourth, environmental and other stressors need to change accordingly with input coefficients. In a constant price setting, the same growth rates can be applied.

In addition, it must be re-emphasized that the approach here is focused on producing static comparative assessments of global supply chain relationships, given exogenous information on how the global economy will change. As most of the exogenous information is produced by specific sectoral (e.g. partial equilibrium) models, it must be acknowledged that discrepancies will arise between exogenous estimates of supply on one side, and demand on the other. Here, we discuss three major shortcomings of the model. We suggest that our "simple" approach may be an advantage for deducing policy implications, as the changes in the model are easily traceable from implementation to effects, if only few changes are implemented at the same time.

First, one of the major determinants of consumption-based footprints is international trade. Assuming constant trade shares has therefore a significant influence on the resulting footprints. Currently, the results show what is going to happen given the current trade shares. From this, it is straightforward to deduce what policy outcomes are necessary to counteract undesirable outcomes or support desirable outcomes. The model can be changed to incorporate additional information on changes in the bilateral trade structure (**T**) of the global economy.

Second, prices do not change and, therefore, there is no channel for dynamic demand adjustments. But, the goal here is not to create the scenario, but to take an exogenously specified scenario, where these price adjustments have already been considered, and show what this means in terms of flows of embodied materials, emissions and other resources around the world. Still, this price information can be considered, if the modeller regards it as relevant for the analysis, and the related changes can be implemented exogenously.

The third major shortcoming relates not to the general modelling framework, but rather to the actual implementation of the scenarios. As no sufficient data are available for all the required infrastructure investments, e.g. increased storage capacity for electricity from renewables or electric vehicle charging stations, these are not explicitly considered in the scenarios presented here. This also relates to a more general addition to the model regarding changes in the investment structure. Similar to the modelling of household demand, we suggest that it is necessary to include changes in the structure of capital formation. For now, this results in less accentuated differences between the scenarios. This structure not only depends on the total level of investments, but also on the existing capital stock, and, more importantly, on expected demand for capital stock. This in turn depends on future production and could be modelled using a bridge matrices from capital consumption to capital formation, as has been done in Södersten et al. (2017) to estimate the environmental impacts of capital formation. When doing this, possible supply and production capacity constraints should be considered. The model presented in this paper is set up in a way that a dynamic capital formation module could be incorporated, if desired.

6 Conclusions and way forward

In this paper, we set out the methodological framework for producing a scenario of the world economy based on multi-regional input–output tables, and informed by changes in technology of sector specific models coupled with scenarios of changing final demand. We apply the framework in a consumption (or "footprint") based model of CO_2 emissions, fossil fuel and metal demand. Distinctions between investment and current production are highlighted, as well as the changing structure and volume of final demand. The scenarios highlight the changes in structural relationships between production and consumption globally, providing insight into what life-cycle impacts due to the consumption of products are likely to be most important in the future.

Results show a 10% decrease in the fossil fuel dependency of the EU on embodied fossil fuel imports between baseline and low-carbon scenarios; while the metal dependency sees an increase in the net-imports. Given the strong coupling between metals and low-carbon infrastructure and the increased environmental damage that occurs in increasing metal ore extraction, insights into this potential future problem area are highly relevant. The EU's consumption-based emissions decrease stronger in the 2-degree scenario, relative to both production-based emissions in the 2-degree and consumption-based emissions in the 6-degree scenario, highlighting the importance of global action to decrease emissions. In this context (Wiebe 2016, 2018) suggests to increase technology transfer programs, to support the decarbonization in upstream value chains.

Next steps to improve the model presented here include dynamic investment (GFCF) modelling including the material base of the capital stock, further analysis on how changes in household demand influence global emission and material use, and an in-depth analysis of changes in future trade structures and their impacts on the model outcomes. Based on these analyses, it will also be possible to estimate some uncertainties associated with the model outcomes. Feedback effects between value added and final demand at the country level can be endogenized in the model, when modelling the dependence of final demand on value added (the light grey arrows in Fig. 1). Furthermore, supply constraints on production capacity as well as factor endowments and natural resources can be introduced to further endogenize feedback effects between demand and supply. For this, it would be necessary to also include the development of relative prices.

Additional file

Additional file 1. Supplementary information.

Authors' contributions

KSW and RW designed the study. KSW developed the approach, set up the framework and conducted the analysis. ELB and JT contributed to the modelling. KSW wrote the paper with contributions from all authors. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The data and code for the results presented in this paper are available at https://zenodo.org/communities/indecol (Wiebe et al. 2018) and https://github.com/kswiebe/FEMRIOv1_EXIOfuturesIEAETP.

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