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Analysis

Pathways to a Resource-Efficient and Low-Carbon Europe☆

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ABSTRACT

Various environmental footprint concepts have already been developed and applied in sustainability research. However, these analyses tend to remain restricted to historical observation samples. At least in comparison with related research activities in other environmental policy domains (like, e.g., climate policy), it seems that applications of integrated assessment tools represent rather seldom exceptions within the resource policy domain. Our paper is, therefore, intended to strengthen the related evidence base. We present recent projections from the dynamic Multi-Region Input-Output (MRIO) simulation model GINFORS (Global Inter-Industry Forecasting System), which provide an outlook on global development trends until the year 2050. Our detailed material footprint and climate policy assessment indicates that a global agreement on a policy mix will allow a clear turnaround towards climate protection and a sustainable use of natural resources without deteriorating economic performance. If the EU decides unilaterally to lead the way, then this turnaround could also be achieved for the EU while the EU would also benefit economically from this pioneering role. A third pathway towards a resource efficient and low-carbon Europe quantifies the environmental and economic impacts of a strong transitional change induced by European citizens' commitments to far-reaching sufficiency objectives.

1. Introduction

Looking at twentieth century development patterns, economic historians have compiled broad scientific evidence of unprecedented growth in global per capita production activities in this period (see, e.g., Bolt and van Zanden, 2014, Maddison, 2001, De Long, 1998). Following Krausmann et al. (2009) and UNEP (2017), the quadruplication of global population levels over the twentieth century was accompanied by a 19–24 fold increase of global GDP. The implied rise of average global per capita GDP by a factor of about five to six was, however, unequally distributed across the world's regions. Referring to the upper left panel of Fig. 1, we can assert that traditional industrialised regions notably experienced lasting increases in per capita GDP within the last few decades. Several historical analyses have already documented that the metabolic profiles of such highly industrialised economies differ tremendously from those of developing economies (see, e.g., Schaffartzik et al., 2014a, Krausmann et al., 2008, Schandl and Schulz, 2002).

In the upper right panel of Fig. 1 the globally used resource extractions of the 1980–2013 period have been decomposed to material categories. With an average percentage increase of about 1.5% p.a., global biomass extractions seem to feature dampened growth dynamics within this observation sample. Yet, it is interesting to note that these most recent average growth rates equal the historical peak rates reported for this material category by Krausmann et al. (2009) for the post World War II period. Thus, compared to their individual growth histories, the extraction activities of other material categories have been rather slow-growing in the 1980s and 1990s but they exhibit some striking alterations with the beginning of the new millennium. The global use of fossil energy carriers grew by only about 1.1% p.a., ore extractions increased by about 2.5% p.a. and the extraction of non-metallic minerals grew by 2.7% p.a. in the first decades of the new century. For the years 2000 to 2013, these average yearly growth rates increased significantly by up to 2.9% (fossil fuels), 4.4% (ores) and 5.5% (non-metallic minerals).

The graph in the lower right panel of Fig. 1 plots time series of global material productivity (defined as the ratio of global GDP to global extractions used) per material category. Overall, global material productivity remained almost constant between 1980 and 2013 as increases until the year 2001 have been virtually offset by a subsequent decline (yellow line). Whereas biomass featured a persistent increase in global resource productivity since 1980, all of the other material categories feature stagnating (fossil energy carriers) or even declining productivity trends over the most recent past.

According to UNEP (2017), recent declines in global material productivity can be attributed to multinational outsourcing trends favouring production shifts from world regions with high material

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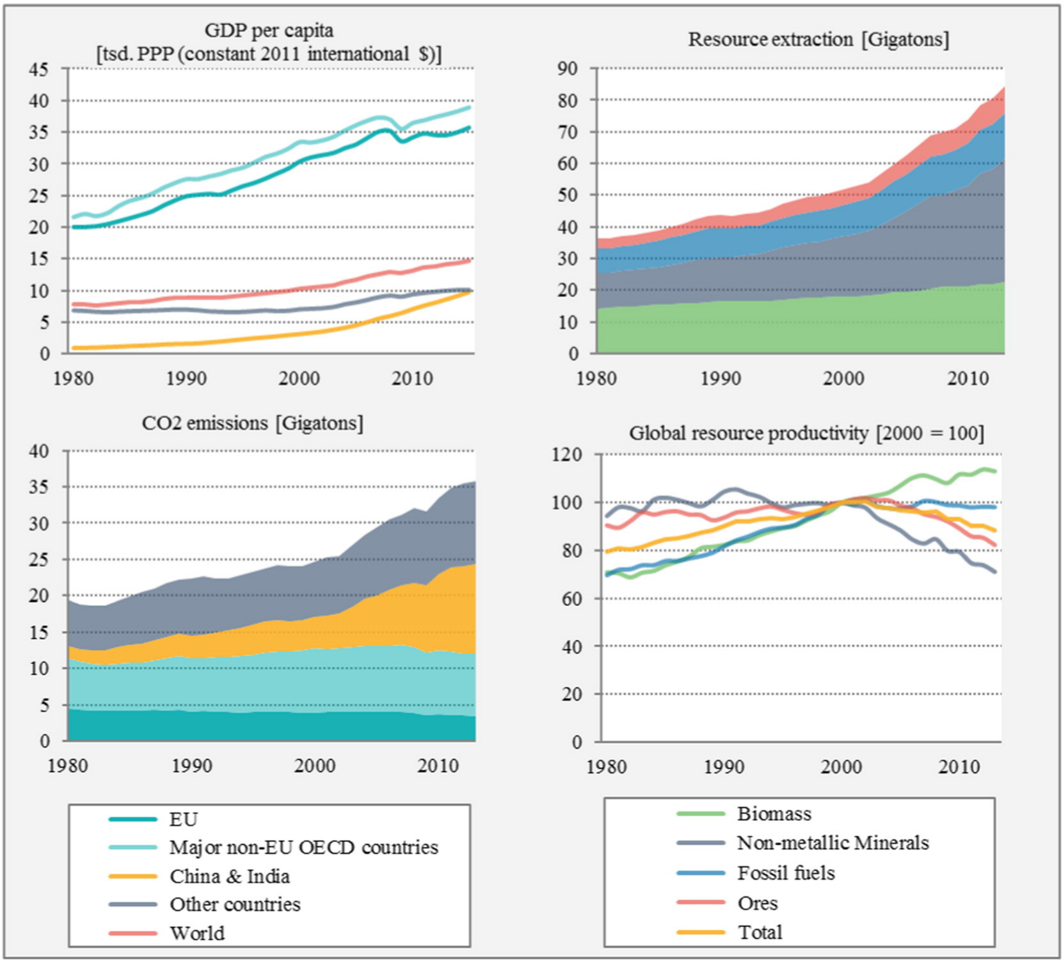

Fig. 1. Global development trends Own illustration.
Sources: World Bank (World Development Indicators), SERI and WU (Global Material Flows Database)

productivity to regions with lower material productivity. Between 1980 and the early 1990s, the average share of imported goods and service in global GDP rose only gradually from 15% to 17%. The surging globalisation trends of the following decade boosted this share to a level of 29% in 2008. After a significant decline following the global year 2009 recession, this level seems to have been re-established and maintained by the global economy until today.

From an upstream perspective, these salient globalisation trends tended to decouple national production activities from domestic resource extractions. Globally evolving supply chains advanced a spatial separation of resource extractions (and induced environmental pressures) from further processing activities, as well as a spatial separation of production activities from final demand across countries.[1] Therefore, the current raw material consumption levels of individual nations or regions cannot be reliably assessed by a sole inspection of domestic extraction figures.

Such assessments rather demand for applications of so-called “environmental footprint” concepts. Various footprint concepts have been developed and applied in sustainability research during the past two decades (see, e.g., Hoekstra and Wiedmann, 2014 for a literature review). Generally they might be understood as accounting routines which are intended to accumulate all direct and indirect environmental pressures which emerge from the global supply chains of regional consumption activities.

Methodologically, these concepts are usually based on life cycle assessment techniques or Environmentally Extended Input–Output (EEIO) frameworks (or hybrid combinations of both methodologies). Considering global material footprint analyses, it seems that applications of EEIO techniques to Multi Region Input–Output (MRIO) databases are widely recognised as the most advanced approaches for consumption-based analyses of global material flows. See, for example, Ivanova et al. (2016), Giljum et al. (2015), Wiedmann et al. (2015), Bruckner et al. (2012) or Wiebe et al. (2012) for relevant references in this regard.[2] These historical analyses have provided ample proof of developed countries offshoring the extraction activities induced by their material needs to emerging economies via international trade.

Furthermore, pronounced inequalities in regional material consumption patterns have been documented. See, for example, Bruckner et al. (2012), who (i.a.) found that per capita material footprint levels of OECD members differ from respective figures of non-OECD Member States (roughly) by a factor of about four.[3] These contemporary inequalities imply that a catching up of emerging economies to per capita raw material consumption levels of traditional Western industrialised

[1] Wiedmann et al. (2015), e.g., estimate that in 2008 more than 40% of total global resource extractions was associated with international trade flows.

[2] Exemplary applications of hybrid approaches were (i.a.) documented by Schaffartzik et al. (2014b), Schoer et al. (2012) or Weinzettel and Kovanda (2009).

[3] This approximate relation refers to OECD countries with high population density like, i.a., France, Germany, Italy, Japan, Korea and the United Kingdom. The applied footprint measure is given by the indicator RMC. See, for example, UNEP (2017), p. 40 for a brief overview of the key indicators in material flow analysis and their definitions.

nations would, ceteris paribus, drive global extraction activities to hardly conceivable levels. Simple rule of thumb calculus indicates that globally used extractions might level at around 180 billion tonnes in the year 2050 in such a scenario (Dittrich et al., 2012).[4] This boost in global extraction activities will inevitably increase social as well as environmental pressures (Bringezu, 2015). Given that diverse planetary boundaries for resource use and emissions might already have been crossed (Steffen et al., 2015; Rockström et al., 2009),[5] policy makers have thus identified the decoupling of affluence levels from resource consumption and environmental impacts as one of the key challenges of the twenty-first century in order to promote social equity by a fair sharing of resources among countries (see, e.g., UNEP, 2017, UNEP, 2014, UNEP, 2011a, European Commission, 2011).

Accordingly, we assert increasing necessities for comprehensive assessments of the prospects of different policy measures triggering economy-wide improvements in resource efficiency as well as the implied socio-economic effects of alternative transformation scenarios evolving from the application of these policy measures. However, until now, researchers do not seem to have acted on these necessities by extensively applying dynamic simulation models mapping the overall economic as well as environmental consequences of future decoupling scenarios in a systemic way. As a matter of fact, all of the previously mentioned applications of MRIO frameworks have remained limited to historical observation periods. Thus, they did neither provide guidance about the potential pathways towards increased resource efficiency nor were they intended to provide a dynamic mapping of the complex interdependencies and dynamic feedbacks between physical metabolic systems and macroeconomic developments. Apparently, integrated dynamic assessment frameworks are needed to fulfil this task. Referring to Hoekstra and Wiedmann (2014) we thus confirm that (at least with regards to the material consumption of national economies) “work remains to be done also in embedding EFA [environmental footprint assessment] in dynamic, integrated assessment models to better understand how complex processes of global change ultimately affect the natural environment and human development” (Hoekstra and Wiedmann, 2014, 1117).

Our paper is intended to advance this research assignment by presenting key scenario insights from the global simulation model GINFORS. We present some selected results from three alternative transformation pathways, which have been parametrised following the narrative of a “vision for a resource efficient Europe” (O'Brien et al., 2014). Our findings indicate (i.a.) that joint efforts of European Union Member States could suffice to achieve an absolute decoupling of the Member States' material footprint from economic growth, even if other world regions maintained traditional development patterns. However, strong European commitments in favour of an implementation of a comprehensive policy mix represent a basic requisite for this outcome.

The presentation of our results is structured as follows: Section 2 introduces our modelling framework, comments on distinguished methodological features with regards to the most recent related simulation studies and it provides a self-contained overview of the parametrised scenarios. Section 3 summarises our key results and completes these findings by conducting a more detailed discussion of the main underlying causalities. Section 4 concludes this paper.

2. Methods

2.1. GINFORS

The impacts of environmental policy issues can be assessed with various modelling tools. However, given that the impressive stock of generally available models evolved from distinguished research communities targeting different research questions,[6] any model prioritises selected thematic issues and features discrete individual advantages in doing so. This subsection provides a short overview of the essential features of GINFORS$_3$, which is the latest version of the global dynamic environmental economic MRIO model that has been developed over the last decade at GWS and is maintained by the authors of this paper.

GINFORS$_3$ is based on the WIOD dataset, a Multi-Regional Input-Output (MRIO) database with global coverage (Timmer et al., 2015; Dietzenbacher et al., 2013). It features a detailed mapping of 38 national economies and a rest of world region, and it facilitates simulation studies until the year 2050. Accounting for economic activities in 35 industries, which provide and demand 59 products and services, each simulation is soundly rooted on an endogenous mapping of detailed national economic structures. Primary income distributions result from value added while their re-distribution through taxes and subsidies, as well as the resulting dynamics of globalised trade patterns are endogenously determined.

Concerning monetary flows of funds, the modelling framework features an integrated modelling of several macroeconomic accounting schemes. The income effects resulting from (i.a.) diversified investment expenditures, induced efficiency improvements or sustained shifts in consumption patterns are explicitly modelled. Thereby, each simulation run also accounts for potential macroeconomic rebound effects (Sorrell and Dimitropoulos, 2008, Sorrell et al., 2009) in a variety of ways. This enables GINFORS$_3$ to expose multi-dimensional networks of economic drivers for environmental pressures with a high degree of socio-economic policy relevance.[7] See Wiedmann et al. (2007) for an in-depth account for the merits of early GINFORS versions in assessing the environmental impacts of international trade compared to other single- as well as multi-region Input–Output models. See Meyer and Ahlert (in this issue) for a more detailed discussion of the included causality structures of to the current model version.

Concerning environmental questions, the modelling of the economic system is consistently interlinked with subsystems that explain energy use, electricity production, air emissions and material extractions in physical terms. An early example of a GINFORS-based modelling study of the economic effects of climate mitigation measures has, for example, been published by Lutz and Meyer (2009). Compared with previous GINFORS versions (e.g. the version applied by Giljum et al., 2008) the most distinguished feature of GINFORS$_3$ is given by its recently completed integration of a Global Resource Accounting Module (GRAM, see, e.g., also Wiebe et al., 2012 for a methodological representation of the implied calculation steps). We are, therefore, able to provide projections of regional raw material demands that not only report about domestic extractions and direct material imports but also provide an account of all of the raw materials used in the production of the traded goods across their respective global supply chains. This model feature represents significant methodological progress—it embeds detailed footprint indicators that are well-known from historical MRIO analyses into a dynamic assessment framework. Current GINFORS applications, therefore, feature medium to long term projections of national material

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[4] In their kind of static spreadsheet extrapolation Dittrich et al. (2012) assume that all countries equal (on average) current per capita material consumption levels of OECD countries from 2030 on and world population will grow to a level of nine billion people by 2050.

[5] To avoid misinterpretation, we would like to note that (in total accordance with Bringezu, 2015) any assessment of the environmental impacts of resource extractions inevitably depends on value judgments. Therefore, “one may not assume fixed thresholds or tipping points beyond which whole regions would become devastated, rather than a continuous, steadily creeping change of the living environment through a growing number and extent of mining, quarrying, construction and disposal activities, so that the safe operating space might be determined rather by factors of societal acceptance of such a change rather than earth science modelling.” (Bringezu, 2015, 28).

[6] See, for example, the scoping study of Köhler et al. (2016) for a broad up-to-date overview of this point.

[7] See, e.g., Hirschnitz-Garbers et al. (2016) for an analytical illustration of interdependent complexities and feedback structures causing unsustainable resource use.

Table 1
Policy mixes in the target scenarios (main instruments).

<table>
<tr><th></th><th>Global Cooperation</th><th>EU Goes Ahead</th><th>Civil Society Leads</th></tr>
<tr><td>Climate policy</td><td>upstream carbon tax, regulation of the share of renewables, regulations and economic instruments favouring e-mobility & investment in energy efficiency of buildings</td><td rowspan="4">Difference to Global Cooperation:
In EU:
Economic instruments are designed, so that they do not endanger international competitiveness
• e.g. taxes on final demand instead of upstream taxes
• or direct compensation of taxes
In Non-EU:
• Moderate climate policy that allows to stay at 4 degree warming pathway
• No resource policy action</td><td rowspan="4">Difference to EU Goes Ahead:
In EU:
• Resource policy instruments : Instead of top down bottom up, changes driven by intrinsic motivation of consumers
• more leisure time, less total consumption
In Non-EU:
The same as in EU Goes Ahead</td></tr>
<tr><td>Decoupling of economic development and the use of minerals</td><td>regulation for recycling, upstream tax, public innovation fund for the material efficiency</td></tr>
<tr><td>Sustainable agricultural land and water use</td><td>regulation for water abstraction of agriculture, information programs to avoid food waste & to reduce yield gaps, tax on meat consumption</td></tr>
<tr><td>ETR</td><td>tax revenues are used for a reduction of taxes on goods and services with low carbon and resource contents</td></tr>
</table>

Own illustration.

footprint indicators, such Raw Material Consumption (RMC) or Raw Material Input (RMI, see again UNEP, 2017, p. 40 for a summarised definition).

2.2. References to Other Modelling-Approaches

UNEP (2017) notes that within the past few years, the macroeconomic effects of resource efficiency tended to be discussed almost exclusively with a focus on energy carries. According to their overview, salient exceptions are given by Meyer et al. (2015), Böhringer and Rutherford (2015), CE and BioIS (2014) and modelling performed for UNEP (2011b).

As a matter of fact, this article represents a summarised introduction to key findings from the Meyer et al.'s (2015) study. Thus, this reference does not require any further annotations. CE and BioIS (2014) applied the E3ME model, which is a dynamic macroeconometric model that was developed by Cambridge Econometrics following a modelling methodology that is generally comparable to the one underlying GINFORS$_3$. Yet, a weakness of CE and BioIS's (2014) study is given by the fact that the applied model version did not feature global coverage.

Böhringer and Rutherford (2015) calibrated their model on version 8 of the GTAP database. National datasets were aggregated to five major world regions by the model's authors. Thus, their modelling framework features a globally closed multi-region coverage. But as their projections are based on a static computable general equilibrium (CGE) modelling framework, they are only able to compare alternative (hypothetical) equilibria assumptions with each other. Hence, compared to applications of dynamic CGE models (e.g., the simulation work carried out with EXIOMOD 2.0 in the POLFREE project),[8] this approach cannot map any feasible pathways towards assumed equilibria outcomes. The modelling performed for UNEP (2011b) relies on Threshold 21, which is a dynamic model that integrates economic and physical modelling experiences in a system dynamics tradition. However, as industrial production structures and service supplies are not further disaggregated, biotic materials as well as further resources primarily related to agricultural developments (such as, i.a., water and land use) were focussed by this study. In the absence of any regional disaggregation, the model cannot account for the effects of international trade. Moreover, it does not account for the different objectives of individual agents. Thus, "the global model does not address explicitly the responsibilities or reactions of different actors, particularly governmental authorities" UNEP (2011b, 510).

New modelling activities closely related to the original UNEP (2017) approach have most recently been published by Hatfield-Dodds et al. (2017). Their study builds on a previous decoupling analysis which, however, had not been able to consider linkages and feedbacks from physical resource flows to macroeconomic interdependencies (Schandl et al., 2016). Hatfield-Dodds et al. (2017) are able to overcome this weakness by coupling the dynamics of 10 material flow categories to the input-output structure of GTEM, a global CGE model with 28 regions and 21 industry sectors. However, whereas the authors acknowledge that material footprints are certainly more appropriate indicators of regional material demands, their reporting about future global resource use remains limited to domestic extraction figures. Nevertheless, compared to the initial work of Schandl et al. (2016), the integration of physical material flow categories into economic accounting structures under explicit consideration of the economic drivers of and dynamic feedbacks evolving from global resource use represent important advances that enable the authors, i.a., to trace evolving economy-wide rebound effects over time. In this regard, Hatfield-Dodds et al. (2017) present a highly elaborated CGE-based modelling framework.

Given that fundamental methodological differences between CGE-based modelling approaches and econometrically estimated inter-industry models (like GINFORS$_3$ or E3ME) are well documented in the literature (see, e.g., Scrieciu et al., 2013 or Grassini, 2007), it would be highly interesting to compare the systemic responses of GINFORS$_3$ and GTEM to selected policy measures in a model comparison study. Meyer and Ahlert (in press, in this issue) have discussed some insights from comparable simulation exercises with the models GINFORS$_3$ and EXIOMOD 2.0. More extensive analyses covering a broader set of methodological issues and incorporating further simulation models remain for future research.

2.3. Scenario Settings

2.3.1. Scenario Implementation

Our parametrisation of the four future scenarios considered in this article has been guided by narrative scenarios prepared by Jäger and Schanes (2014) and comprehensive analytical work on policy mixes

[8] See Bulavskaya et al. (2016) for detailed methodological references to EXIOMOD 2.0 and a short overview of respective findings from the POLFREE project.

Table 2
Core simulation results.

		2010	Business as Usual	Global Cooperation	EU Goes Ahead	Civil Society Leads
			2050			
GDP (in trillions of 2010 US-$)	World	65.9	157.4	165.7	171.0	155.3
	EU	17.0	24.1	26.0	27.1	19.0
	Major non-EU OECD countries	26.3	43.7	46.2	47.4	45.4
	China & India	7.8	47.4	51.5	53.2	51.4
	Other countries	14.8	42.2	41.9	43.3	39.6
CO_2 emissions (in Gt)	World	33.5	53.2	21.2	38.9	37.2
	EU	3.7	2.6	1.1	1.0	1.1
	Major non-EU OECD countries	8.8	7.8	2.4	4.7	4.5
	China & India	10.5	24.3	9.2	17.9	17.2
	Other countries	10.6	18.4	8.5	15.3	14.4
Abiotic material footprint per capita (in tons)	World	7.6	10.4	4.4	9.9	9.7
	EU	13.0	12.9	4.7	6.0	7.2
	Major non-EU OECD countries	16.0	16.2	5.6	14.4	13.9
	China & India	8.9	18.7	7.1	19.3	18.8
	Other countries	3.7	4.4	2.6	4.1	4.0

Own illustration.

by Wilts et al. (2014). Table 1 summarises the key elements of the individual scenario settings.[9]

The parametrised scenarios illuminate different global development pathways until 2050. The "*Business-As-Usual*" scenario assumes that the EU strengthens its ETS system by implementing active supply side actions whereas all climate and resource policy measures in non-EU countries remain unaltered. In the "*Global Cooperation*" scenario, all countries co-operate through international agreements on harmonised economic and regulatory policy instruments to pursue decarbonisation and a resource-efficient global economy. In the "*EU Goes Ahead*" scenario, the EU pursues the development of a low-carbon, resource-efficient economy unilaterally, through strong EU-level economic and regulatory policy instruments instituted by Member States While the rest of the world fails to increase existing ambition. The latter is also the case in "*Civil Society Leads*", but now European citizens/consumers and businesses drive resource-efficiency through voluntary changes in preferences and behaviour. Qualitatively, this EU-sufficiency scenario appears, therefore, comparable to the exogenous resource demand shift measure that was simulated by Hatfield-Dodds et al. (2017).

For each of the three alternative future scenarios, an overall set of 20 to 30 policy instruments (in case of *Civil Society Leads*: voluntary behavioural changes) was identified and quantified.

All of the scenarios rely on the medium variant of the World Population Prospects as an exogenous specification for the demographic development for three age groups (0 to 14 years, 14 to 65 years, and over 65 years) in the different countries/regions of the world (United Nations, 2013). This means that the world's population will grow up to 9.5 billion people in 2050.

Exogenous specifications for the development of fossil fuel prices have been taken from the IEA Energy Technology Perspectives, 2015, which give price developments for coal, oil and gas up to 2050 for, respectively, 2 °C, 4 °C and 6 °C average global temperature increase. Given that the GINFORS simulation results for global CO_2-emissions (and demand for fossils) in the *Business-as-Usual* scenario more or less fit to a 6 °C pathway, those for the *EU Goes Ahead* and the *Civil Society Leads* scenarios approximately fit to a 4 °C pathway and those for the *Global Cooperation* scenario roughly fit a 2 °C pathway, the respective price trajectories are applied.

A reference for long run developments of world market prices for metal ores until 2050 has not been available. During the last 20 years, these prices (in constant US-Dollars) featured an average increase of 2.4% per year. Based on this information, the expectation is that ore contents in the deposits will further diminish whereas demand for virgin metal ores will further increase. Consequently, an annual growth rate of the real price for metal ores of 4% p.a. is assumed.

The scenario *Global Cooperation* features considerably weaker demand for virgin ores. Thus, the growth rate of the real world market price for ores declines linearly from 4% to 0% p.a. in this scenario.

Usually, all tax rates on income and wealth, on goods and services and on production as well as the rates for the contributions to social security as key fiscal policy parameters are assumed to stay constant in time. However, in case of severe public budget deficits, some automatic stabilisation procedures were applied in order to mimic internationally applied fiscal policy rules.

3. Results and Discussion

Our discussion of the results begins with key insights from the *Business As Usual* scenario (Section 3.1) and proceeds with an analysis of key impacts of the three parametrised transition scenarios (Section 3.2). Apart from aggregated findings concerning macroeconomic developments, CO_2 emissions and resource extractions, the impacts on sectoral value added and employment are also presented. (See Table 2.)

We would like to note that all of the results presented within this paper have been generated in a soft-linked simulation setup. Accounting for regional water and land availabilities and resultant thresholds of regional extraction activities for individual biomass categories, $GINFORS_3$ was linked to the global vegetation model LPJmL (Beringer et al., 2011) in all simulation runs. This enabled us to provide thorough accounts of the economy-wide impacts of the feedbacks arising from increased crop demand on crop supply and crop prices.[10] Due to space constraints, we decided not to represent any of the methodological details of the applied soft-link approach. Supplemental information is, of course, available upon request by the authors.

3.1. Results of the Business-As-Usual Scenario

3.1.1. Economic Growth

General indications of the long-run growth dynamics emerging within the *Business-as-Usual* scenario can be identified in Fig. 2. As can be seen, global GDP is expected to grow over the simulation period but it grows less dynamically than in the 20th century. For the period

[9] Individual parametrisation details of each scenario have been completely described by Meyer et al. (2015). Due to space constraints, we have decided not to recap these items within this article. Nevertheless, further parametrisation details are of course also available upon request by the authors.

[10] It should be mentioned that stand-alone applications of $GINFORS_3$ also feature dynamic projections of regional biomass demand. However, the soft-link with LPJmL enhanced our usual modelling capabilities by a very detailed mapping of corresponding supply side dynamics.

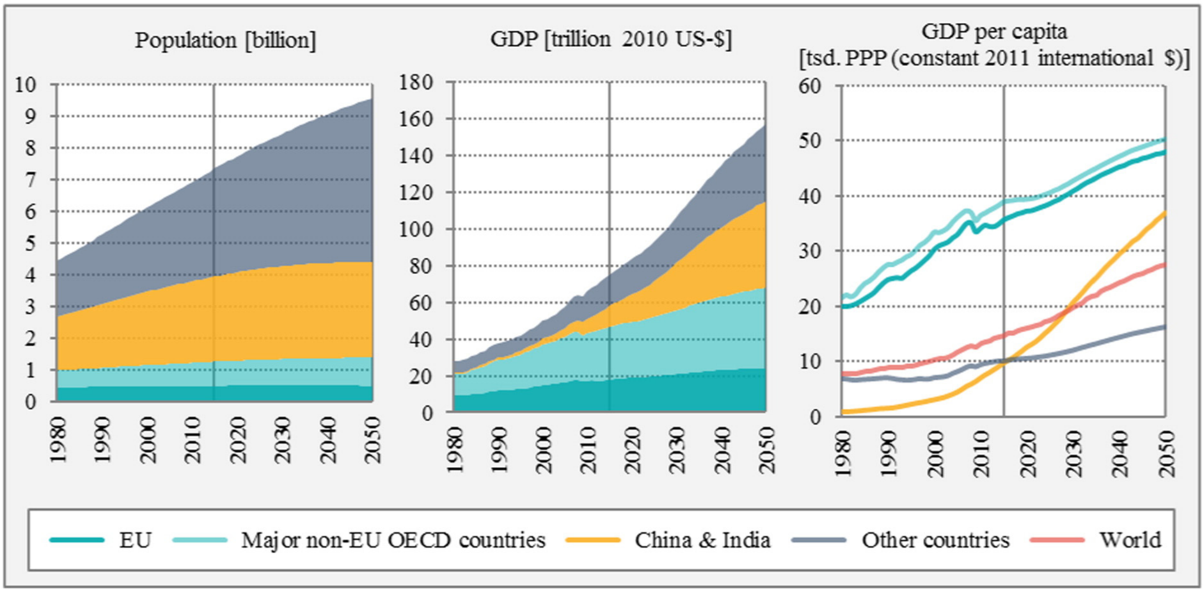

Fig. 2. Growth dynamics within the *Business-as-Usual* scenario. Own illustration.

up to 2050, global GDP is projected to increase by almost 110% compared to 2015, which corresponds to an average growth rate of 2.1% p.a.

Referring to the Shared Socioeconomic Pathways (SSP), our rather moderate growth projections of the *Business-as-Usual* scenario features narrative and quantitative characteristics comparable to SSP2 (Dellink et al., 2017; O'Neill et al., 2017). Likewise, the overall change in world economic activity reported from the *Existing Trends* projection by Hatfield-Dodds et al. (2017) (+116% from 2015 to 2050) happens to be fairly comparable to our endogenously derived *Business-as-Usual* result.

Fig. 3 illustrates that the common share of the industrialised countries' contributions to total global GDP is projected to decline significantly over the next few decades. The EU share is expected to decline from 23.8% in 2015 to 15.3% in 2050 and the respective share of the major non-EU OECD countries[11] is expected to decline from 38.6% to 27.8%.

These developments are generally driven by the respective population dynamics in individual world regions. Accordingly, India and China are projected to continue gaining shares in total global GDP, although with lower speed than in the past. While the contribution of China and India to global GDP increased almost by a factor of five between 1980 and 2015, a further doubling of the respective percentages figures over the next 35 years to 30.1% in 2050 is expected.

3.1.2. CO_2 Emissions

In the absence of ambitious climate policies, sustained economic growth (especially in China, India and the developing countries) is expected to outperform projected efficiency gains. As can be detected from Fig. 4, it is expected that global CO_2 emissions will further increase by 44% up to 53 Gt in 2050 (left graph), although the global average CO_2 intensity is projected to decline by more than 30% against 2015 (red time series in the right graph of Fig. 4). The strongest progress towards lower CO_2 intensities (of GDP) is projected for China and India. Nevertheless, their average per capita CO_2 emissions are expected to rise by more than 65% until 2050 (yellow time series in the mid-graph of Fig. 4). The contributions of China and India to global total CO_2 emissions will thereby further increase from 35.5% in 2015 to 45.8% in 2050 (see Fig. 5). At the same time, the EU's share is expected to decline to 4.9%, while the share of major non-EU OECD countries will be 14.7%.

Overall, global CO_2-emissions would accumulate over the 2011–2050 period to roughly 1800 Gt, which is far above any reference value for limiting global warming to 2 °C or less (Meinshausen et al., 2009). According to the IPCC (2014, p. 64), the remaining cumulative CO_2 emissions from 2011 onwards imply more than 66% probability of limiting global warming below 2 °C, which is in a range of 1000 Gt. This CO_2 budget will be completely depleted in the reference scenario until 2035 and any emission from that time on—and there is still plenty of them in the system—will cause an overshoot of global warming above the ceiling.

Referring to related research it seems that our endogenous *Business-as-Usual* projections for global CO_2 emissions are fairly comparable to the *Existing Trends* scenario of Hatfield-Dodds et al. (2017), which indicates a global increase in total CO_2 equivalents (CO_2e) by 41% from 2015 to 2050 and replicates RCP 6.0 values.[12]

3.1.3. Resource Extractions and Uses

3.1.3.1. Global Extractions. Our *Business-As-Usual* scenario features rather weak global extraction dynamics. Schandl et al. (2016) as well as Hatfield-Dodds et al. (2017) and UNEP (2017) each project total global material extractions to achieve a level of more than 180 Gt by 2050.[13] To a significant extent, the aggregated result in these studies seems to be driven by the extraction activities for non-metallic minerals increasing towards 100 Gt in 2050 (compared to 57 Gt in our *Business-As-Usual* scenario). According to WU Vienna,[14] China's and India's share of global resource extractions increased from 12.6% in 1980 up to 40.6% in 2013. Accordingly, current observable global extraction dynamics are

[11] That is: Australia, Canada, Japan, Korea, Mexico, Turkey, and the United States.

[12] The accordance of CO_2e-trajectories in the *Existing Trends* scenario of Hatfield-Dodds et al. (2017) with RCP 6.0 reference values has been enforced by the model builders by suitable adjustments of emission coefficients. Only short time ago on the same methodical basis, a much higher increase in global CO_2 emissions (+100% from 2010 to 2050) has been projected (see Schandl et al., 2016).

[13] This is notable as the modelling of material flows applied by Schandl et al. (2016) relied solely on technical and physical influences. Hatfield-Dodds et al. (2017), therefore, (with good cause) point out: "The research we present here extends our previous decoupling analysis [Schandl et al.] by integrating the material flows in the CGE model and enabling a thorough assessment of the rebound effect that results from resource efficiency improvements" (Hatfield-Dodds et al., 2017, 404).
Given that both studies also seem to vary considerably in their global GDP projections, with Hatfield-Dodds et al. (2017) assuming considerably weaker economic growth dynamics (aligned with social-economic pathway SSP2), it is thus astonishing that two different modelling frameworks generate fairly equal global extraction figures.

[14] WU Vienna: Global Material Flows Database. (www.materialflows.net)

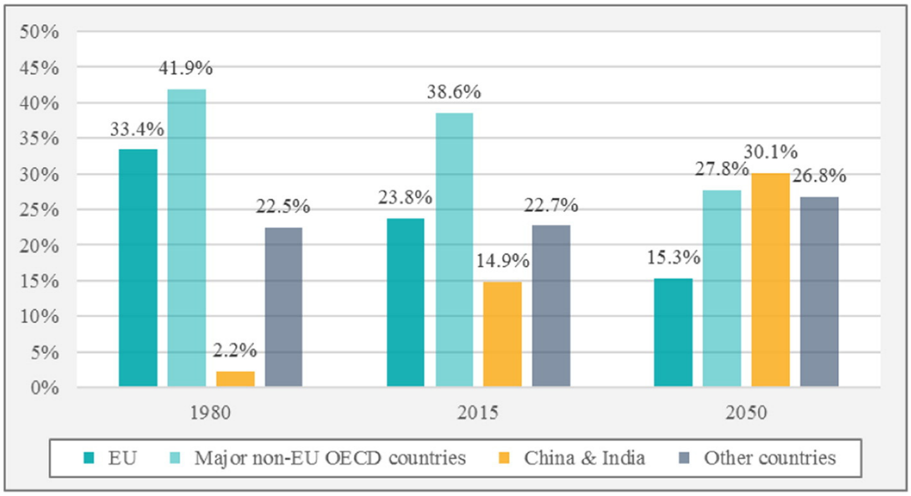

Fig. 3. Contributions to global GDP in the *Business-as-Usual* scenario. Own illustration.

fundamentally influenced by surging extractions in these world regions. China's extractions of non-metallic minerals, for example, represent about 50% of all respective contemporary global extraction activities. However, it seems doubtful to extrapolate the fast-increasing demands for non-metallic minerals of currently urbanising world regions into further accelerating demand patterns over the next decades.

Our projections are, thus, based on the hypothesis that once sufficient levels of buildings and infrastructure stocks have been established, accumulation patterns of currently urbanising countries converge to those of developed countries. (Also see Fishman et al., 2016 for a recent analysis of stochastic trends in international construction material extractions in this regard.) We, therefore, expect that also China's demand for non-metallic minerals will peak over the projection period, followed by a reduction due to national population developments. Our *Business-As-Usual* projection, therefore, features only slight increases of China's and India's overall share in global extraction activities to about 44% in 2050.

As can be seen in Fig. 6, the *Business-As-Usual* scenario nevertheless projects an ongoing increase of globally used resource extractions, with a total sum levelling about 125 Gt in 2050.

EU countries as well as the major non-EU OECD countries feature more or less stable extraction patterns over time. While for the non-metallic minerals up to 2050 a further increase by "only" 48% is projected, the respective value for ores is 159%.

3.1.3.2. Material Footprints. The previous subsection documented our *Business-As-Usual* projections for global material extractions. This subsection completes these figures with corresponding footprint assessments. We report our own estimation results for the indicator RMC. Due to provisional data limitations, our presentation of results remains restricted to abiotic material footprint calculations. The left-hand diagram in Fig. 7 illustrates that resource consumption in China and India as well as in other (predominantly emerging) countries is projected to induce lasting increases in abiotic material extractions until 2050. Compared to the considerable dynamics of the corresponding yellow and grey areas, the *Business-As-Usual* scenario implies rather constant abiotic material footprints in the case of the EU and major non-EU OECD countries.

Overall, similar qualitative findings arise with regards to per capita footprint assessments (mid-time series plot of Fig. 7). The most interesting findings are certainly given by the developments in China and India, which, according to our assessments, on the whole almost caught up to

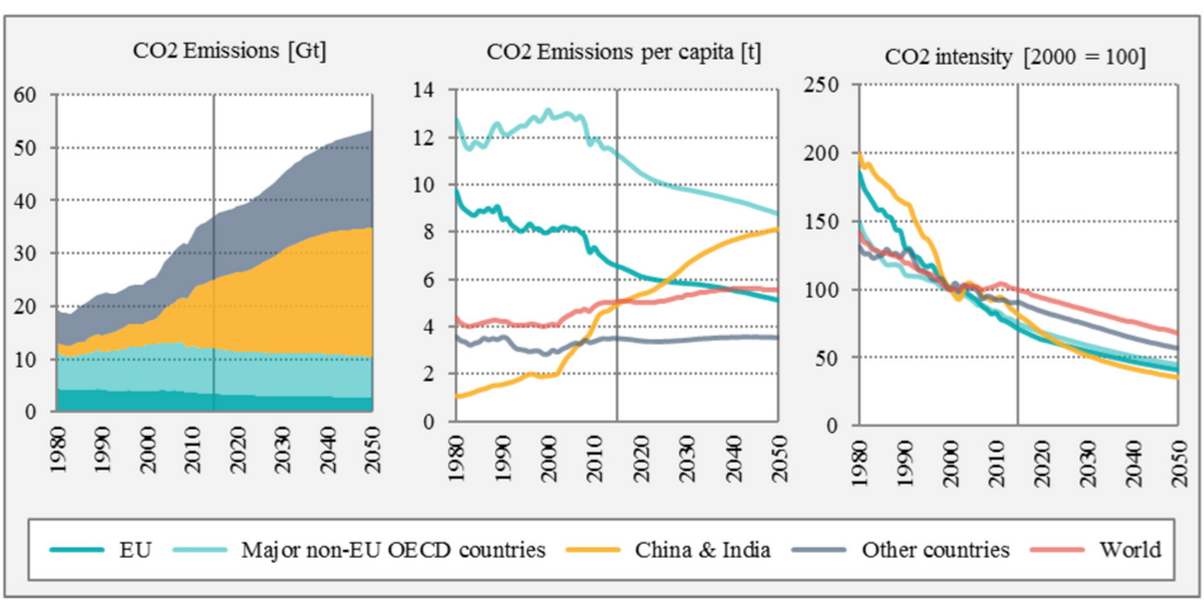

Fig. 4. Dynamics of CO_2 emissions within the *Business-as-Usual* scenario. Own illustration.

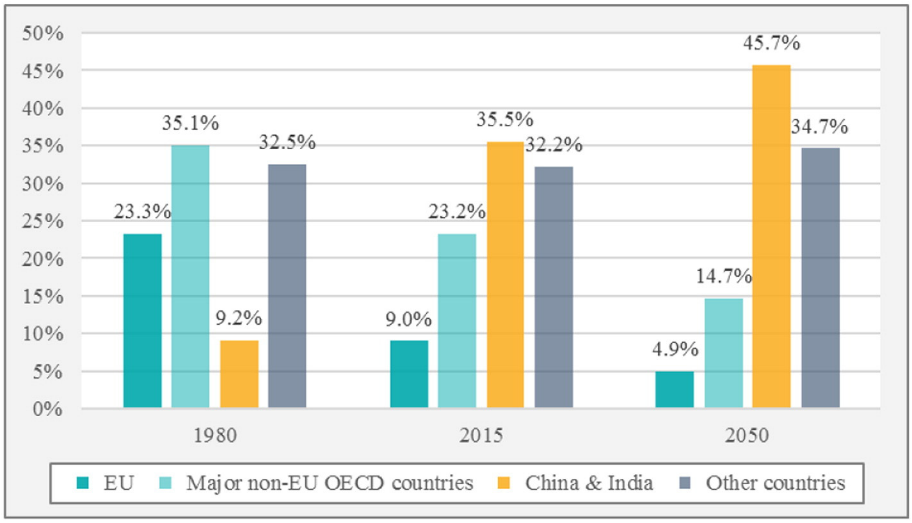

Fig. 5. Contributions to global CO_2 emissions in the *Business-as-Usual* scenario. Own illustration.

EU average per capita footprints in the recent past. Although our modelling foresees China and India becoming top performers with regards to abiotic material intensities (material footprint/GDP, see the right-hand time series plot in this Figure), an unparalleled further increase in per capita footprints is projected for these countries.

Following Bringezu (2015) worthwhile year 2050 RMC per capita target values might (under the imperative of an equal distribution of resource consumption among the world population) approximately range between 3 and 6 metric tons per persons. The upper bound of this assessment is based on the somewhat arbitrary objective to reduce annual global extraction activities to year 2000 levels by the year 2050. One might tend to assume that this target is rather moderate (see, e.g., Jacob et al., 2015). But in any case, it poses challenges to withdraw the most recently observed increases in globally used extractions and to simultaneously accomplish an equal distribution of regional per capita raw material consumption patterns across the globe within the next few decades.

Following straightforward rule of thumb calculus (considering average nutrition needs and assuming medium to high population growth), each world region would then have to strive for an abiotic material footprint of approximately 4 tons per capita (or rather less) if the global extraction activities in 2050 should not exceed their year 2000 benchmark values. Thus, although our baseline projection foresees a by far lower global extraction in 2050 than, for example, Hatfield-Dodds et al. (2017), these target values will be far exceeded. This applies for the global average as well as for most world regions (e.g., see the European case where the aforementioned benchmark is exceeded by a factor of more than three).

The EU as well as non-EU OECD countries have already featured higher abiotic material footprints compared to respective domestic extraction values. Thus, these regions prove to be substantial net importers of abiotic raw materials if the raw material equivalents along global supply chains are considered. A comparison of the green bars in Fig. 8 illustrates that—for example, in case of the EU—year 1995

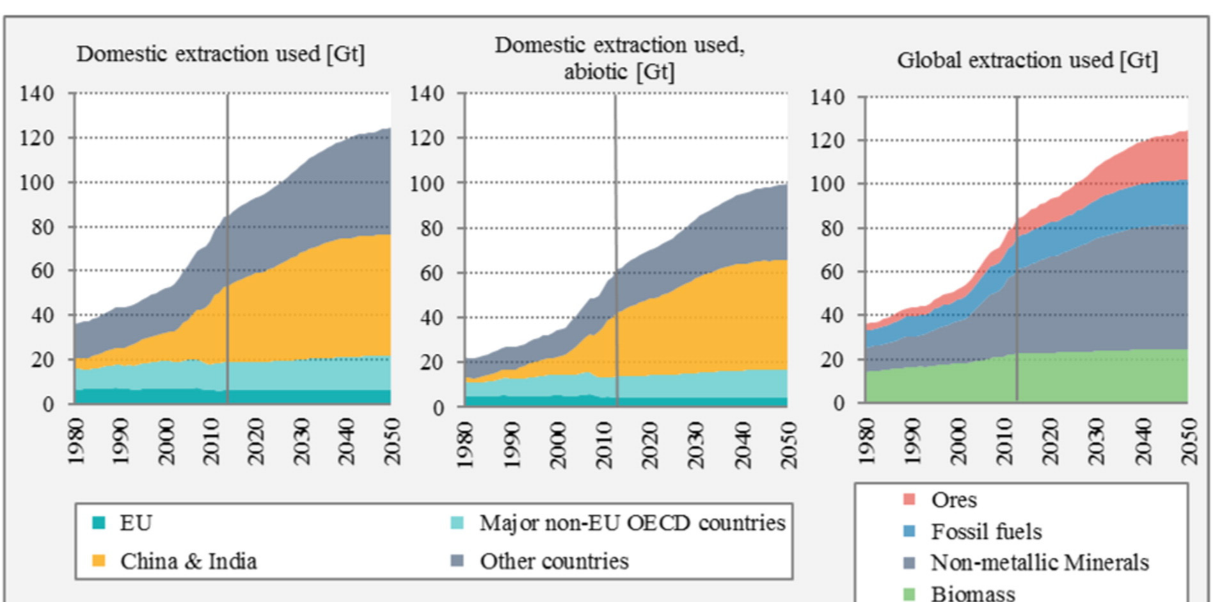

Fig. 6. Dynamics of resource extractions within the *Business-as-Usual* scenario. Own illustration.

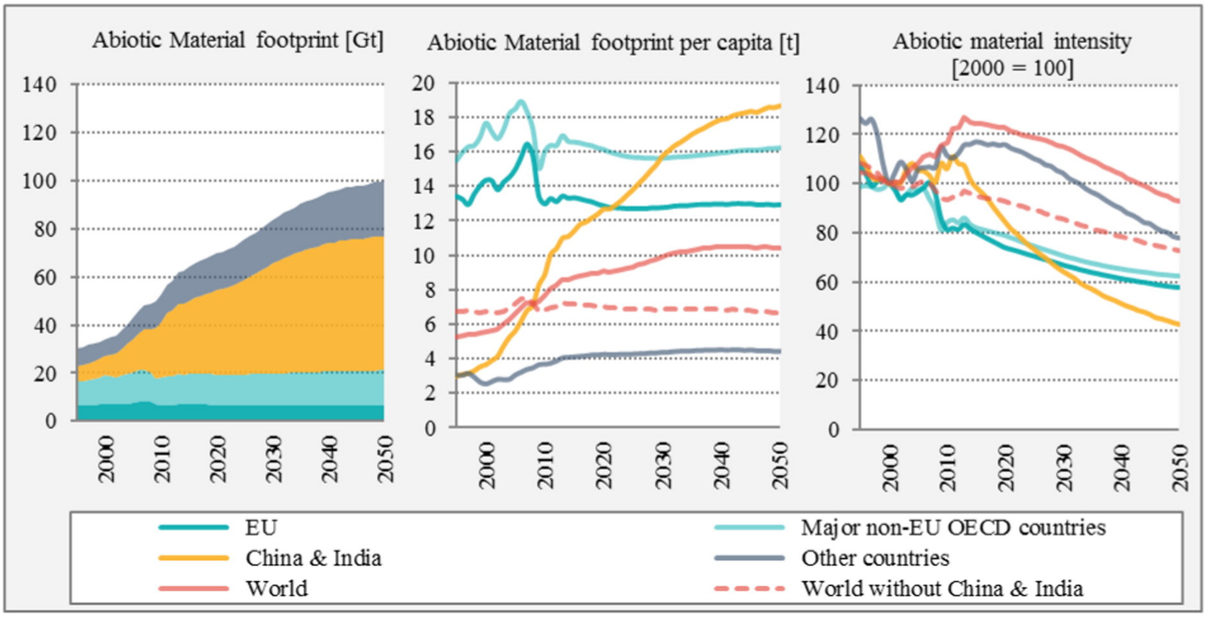

Fig. 7. Dynamics of abiotic material footprints within the *Business-as-Usual* scenario and contributions to global abiotic domestic extractions and material footprint in the *Business-as-Usual* scenario. Own illustration.

domestic extractions represented only 16% of all global abiotic resource extractions (left-hand diagram) whereas the abiotic material footprint of European Union Member States represented about 22% of all abiotic global extraction activities (right-hand diagram).

Our projections indicate that these characteristics tend to persist until 2050. However, whereas the observed gap between domestic extraction shares and respective footprint results tends to narrow in the case of non-EU OECD countries, our future outlook is in particular characterised by an increasing gap between China and India's footprint and respective domestic extraction activities. Thus, these regions are projected to emerge as substantial net importers of abiotic raw materials over the next few decades.

3.2. Results of the Alternative Scenarios

3.2.1. Economic Growth

Compared to the *Business-As-Usual* scenario, the *Global Cooperation* scenario, as well as the *EU Goes Ahead* scenario both feature significant medium- to long-term gains in global GDP (left-hand diagram of Fig. 9). The main causalities for these assessments can be outlined as follows: investment needs for new renewable energy technologies and grids, enhanced energy efficiency of buildings and extensive applications of recycling technologies promote the circular flow of income and induce economy-wide growth effects.

This extension of capital stocks does, ceteris paribus, imply a long run increase in capital costs, which is balanced by increased price dynamics. This has negative effects on GDP in later years but, coincidentally, a lowered material intensity of the global economy reduces costs and dampens price dynamics in manufacturing. From a global perspective, the net growth impacts are clearly positive in the *Global Cooperation* scenario (+5.2% in 2050). In the *EU Goes Ahead* scenario, the corresponding gains in global GDP are even higher (+8.6%). In this scenario, the EU represents the only world region which improves its resource efficiency rigorously. Thus, due to domestic cost advantages, EU exports are boosted whereas European import demand evolves rather weakly. Accordingly, European Union Member States realise first-

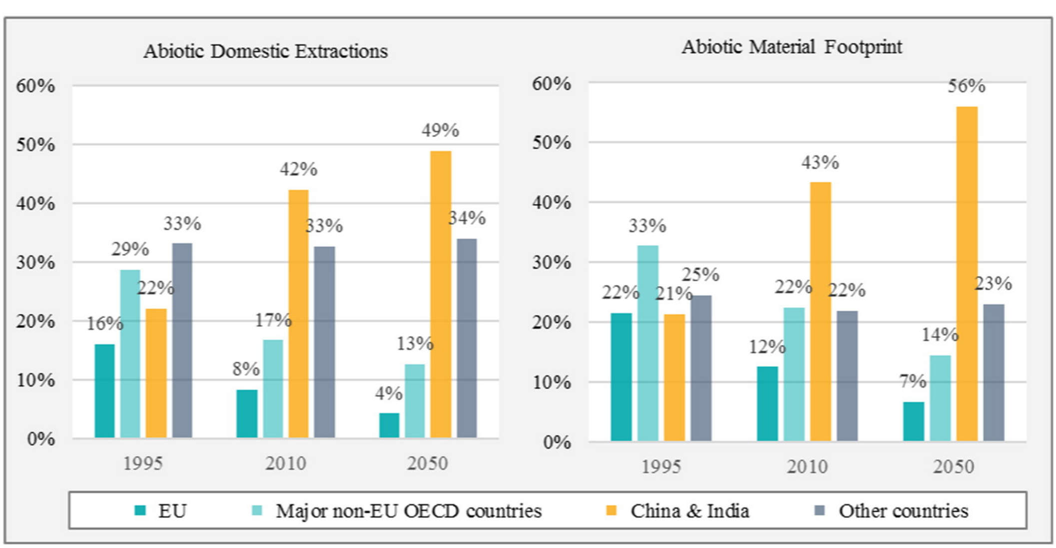

Fig. 8. Dynamics of domestic extractions and global material footprints in the *Business-as-Usual* scenario. Own illustration.

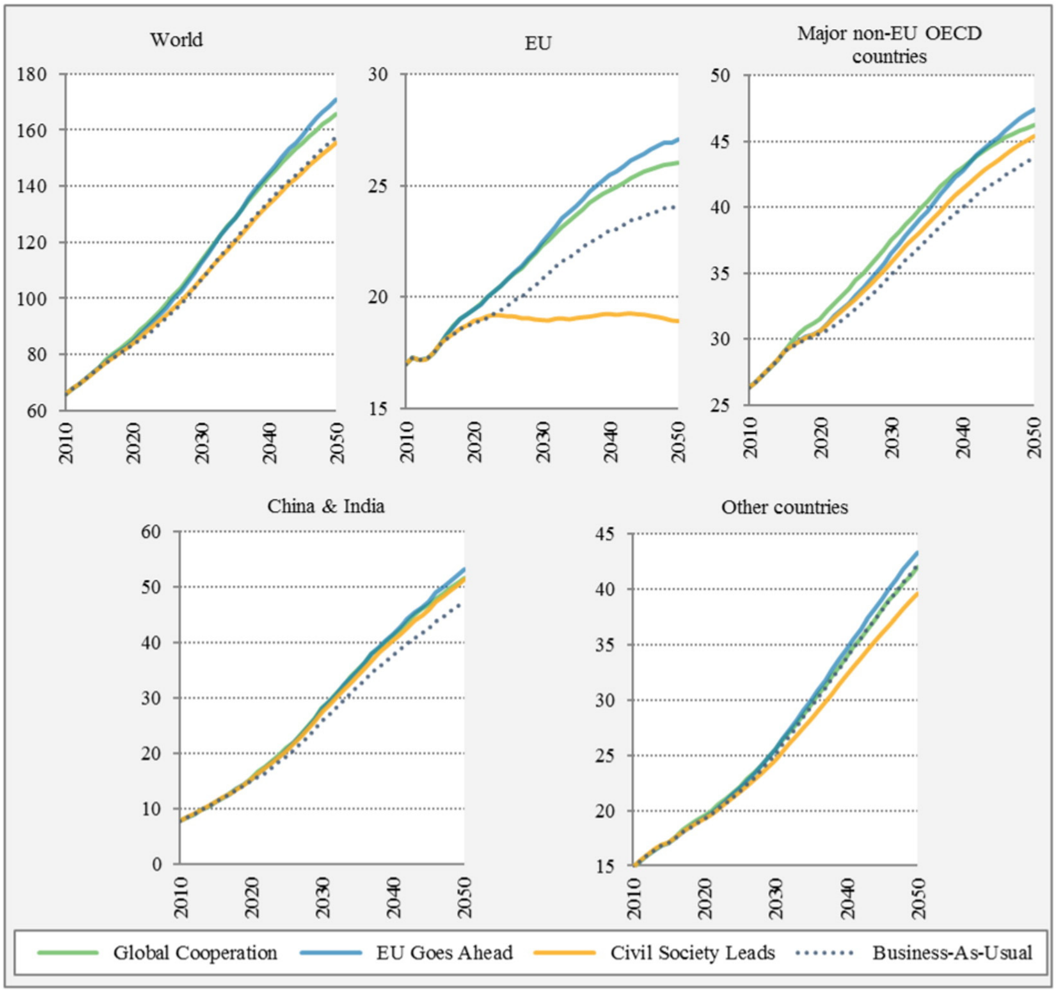

Fig. 9. Global and regional GDP results for transition pathways towards climate protection and resource efficiency [GDP in trillions of 2010 US-$]. Own illustration.

mover advantages: extra-EU trade surplus increases by roughly 22% compared to the *Business-As-Usual* scenario.

Only in the case of the *Civil Society Leads* scenario can a slight weakening of global GDP growth be identified. However, in this scenario, where the intrinsic motivation of European consumers, employees and firms is assumed to induce an all-embracing transition towards a sufficiency-oriented EU27-economy, GDP should definitely not be interpreted as an indicator of welfare.

For the EU, positive impacts on GDP (*Global Cooperation* +8% in 2050, *EU Goes Ahead* +12.3% in 2050) tend to outperform the respective global average figures. This result illustrates that, from a European perspective, negative economic impacts of the modelled scenarios emerge predominantly in relatively less distinguished economic sectors (such as mining and quarrying and other basic industries).

In the *Civil Society Leads* scenario, several intrinsically motivated activities change structures and volumes of consumption, reducing environmentally harmful commodities such as consumer durables, high-carbon, material-intensive transport and meat consumption. Furthermore, employees seek to reduce hours worked in the formal economy, inducing an increased share of part-time employment in order to have more time for the family, engagement in society, volunteering and leisure. The increased share of part time employment—hours worked per person are reduced by 20%—implies a reduction of total consumption. Households reduce their average propensity to consume until 2050 by 10%. This induces a negative multiplier/accelerator effect. International trade stabilises the fall of GDP driven by domestic demand. Extra-EU imports decrease together with domestic demand, while export demand from outside the EU is more or less unaffected by the behavioural changes of EU citizens. The trade surplus of the EU is 30% higher than in *Business-As-Usual*. The total effect on GDP is a reduction of 22% compared with the *Business-As-Usual* scenario, which means zero growth—the level of GDP in 2050 will be more or less the same as in 2015. The level of total consumption equals that of 1995.

For the group of major non-EU OECD countries,[15] as well as for China and India, all three alternative scenarios show positive GDP impacts. Only the other countries show neutral to slightly negative impacts on economic growth because there the negative impacts on mining and quarrying sectors and the directly following stages of production tend to outweigh the positive impacts on the other sectors.

3.2.2. CO_2 Emissions

Only the *Global Cooperation* simulation features an absolute reduction of global CO_2 emissions (see upper left diagram in Fig. 10). CO_2 emissions are projected to decrease by more than 42% from 2015 until 2050.[16] Compared to *Business-As-Usual*, the *EU Goes Ahead* and *Civil Society Leads* scenarios also feature substantial reductions of global CO_2-emissions. This observation points to the fact that, in contrast to our

[15] That is: Australia, Canada, Japan, Korea, Mexico, the United States and Turkey

[16] Comparing these results with Hatfield-Dodds et al. (2017), who assess respective CO_2e reductions in an order of 56% in their *Ambitious Climate* scenario, one should note that they aligned the implied abatement to match the respective RCP 2.6 figures. In contrast, our study was primarily intended to illustrate that a simultaneous absolute decoupling of CO_2 emissions as well as material use from economic development seems feasible and to explore alternative pathways to achieve such a decoupling from a European perspective. Thus, we refrained from further modelling works in order to align endogenous CO_2 trajectories to any external references.

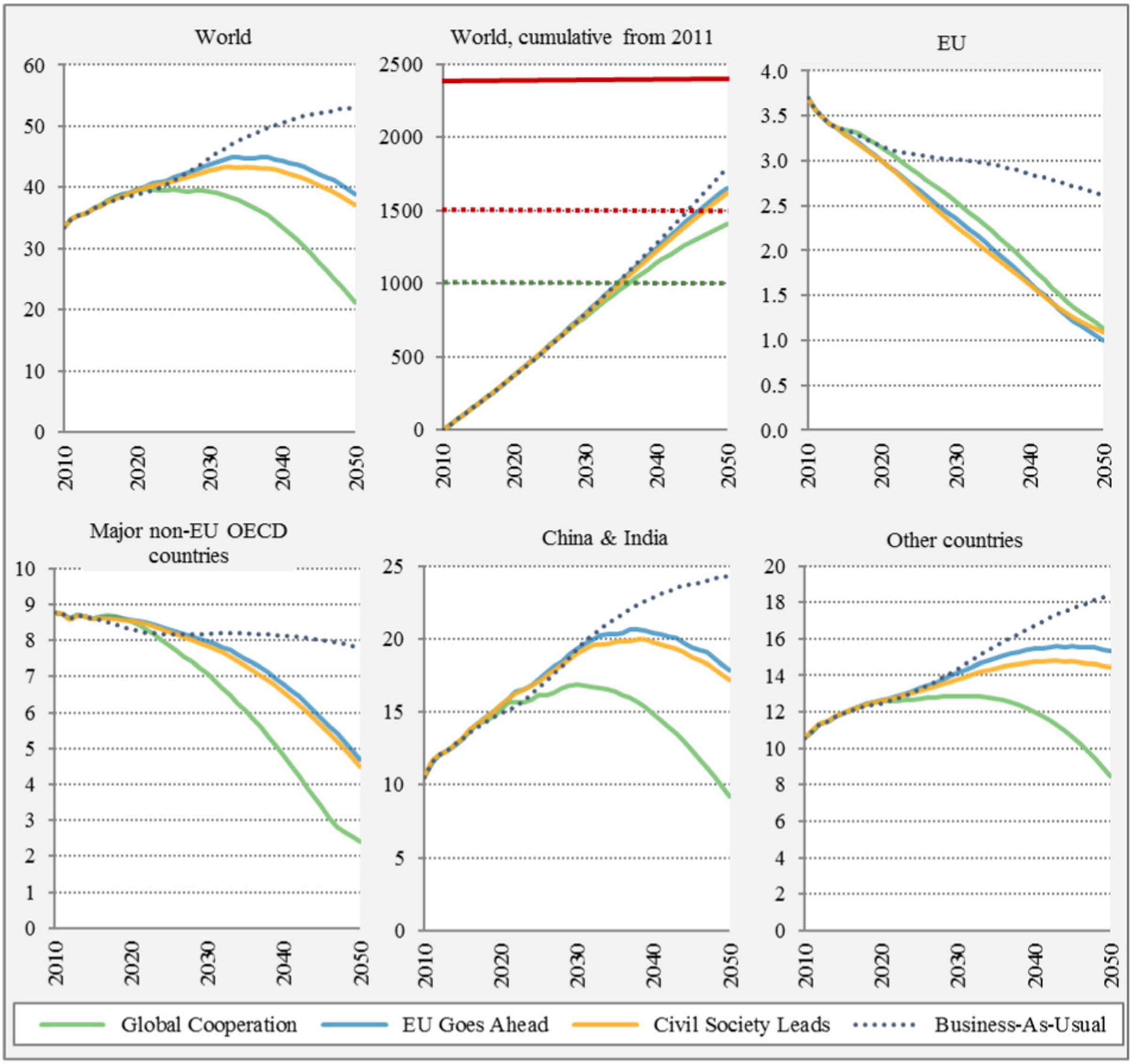

Fig. 10. Global and regional results for CO_2 Emissions for transition pathways towards climate protection and resource efficiency [in Gigatons]. Own illustration.

implied resource policy assumptions, these scenarios also imply (moderate) climate policy actions outside the EU, especially with regard to fostering renewable energies.

Prospective climate impacts implied by these CO_2 trajectories are visualised in the upper mid-diagram of Fig. 10. Based on IPCC (2014), the green-dotted straight line represents the threshold for cumulative CO_2 emissions in light of a 66% probability of limiting global warming below 2 °C. The red-dotted line represents a respective probability of 33% and the red line a more than 66% probability for a warming below 3 °C. Even in the *Global Cooperation* scenario, the cumulative global CO_2 emissions from 2011 will exceed the 66%, 2 °C benchmark well before 2050.

Domestic CO_2-emissions of the EU are reduced by about 72% against year 1990 levels in the *Global Cooperation* scenario (upper right diagram of Fig. 10). In the *EU Goes Ahead* scenario, these figures are further reduced (approximately 75% reduction against year 1990 levels). Recalling the comparably higher GDP growth rates of this scenario, this observation is quite remarkable. Especially as the main drivers of emissions reductions—renewables in electricity production, e-mobility and investment in energy efficiency in buildings—are driven by identical assumptions in both scenarios. However, the assumed world market price trajectories for fossil fuels feature stronger price dynamics in the *EU Goes Ahead* scenario. Thus, given that the purchasers' prices for fossil fuels are a bit higher in the *EU Goes Ahead* scenario than in *Global Cooperation*, intensified cost pressures do induce stronger global incentives to reduce CO_2-emissions in this scenario.

Whereas the 80% reduction target of the EU is slightly missed in all scenarios, intensified parametrisation work would certainly suffice to generate CO_2-trajectories featuring a (more than) 80% reduction of European domestic emissions.[17] Yet, referring to the rather general purpose of our paper, the presented findings are already very informative. Given that the three scenario trajectories do not feature significant deviations, European Union Member States have a good chance to meet their ambitious CO_2-targets with each pathway.

In the other regions (lower row of time series plots in Fig. 10), the resulting time series mainly represent the direct effects of varying international efforts in order to prevent climate change. Given that in this case only moderate international progress is assumed within *EU Goes Ahead* and *Civil Society Leads* scenarios, extra-EU regions do not feature sufficient (i.e., suitable for a 2° target) decoupling of CO_2-emissions from economic growth in both scenarios. Much stronger progress is observed within the *Global Cooperation* scenario with CO_2 emissions in the major

[17] For example, the modelling and parametrisation exercises in GINFORS until now do not consider further climate protection potentials from Power-to-X technologies or from carbon capture technologies.

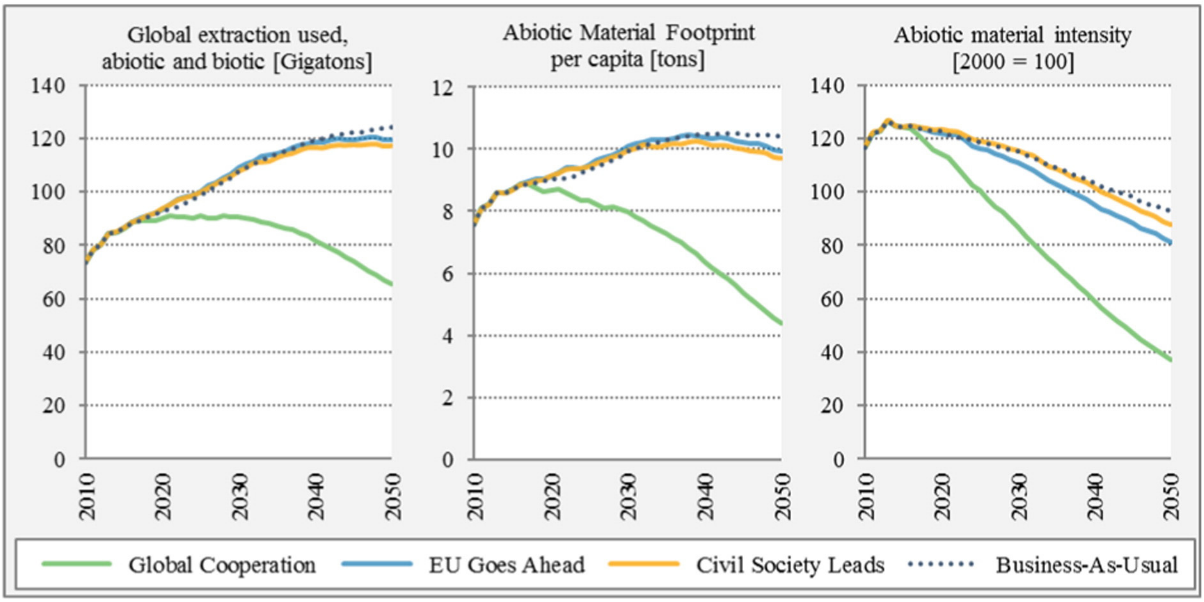

Fig. 11. Global results on raw material uses for transition pathways towards climate protection and resource efficiency. Own illustration.

non-EU OECD countries slumping to a level of about 2.4 Gt until 2050 and emissions of China & India being reduced to about 9.2 Gt.

3.2.3. Raw Material Uses

As regards global abiotic material uses, only the *Global Cooperation* scenario lends itself to an absolute decoupling from global economic growth (see Fig. 11). The observed reduction in global abiotic material uses until 2050 (which represents about one third of current year 2050 levels) is mainly driven by regulations concerning the recycling of metals and non-metallic mineral products, as well as by applied taxation patterns on the use of metals and non-metallic minerals.

The assumed global implementation of ambitious climate policy instruments also induces a reduction of global extractions of fossil energy carriers. This indicates that far-reaching absolute decoupling potentials on the global scale represent a distinguished outcome of our simulation studies.

As regards global resource use, Hatfield-Dodds et al. (2017), for example, do not illustrate any absolute decoupling potentials. This paper is not intended to provide a detailed comparison of various underlying mechanisms which might be considered accountable for these apparent differences. However, some suggestive ideas for future research in this regard might be summarised as follows: it would be very interesting to discuss more details of the rebound effects occurring in resource efficiency simulations. Hatfield-Dodds et al. (2017) note that, ceteris paribus, reduced input costs for natural resources provide incentives for increased materials demand. However, because their modelled innovation measures do actually decrease the prices of non-fossil resources only by less than 1% from the *Existing Trends* scenario in 2050, it seems rather counterintuitive to blame this effect for the weak impacts on global resource extractions (−1.3% deviation from *Existing Trends* scenario in 2050). Presumably, this effect should rather be assigned to the simulated increase of global economic activity.

Whether or not an increase of global affluence levels by almost 9% (year 2050 deviation from the *Existing Trends* scenario) might indeed suffice to compensate the assumed technical improvements almost entirely remains as an open question for future research.[18] Anyway, compared to the previous assessments of Schandl et al. (2016), this question explicitly demonstrates that the societal impacts of widespread transformations should not be assessed in the absence of any considerations of the feedback effects which might occur from the economy-wide implications of the analysed measures. In addition, Hatfield-Dodds et al. (2017) also model a resource extraction tax with tax revenues being transferred to households on a lump sum basis. Whereas this setup is commonly applied in tax reform simulations, our modelling experience suggests that the intended effects on resource consumption tend to be largely offset by this compensation scheme. Thus, our implementation of an upstream tax on metals, non-metallic minerals and carbon, and the accompanying termination of environmentally harmful subsidies on ores, coal, air and water transport services assumes that respective government surpluses are compensated by a reduction of other taxes.

Whereas the absolute decoupling potentials exposed by our simulations might be interpreted as a novel and rather promising contribution to the academic literature, we have to assert that the observed reduction in global abiotic material extractions does not imply a recurrence to global year 2000 extraction levels. Until 2050, average per capita extraction levels of abiotic resources are reduced to approximately 4.1 tons per capita in our *Global Cooperation* scenario. Concerning this issue, our results illustrate that the rather arbitrary reference to year 2000 raw material use essentially implies very ambitious target values. By referring to the global impacts of the alternative scenarios, it becomes evident that global material extractions cannot be significantly reduced by isolated variations of European demand patterns (*EU Goes Ahead* and *Civil Society Leads*).

For the EU, in the *Global Cooperation* scenario the per capita abiotic Material Footprint is reduced to 4.6 tons in 2050 (upper left graph in Fig. 12). In case of the *EU Goes Ahead* scenario, this indicator tends to fall to a level of 5.8 tons per capita. The main reason behind these simulation results is the lack of significant resource-efficiency improvements outside the EU. Given that substantial shares of domestic final demand are imported from non-EU countries, this hampers the opportunities of unilateral policies (i.e. taxes on final demand for material intensive products) that try to limit the material footprint.

The same applies in case of the *Civil Society Leads* scenario, which features the relative highest European abiotic raw material uses (7.0 tons in 2050). This value refers to the fact that the assumed changes in domestic demand do not induce significant effects on the supply side in favour of additional resource efficiency achievements.

With regards to the other regions shown in Fig. 12, we can identify that the assumed international policy measures of the *Global*

[18] One might also refer to their modelled Demand Shifts in this regard. These feature more or less comparable economic effects (on the global level) but much stronger price reductions. Yet, concerning resource extractions, considerably stronger reductions apply for this measure (−8.4% deviation from *Existing Trends* scenario in 2050).

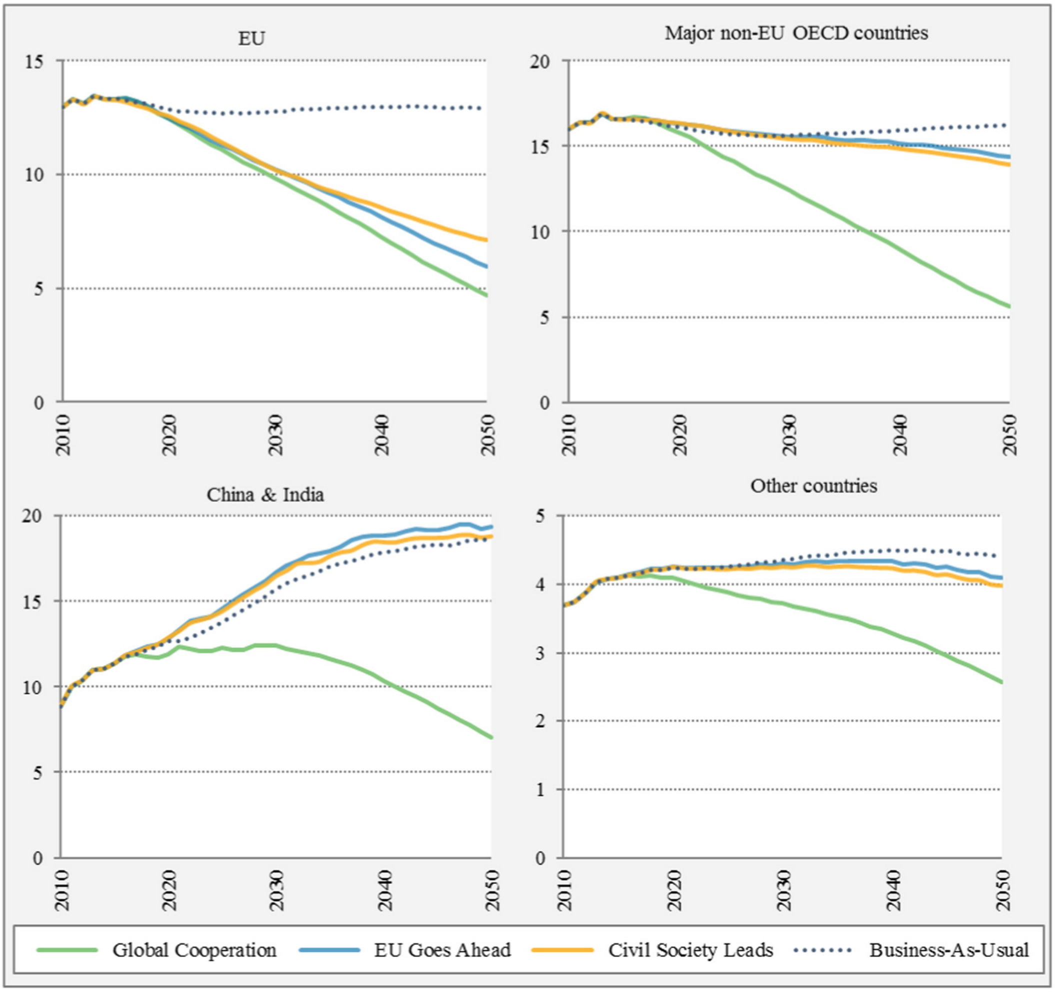

Fig. 12. Regional results on abiotic raw material uses for transition pathways towards climate protection and resource efficiency [abiotic material footprint in tons per capita]. Own illustration.

Cooperation scenario are indeed able to induce an absolute decoupling from economic growth around the world and regional disparities in material footprints can be decreased.

Diverse international responses emerge when extensive resource policy measures are solely applied within European regions. In China and India, income effects seem to dominate the overall impacts on their resource consumption. In the scenario *EU Goes Ahead* as well as in the *Civil Society Leads* scenario, the assessed GDP increases are accompanied by rising material footprints. This does not apply in case of the major non-EU OECD countries or for the other countries. This might be explained by the fact that considerably lower income effects are assessed for these regions.

3.2.4. Sectoral Impacts

This subsection provides deeper insights into sectoral developments across the simulated scenarios. For the sake of clarity, the original model results (which rest on a detailed mapping of 35 industries) have been aggregated to a 12 sector-scheme.[19] Fig. 13 illustrates the observed variations in industries' value added. Shown are year 2050 deviations of the relative contributions of the indicated sectors to overall macroeconomic value added (globally as well as for the EU region).

Apparently, the mining and quarrying industries, as well as other basic industries (such as food and beverages, refineries or the pulp and paper industry) suffer in all of the simulation runs. These industries are directly affected by diminished demand for their products in a resource efficient economy, which might also be causative for the observed decrease of trade services' (including the sales of motor vehicles) margins in all of the simulation runs. The same tends to apply in case of the agricultural sector (which, nevertheless, is projected to increase its relative share in overall value added within the *EU Goes Ahead* scenario) as well as in case of the non-metallic minerals and basic metals industries.

As beneficiaries of the transitions, we can identify the energy and heat suppliers as well as service sectors. As regards energy supply, these findings are especially triggered by strong increases in electricity production, which are mainly driven by the assumed diffusion of e-mobility technologies. The service sectors benefit from relative cost advantages as rigorous measures to improve resource efficiency essentially trigger production costs in the non-service industries.

Overall, no simulation run provides any indication of disruptive distortions of traditional economic structures. One important element which satisfies these characteristics seems to be given by the assumed recycling scheme with regards to environmental taxes: because all additional environmental tax revenues are given back to the economy, even remarkable high tax revenues do not cause strong structural side effects. This might be identified as a crucial issue promoting the feasibility of real world policy implementations.

At the same time, all three scenarios feature distinctive positive employment effects for the EU aggregate. See Fig. 14 in this regard, which merges the total difference of employed persons per sector within the

[19] Additional details are of course available upon request by the authors. See, for example, Meyer et al. (2013) for a detailed overview of the applied sector classifications.

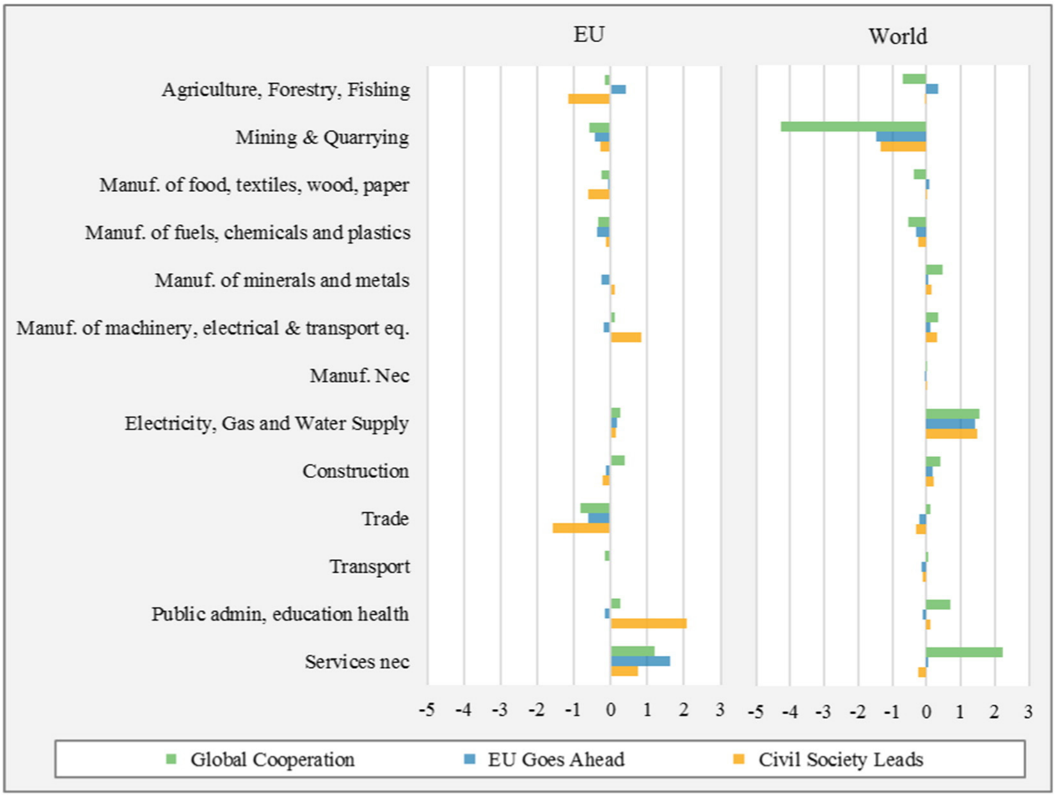

Fig. 13. Impacts of transition pathways towards climate protection and resource efficiency on sectoral shares in total value added [deviations from Business-As-Usual scenario in 2050 in percentage points]. Own illustration.

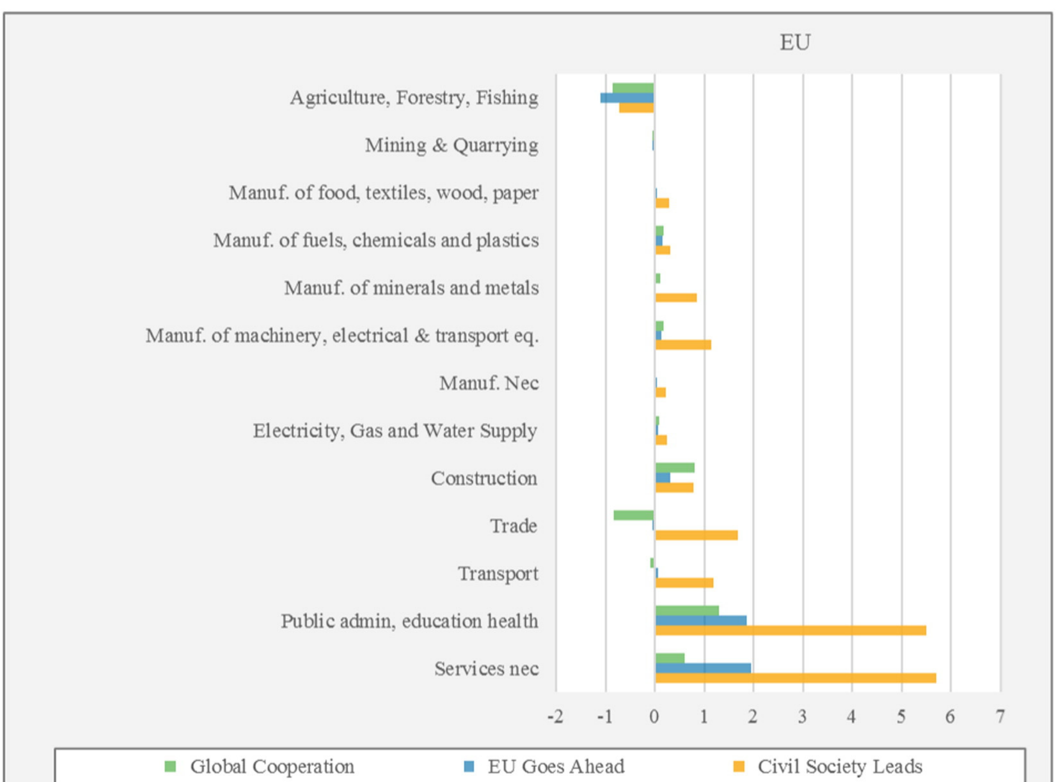

Fig. 14. Impacts of transition pathways towards climate protection and resource efficiency on sectoral employment [deviations from *Business-As-Usual* in 2050 in millions of persons engaged]. Own illustration.

EU for the year 2050. Generally, the European economy reduces its material intensity and raises the capital intensity of labour in all transition scenarios. This is accompanied by gains in employment and economic growth. In the *Global Cooperation* scenario, these differences amount to an overall employment increase of about 1.4 million people in the year 2050.

Notably, the positive labour market effects emerge considerably stronger in both remaining scenarios. Compared to the *Business-as-Usual* reference, the *EU Goes Ahead* Scenario raises overall EU27 employment roughly by 3.5 million jobs in 2050. As such, if global cooperation to achieve a resource-efficient, low-carbon economy is not forthcoming, then unilateral action at the EU level to pursue these goals is clearly an economically attractive position.

Furthermore, in the *Civil Society Leads* scenario—where employees are assumed to reduce hours worked in the formal economy, inducing an increased share of part-time employment in favour of enhanced time budgets for family issues, engagement in society, volunteering or leisure time—the hours worked per person are reduced by 20%. About 17 million new (part time) jobs will be created compared to the *Business-As-Usual* scenario, which represents a rise by more than 9%. This feature is caused by a reduction of labour productivity that dampens wage dynamics, so that the overall effect on jobs in the EU is larger than expected by simple ceteris paribus assessments.

4. Conclusions and Outlook on Further Research

The scenario projections presented in this paper rest on an established multi-regional dynamic simulation framework that features a systemic account for international socio-economic rebound effects induced by regional or global economy-wide transformative actions. See, for example, Giljum et al. (2008) or Lutz and Meyer (2009) for previous model applications in this tradition.

Miscellaneous global environmental challenges might be addressed. In this regard, our analysis merges insights which tended to be discussed in isolated policy domains before. According to our results, the assumed world population growth to approximately 9.5 billion people will be accompanied by persistent economic growth in rapidly emerging world regions. Western industrialised regions such as the European Union and further G7 Members are in parallel expected to experience a weakening of economic growth which, due to rising unemployment rates and aging population patterns, also tend to challenge established social security arrangements. Simple economic reasoning, therefore, calls essentially on traditionally industrialised world regions to question established preferences patterns, ensuing production structures and resulting income distributions. Yet, our results indicate that (i. a.) the percentage growth in real per capita GDP of India and China will on average exceed the respective growth rates of European Union Member States by a factor of approximately eight. Consequently, it does not seem very likely that traditional OECD countries could improve their economic perspectives significantly through partial modifications of traditional economic structures initiating within isolated policy domains. Our *Business As Usual* projections indicate a continuous surge in global environmental pressures (CO_2-emissions rise by almost 44% between 2015 and 2050, abiotic extractions are raised by more than 54%). Therefore, we advocate for a systemic approach that integrates comprehensive policy measures from the climate as well as the resource policy domain under thorough consideration of mutual socio-economic interdependencies across sectors and multi-national supply chains.

Our simulation of a comprehensive policy embracing fiscal (like, i.a., an upstream carbon tax, an upstream tax on metal ores and non-metallic minerals and the general termination of subsidies on air and water transport services), regulative (like, i.a., mandatory recycling quotas, binding emission standards in the approval of new cars and obligatory shares for renewable energy carriers in electricity production) and information instruments demonstrates that a synergetic interplay of resource efficiency measures and abatement polices might achieve an essential reduction of global CO_2-emissions and globally used extractions while stimulating global economic activity. Moreover, our simulations indicate that European Union Member States would economically benefit from first mover advantages if these measures were initially implemented in Europe. Given that Europe would also be able to significantly reduce domestic environmental pressures in this *EU Goes Ahead* scenario, we cannot identify any reasons why Europe should wait for the formation of global agreements. The desired achievement of ambitious global environmental targets certainly demands for global actions but there are good reasons to assume that other world regions will follow once when the economic benefits of a transformation towards low-carbon and resource efficient societies have been approved by European Union Member States.

It is self-evident that in absence of global actions, resource efficiency as well as abatement policies can be regionally implemented. However, in consideration of environmental targets, our simulations illustrate that both fields of action inevitably demand for global action. Compared to year 2050 *Business As Usual* projections, only the *Global Cooperation* scenario features (almost) adequate reductions in environmental pressures. We do not doubt that further research on prospective integration of additional instruments into the policy mix as well as continued simulation work with reparametrised policy settings on augmented modelling frameworks might be able to indicate additional decoupling potentials for each simulated scenario. Nevertheless, we are convinced that only global efforts will enable humanity to accomplish the environmental challenges that have been discussed in our study. Hence, it would be highly preferable if European Union Member States started enhanced collaborative action now.

Apart from these policy lessons, we would like to conclude with some methodological annotations. Only a couple of studies have previously assessed prospective global evolution pathways of resource use and CO_2-emissions by applications of fully integrated dynamic macroeconomic multi-region modelling frameworks. Accordingly, compared to the vast literature on the effects of isolated abatement measures in climate policy studies, scientific evidence in light of the linkages between natural resources and climate appears rather narrow today. Our simulation results provide indications in favour of the hypothesis that increased resource efficiency promotes the achievement of greenhouse gas abatement targets. Future research activities should naturally intend to deepen the respective evidence base. This might, for example, be achieved by application of simulation frameworks that link dynamic economy-wide projections (provided by models like $GINFORS_3$) with bottom-up information from various partial equilibrium models.

Given that only few research teams from different continents are currently conducting comparable scientific studies, it would be beneficial if regular exchange of relevant information between the respective modelling teams would consolidate a common knowledge base. See, for example, our discussion of the apparent uncertainties concerning the expectable amounts of future global extraction activities in this regard. UNEP (2017) assumes that a *Business-As-Usual* development will boost globally used abiotic resource extraction to level above 140 billion tonnes in 2050. Whereas this figure has also been derived from an elaborated modelling framework under global economic growth perspectives that are fairly comparable to our *Business-As-Usual* projection; however, our *Business-As-Usual* projection implies noticeably lesser abiotic resource extractions in 2050 (90 billion tonnes).

From a scientific perspective, it is highly interesting to discuss which details of the respective modelling frameworks might be accountable for this discrepancy in model outcomes. From a policy perspective, it seems rather crucial to figure these details out at short notice. Global institutions might, therefore, be well advised to advance these discussions by conducting extensive model comparison studies that enable policy makers to better understand which key real world features have been implied and the extent of the respective model parametrisations.

Furthermore, it is recommended that the following issues should be thoroughly discussed within a model comparison study:

- Although the availability and quality of historical data improved significantly in the recent past, we are still far from a perfectly standardised global MRIO dataset that is steadily updated. As a matter of principle, any serious modelling attempt to the international resource-climate nexus essentially requires up-to-date datasets that map historical developments in a reliable and globally comparable manner. Therefore, we call for sustained international efforts in favour of regular advancements with regards to publicly available MRIO datasets.
- This article demonstrates (i.a.) our abilities to assess the historical as well as future global material demand of individual economies by means of material footprint indicators. Our discussion of the *Business-as-Usual* scenario results has already indicated that this feature exceeds usual state of the art assessments of national material consumption developments. Indeed, although national statistical offices do not usually provide regular material footprint reports, this would be desirable because it would provide national governments with a reliable information base for monitoring and further developing their resource policy measures.
- Whereas our discussion of the developments in international resource use focussed on the RMC indicator, we doubt that the analysis of a single headline indicator might afford the thorough monitoring of resource policy advancements. Consequently, indicators for raw material use should also be accompanied by indicators for raw material inputs. Furthermore, other resource categories also have to be assessed by indicators that monitor, i.a., land and water use issues.

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