Supplementary Information

To the paper "Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints" by Kirsten Svenja Wiebe*, Eivind Lekve Bjelle, Johannes Többen, and Richard Wood

* corresponding author: kirsten.s.wiebe@ntnu.no

1 Additional information on implementing scenario specifications in an MRIO

The model code is published on https://zenodo.org/communities/indecol/ (Wiebe et al., 2018) and available at https://github.com/kswiebe/FEMRIOv1_EXIOfuturesIEAETP.

1.1 Global closure of the system

The system is closed at the global level for value added, i.e. value added remains equal to global demand as we do not (yet) model rebound effects in this purely demand driven model. Figure S1 shows the deviation of value added by country in the 2-degree scenario compared to the 6-degree scenario. For most countries, the effect is positive, but very close to zero. Negative outliers are economies, that today are fossil fuel exporters, e.g. the Rest of the World Middle East (-1.9%) or Norway (-1.3%). The change in value added reflects the impacts of the scenarios on industrial production due to changing demand for intermediate and final products. See Section 2 below for more information on why GDP is held constant across scenarios in the IEA Energy Technology Perspectives(IEA ETP).

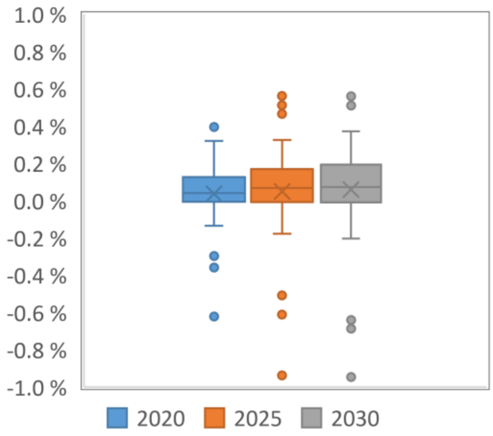

Figure SI1: Distribution of value added deviations of 2-degree from 6-degree scenario at the country level

1.2 Macro-economic estimations of final demand

Aggregated development of the different final demand categories, household consumption (*HOUS*), non-profit organizations serving household (*NPSH*), government consumption (*GOVE*) and gross fixed capital formation (*GFCF*) depend on GDP growth from the exogenous scenarios. The relation between the development of these categories and GDP has been econometrically estimated based on the constant price time series data (1995 to 2014) available in EXIOBASE as specified in Equation (3) in the main paper. Note that the estimation is done in levels and not in first differences, as the former gives more stable modelling outcomes. Household consumption has been estimated in per capita values, i.e. Equation 3 is expressed in per capita terms, i.e. divided by the country's population (*POP*):

$$\frac{HOUS_{tc}}{POP_{tc}} \sim \alpha_c + \beta_c \frac{GDP_{tc}}{POP_{tc}} + \varepsilon_{tc} \tag{3S}$$

Total household consumption is then calculated by multiplying the estimated per capita consumption with the UN World Population Prospects – medium variant. For the projections, the GDP values for each country grow with the exogenous GDP growth rate available from the scenarios.

Figure SI2a and Figure SI2b show the development of core macro-economic indicators for the largest countries in this model for the two scenarios. Note that the final demand components have the exact same development, and the differences between the value added components are minimal as described in Figure SI1.

Figure SI2a: Core macro-economic indicators (in EUR) for selected countries in 6-degree scenario

Figure SI2b: Core macro-economic indicators (in EUR) for selected countries in 2-degree scenario

1.3 Household consumption model

In order to determine the impact of changes in total household spending (HH) on the shares of households spent on the different products, we estimate a general form of the log-linearized Perhaps Adequate Demand System (PADS) (Almon, 2011) for each country. In addition to real income, the PADS specification includes relative prices of all products and a linear time trend as explanatory variables for household expenditure on a certain product. Thus, it allows separating between income elasticities of demand on the one hand and own and cross-price elasticities on the other. The model is estimated as a log-log regression model using the Generalized Maximum Entropy (GME) estimator developed in (Golan et al., 2001), which is much more robust in the case of small samples 2-Step Least Squares estimators. We estimate each country-specific PADS model using data from the final demand matrix of EXIOBASE version 3.4, for 44 countries and 5 rest of the world regions for the years 1995-2015. The 200 products are aggregated into 21 product groups. The expenditure out of total household budget on the 21 product groups are calculated from the data in current prices. Relative prices for the 21 product groups are calculated from the EXIOBASE data in constant and current prices. The product shares within these 21 groups are assumed to be constant, unless other information is available.

1.4 Investment in renewable energy technologies

Investments into renewable energy technologies do not only involve investment into the technology itself, but the projects need to be planned (other business activities), insured, foundations and other infrastructure need to be build (construction) and the new technology needs to be connected to the grid (construction and electrical machinery and apparatus). Therefore, the total investment costs are spread across several products/industries in the gross fixed capital formation vector, using the shares specified in Table SI1.

Table SI1 EXIOBASE industries producing renewable electricity technologies & capital cost breakdown

	Electricity products	Renewable power generation technology [1]	EXIOBASE industry producing the technology TS	Shares in capital costs [2] (capital cost breakdown) (TS)	(29)	(31)	(45)	(66)	(74)	Lifespan in years (may grow over time)	
1	'Electricity by coal'										
2	'Electricity by gas'										
3	'Electricity by nuclear'				42 %	9 %	40 %		9 %	60	[2]
4	'Electricity by hydro'	Hydro	(29)							100	[3]
5	'Electricity by wind'	Wind onshore	(29)	64 %	5 %	7 %	13 %	3 %	7 %	25	[4,5]
		Wind offshore	(29)	45 %	7 %	20 %	24 %	2 %	3 %	25	[4,5]
6	Electricity by petroleum and oil'										
7	'Electricity by biomass and waste'	Biomass, large	(29)	64 %		8 %	15 %		14 %	25	[6]
		Biomass, small	(29)	63 %		10 %	14 %		14 %	20	[6]
		Biogas	(29)	76 %		4 %	14 %		6 %	20	[7]
8	'Electricity by solar photovoltaic'	Photovoltaik	(31)	58 %		18 %	12 %		11 %	25	[2,8]
9	'Electricity by solar thermal'	CSP	(31)							30	[9]
10	'Electricity by tide, wave, ocean'		(29)							20	[10]
11	'Electricity by Geothermal'	Geothermal, deep	(29)	37 %		4 %	52 %		7 %	25	[2]
12	'Electricity nec'										

Product shares in capital costs

(TS) Technology specific (TS) as part of EXIOBASE industry producing technology

(29) 'Manufacture of machinery and equipment n.e.c. (29)'

(31) 'Manufacture of electrical machinery and apparatus n.e.c. (31)'

(45) 'Construction (45)'

(66) 'Insurance and pension funding, except compulsory social security (66)'

(74) 'Other business activities (74)'

[1] Lehr,U., C. Lutz, D.Edler, M.O'Sullivan, K. Nienhaus, J.Nitsch, B. Breitschopf, P. Bickel und M. Ottmüller (2011) Kurz- und langfristige Auswirkungen des Ausbaus der erneuerbaren Energien auf den deutschen Arbeitsmarkt, Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz und und

[2] Mott MacDonald. (2011). Costs of low-carbon generation technologies. Mott MacDonald for Committee on Climate Change.

[3] http://www.nrel.gov/docs/fy04osti/34916.pdf

[4] http://www.dtu.dk/english/news/2015/07/life-cycle-assessments-map-wind-turbine-lifespan?id=2cdee1b5-bc87-4923-ba06-5b21306463b2

[5] http://www.renewableenergyfocus.com/view/43817/the-end-of-the-line-for-today-s-wind-turbines/

[6] https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf

[7] esu-services.ch/fileadmin/download/publicLCI/stucki-2011-biogas-substrates.pdf

[8] https://info.cat.org.uk/questions/pv/life-expectancy-solar-PV-panels/

[9] http://www.nrel.gov/analysis/sustain_lca_csp.html

[10] http://link.springer.com/article/10.1007/s11367-016-1120-y

1.5 Technical steps for changing the use coefficient matrix

When running the projections, the previous year's multi-regional table is taken as an initial estimate for the current year. Technological change in the table is implemented in several steps, based on methodologies developed, reviewed and used in e.g. (Cooper et al., 2016; Rose, 1984; Wiebe, 2016; Wilting et al., 2004; Wood et al., 2017) and described in detail in (Wiebe, 2018)

1) The multi-regional matrix is collapsed to national tables.
2) For each industry in each country that undergoes technological change, the corresponding input-coefficient vector and the value added coefficients are extracted from the table.
3) For each of these, the input coefficients and value added coefficients are altered according to change that is modelled. They still need to add up to one, to comply with the row-column balance constraints. If the changes result in a value of the sum different from one, the entire vector is rescaled, either only the intermediate or (or and) the value added coefficients, depending on the modeler's aim. The combination of benchmarking, changing those coefficients where there exists information, and scaling has already been used by (Leontief et al., 1977, p. 24) to ensure that the sum of the scaled coefficients

give the desired column sum, i.e. 1 for the sum over all intermediate input coefficients (domestic and imported) and the value added coefficients.
4) Using the balanced total and bilateral import shares the coefficients are split into the multi-regional table.
5) This new multi-regional table of direct coefficients is then used to calculate the multiplier matrix, i.e. the Leontief inverse, and subsequently production by industry, value added by industry and the socio-economic and environmental impacts.

Note that this is a demand-driven model, where production by industry, vector **x**, is determined by projected future final demand,y, and the adapted multi-regional intermediate inputs matrix, **A** using the usual Leontief equation $\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$, or in case of the MRSUT system the compound Leontief inverse. As long as the column sums of the intermediate coefficient matrix and the value added coefficients add up to one, the corresponding multi-regional table fulfills the row-column balance criterion. This also ensures that the general balance of an economy is kept: GDP from the consumption side (household, government, investment and net-exports) equals GDP from the production side (gross value added).

1.6 Changing material and energy inputs

The change in energy or material intensity of non-extracting industries can be estimated based on the physical environmental extensions s and the resulting growth rates are then applied to the intermediate input coefficients **a** as well.

$$s_{Ej}(t) = \mathrm{d}_0 + \frac{\mathrm{d}_1}{1+ e^{\mathrm{d}_2(\mathrm{t}-\mathrm{t}_0)}} \tag{6A}$$

The lower bound of the intensity, i.e. material or energy per unit of industry output, is equal to d_0, as $\frac{\mathrm{d}_1}{1+ e^{\mathrm{d}_2(\mathrm{t}-\mathrm{t}_0)}}$ for $t \to \infty$. The upper bound for $t = t_0$ is $\mathrm{d}_0 + \frac{\mathrm{d}_1}{2}$. Note that the time period covered for the estimations for most parts only show fragments of the s-curves for most industries.

1.7 Simultaneous changes in final demand and intermediate input structure with limited data

An example for simultaneous changes in final demand and intermediate input structure with currently very limited IO-related data available is the switch to electric vehicles (EVs), summarized in the transport column in Table 1 of the main document. From the IEA ETP scenarios, the amount of electricity and oil-based fuel use is given, as well as the fact that in 2015 less than 1% of all new vehicle were EVs (p.102/103). We assume an annual growth rate of this share of 6%, leading to a share of EVs in newly registered cars of 96% in 2030. This share is applied to a hypothetical EV production vector, where 45% of the inputs come from electrical machinery and apparatus and all remaining inputs are scaled accordingly. Infrastructure investments for electrical vehicles such as large power outlets are not considered.

2 IEA Energy Technology Perspectives

We use the scenario specifications from International Energy Agency, Energy Technology Perspectives 2015 - www.iea.org/etp/etp2015 (IEA, 2015). GDP growth and population are the same across scenarios "as a means of providing a starting point for the analysis and facilitating the interpretation of the results" (https://www.iea.org/etp/etpmodel/assumptions/).

2.1 Country and region coverage

The scenario specifications are given for WORLD, OECD, NonOECD, ASEAN, Brazil, China, European Union, India, Mexico, Russia, South Africa, United States. For the more detailed EXIOBASE country list, the growth rates of the corresponding regions are taken.

GDP growth in the IEA ETP is assumed to be the same in the different scenarios (6 degree, 4 degree and 2 degree). For GDP growth until 2022, we use additional country-specific information from the International Monetary Fund (IMF).

2.2 Energy and emissions data

Table SI2 shows which of the data is used and gives a reason why the data have or have not been used in the scenario implementation. The data is available for the countries and groups of countries listed above and for the following energy carriers: Oil, Coal, Natural gas, Nuclear, Biomass and waste, Hydro, Geothermal, Wind, Solar PV, Solar CSP, Ocean, Hydrogen, Other.

Table SI2 Data from IEA ETP scenarios

No	Data available in IEA EPT scenarios	Used here	Reason for using or not using the data
1	Total primary energy demand (PJ)	no	Induced indirectly in IO
2	Fuel input electricity and heat generation (PJ)	no	Induced indirectly in IO
3	Final energy demand (PJ)	no	Use of more detailed data 4 - 7
4	Final energy demand industry sector (PJ)	yes	Drives the energy use coefficients of the mining, manufacturing, and construction industries
5	Final energy demand non-energy use (PJ)	yes	Drives the energy use coefficients for non-energy use of energy carriers
6	Final energy demand transport sector (PJ)	yes	Drives the energy use coefficients of transport
7	Buildings, agriculture, fishing, non-specified other (PJ)	yes	Drives the energy use coefficients of the agriculture, fishing and service industries as well as energy use of final demand
8	Gross electricity generation (TWh)	yes	Used to calculate shares of electricity type use
9	Gross electricity capacity (GW)	yes	Used to calculate investment into electricity technologies
10	Direct CO_2 emissions (Mt CO_2)	yes	Drives the CO2 emission stressors
11	CO_2 captured (Mt CO_2)	no	Are not emitted

2.3 Concordance between the IEA EPT data and the EXIOBASE industry classification

Energy efficiency improvements are implemented according to the scenarios using relative growth rates in both the intermediate input coefficients and the environmental extensions. Final energy demand of the economy grows at a lower rate than the economy. The IEA EPT gives fuel specific final energy demand for electricity and heat generation, the industry sector, non-energy use, the transport sector, and buildings, agriculture fishing and non-specified other. We change the use coefficients related to the different fuels for all the industries. The concordance between the IEA EPT data and the EXIOBASE industry classification is displayed in Table SI3.

Table SI3 Concordance between the IEA EPT data and the EXIOBASE industry classification

IEA EPT final energy demand and CO_2 emissions data	**EXIOBASE industries** A full list of EXIOBASE industries can be found in SI9 of (Stadler et al., 2018)
Electricity and heat generation	[96:107]; % electricity
Industry sector	[20:95, 108:114]; % mining, manufacturing incl. energy services and construction
Transport sector	Transport fuels of all industries
Buildings, agriculture fishing and non-specified other	[1:19 , 115:163, all FD]; %Agriculture and fishing, buildings mainly refer to services and final demand

Figure SI3 shows how the model results compare to the scenario data. For most countries/regions, the expected decrease in CO_2 emissions is exactly what has been expected. The lower reduction in Brazil is due to the global increase in demand for biofuels and the constant trade structures, with a large part of the demand for crops for biofuels being satisfied by Brazil. For India, given the assumption of constant trade structures, the global demand for relatively energy-intense products remains directed at India. This is in particular driven by the demand for steel, where we do not model a change in the technology used (currently mainly emission-intense direct reduced iron in electric arc-furnaces).

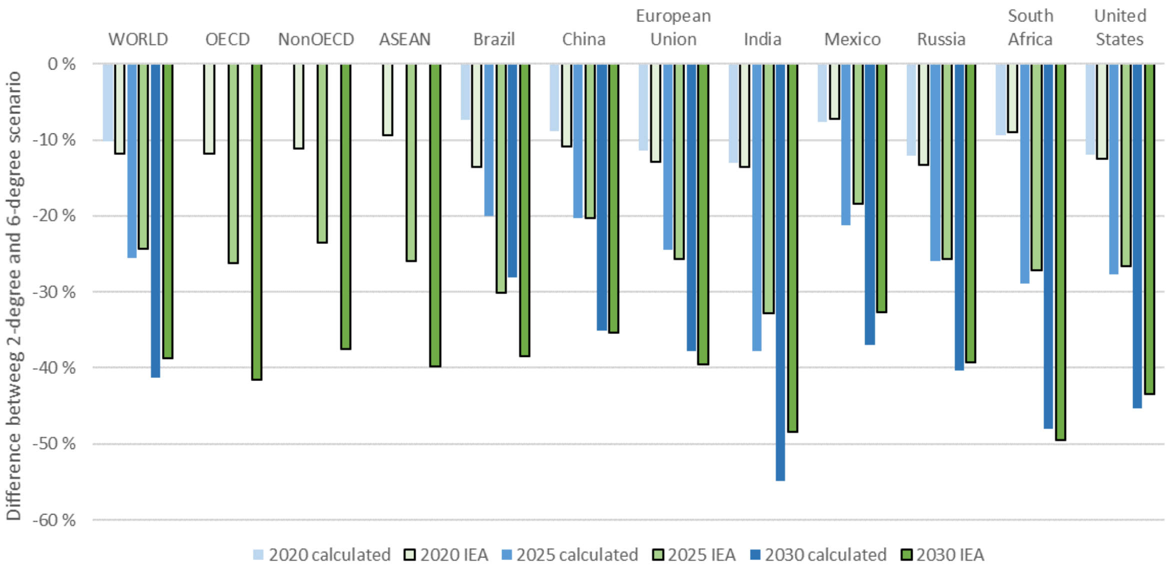

Figure SI3: Showing the deviation of the 2-degree from the 6-degree scenario based on IEA ETP 2015 and own calculations, showing that the reductions in our model in the 2-degree scenario compared to the 6-degree scenario are almost congruent with the differences in the IEA ETP.

3 EXIOBASE: fossil fuel and metal stressors

Table SI4 EXIOBASE: fossil fuel and metal stressors

	ID	Domestic Extraction Used	ID	Unused Domestic Extraction
Fossil fuels	724	Anthracite	1114	Anthracite
	725	Coking coal	1115	Coking coal
	726	Crude oil	1116	Crude oil
	727	Lignite/brown coal	1117	Lignite/brown coal
	728	Natural gas	1118	Natural gas
	729	Natural gas liquids	1119	Natural gas liquids
	730	Oil shale and oil sands		
	731	Other bituminous coal	1120	Other bituminous coal
	732	Other hydrocarbons		
	733	Peat	1121	Peat
	734	Sub-bituminous coal	1122	Sub-bituminous coal
Metal Ores	736	Bauxite and aluminium ores	1124	Bauxite and aluminium ores
	737	Copper ores	1125	Copper ores
	738	Gold ores	1126	Gold ores
	739	Iron ores	1127	Iron ores
	740	Lead ores	1128	Lead ores
	741	Nickel ores	1129	Nickel ores
	742	Other non-ferrous metal ores	1130	Other non-ferrous metal ores
	743	PGM ores	1131	PGM ores
	744	Silver ores	1132	Silver ores
	745	Tin ores	1133	Tin ores
	746	Uranium and thorium ores	1134	Uranium and thorium ores
	747	Zinc ores	1135	Zinc ores

4 References for the Supplementary Information

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