MITIGATION STRATEGIES TO ACHIEVE SUSTAINABLE DEVELOPMENT

Insights from the Carbon Footprint of Manufactured Capital

Master Thesis – Master of Science in Industrial Ecology (MSc), Leiden University & TU Delft

By Tinia De Bruycker (s3006727)

Under the supervision of Dr. Ranran Wang & Dr. Paul Behrens, Institute of Environmental Sciences (CML), Leiden University

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BRICS	Brazil, Russia, India, China, and South Africa
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DE	Developed economies
GHG	Greenhouse gas
GVA	Gross value added
HDI	Human Development Index
LDE	Less developed economies
LEF	Legacy Environmental Footprints
RCB	Remaining Carbon Budget
RoW	Rest of the World
SDGs	Sustainable Development Goals
UNDP	United Nations Development Programme
USA	United States of America

Abstract

In the spirit of equity, all humans should be entitled to a life congruous with a very high level of well-being. The development needed to achieve this would however heavily rely on manufactured assets, the production of which negatively impacts the climate system. Both efficiency- and sufficiency-based strategies have been put forward as solutions to reduce greenhouse gas remissions. Assessing their respective and combined effectiveness in supporting the realization of a fair and sustainable future is essential to guide future policy-making. Here I show that combining both would minimize the risk of a global warming beyond 1.5-2˚C while allowing developing regions, particularly Africa and Asia, to sufficiently raise the well-being of their citizens. Comparing different effort-sharing approaches, I further show that this sustainable development can be supported in international climate negotiations by adopting the Human Development Index (HDI) as a proxy for equitably allocating the remaining carbon budget (RCB). This supports research advocating for equating development with human well-being, rather than economic growth, and thus the introduction of demand-side interventions to reduce emissions. The ensuing discussion also points to need to strategically invest in assets in order to prevent unsustainable lock-ins and additional stranded assets.

Keywords: sustainable development, mitigation, equity, effort-sharing approaches, manufactured capital

Introduction

In the past decades, sustainable development, defined as meeting present needs without jeopardizing future generations (1), has grown to become one of the most prevalent topics on the international community's agenda, notably with the establishment of the Sustainable Development Goals (SDGs) (2). The traditional equating of development itself with economic growth has faced criticism for its narrow focus and lack of quality considerations (3). Although economic growth is still included as one of the SDGs, a more holistic alternative measure for development has lately been proposed: human well-being, assessed through one's happiness and the realization of one's capabilities within society (4, 5).

Yet, all forms of development rely on different types of capital stocks (3) and emphasize the importance of maintaining those stocks over time to achieve sustainable development (6). Strong sustainability further cautions that critical natural stocks, such as the climate system, cannot be replaced by manufactured capital (6). Manufactured stock (i.e., structures, machinery, transport equipment, and other man-made assets) is however pivotal in the achievement of sustainable development, with it influencing more than 70% of the SDG targets (7), such as those relating to healthcare, education, sanitation, energy access, and economic activities. As the stock of manufactured assets increases to support economic growth and human well-being, so can its negative impacts on natural capital (6, 8–10).

The significant environmental impacts of economic growth have been widely recognized, with it being the main driver behind the increase of greenhouse gas (GHG) emissions in particular (11, 12). Moreover, 44% of emission growth between 1995 and 2008 came from changes in emerging countries alone (13). Looking at the risks from further development, emerging countries, with their strong economic growth, face the strongest emission growth rate (14). A similar pattern of increasing GHG emissions caused by the rise in human well-being in developing countries has also been recognized (15). Without climate mitigation actions, this trend can be expected to continue in the future, seeing as a large amount of the global population still remains under the poverty line and well-being thresholds (16, 17).

Research on the environmental impacts of manufactured capital in particular has been growing. Recently, a new measure providing a comprehensive overview of those caused by the production of manufactured assets, the legacy environmental footprints (LEF), has been developed. Results from this footprint show a growth in impacts, with a gap between developed and less-developed regions that remains or even increases (18). Other research emphasizes the central position of manufactured capital in the production-consumption system and recognizes that both its production and usage patterns are crucial to the sustainability of our society and to the amount of global warming it will experience (7, 8, 19–22). Studies further point to the expected increase in GHG emissions due to the accrued accumulation of capital stock to support development, especially from developing regions (20, 23, 24), which moreover tend to invest in more resource-intensive capital, such as infrastructure and machinery (25).

The current trends in GHG emissions, as well as the expectations of increasing growth in developing regions in particular, highlight the need to apply mitigation strategies to reduce those (5, 26). These should be applied in order to achieve sustainable development and to do so while staying within the limit of the remaining carbon budget (RCB) (i.e., quantity of CO_2 emissions consistent with limiting global warming to a given temperature level (27)). Strategies aiming at decoupling economic growth from emissions have mostly targeted production to improve emission efficiency (13, 28–31) and productivity (28, 32, 33). Consumption-side solutions can also effectively supplement these with demand for less carbon-intensive goods and services (4, 26). More demand-side strategies rather focus on decoupling well-being from economic growth itself (17, 34), aiming at reducing affluence (35–38) and limiting economic growth to a sufficient level that can allow all to live a good and sufficient life (16, 34). This is based on the fact that human needs are finite, non-substitutable, and defined (4, 34, 37) and that they can consequently be satisfied at a certain level. Economic growth therefore only contributes to human well-being to a certain extent only, while, past that threshold, it does not increase it anymore (39–43). Several energy use estimates for this threshold have been proposed, with a range of 10-100 GJ per capita per year (44, 45).

These efficiency and sufficiency aspects of achieving sustainable development also come into play in international climate negotiations where claims on 'common but differentiated' sharing of burden and mitigation efforts have been made (17, 46). Using various equity principles, less developed regions claim a higher share of the RCB arguing equality, their lesser responsibility, comparatively limited capability, and right to development (17, 47). These claims have also been quantified using various equity-based effort-sharing approaches to estimate countries' fair RCB shares (14, 48, 49). More information on the principles and derived effort-sharing approaches can be found in *Appendix A*.

In this thesis, I build on the opportunity space provided by LEF to explore future emissions associated with the production of manufactured assets, and complement the research by combining those insights with climate change mitigation strategies and equity perspectives. The question that I aim at answering is: "*To what extent do efficiency and sufficiency strategies contribute to reducing emissions associated with the production of manufactured assets consistent with an equitable and sustainable development?*". To do so, I develop as set of potential futures with varying efficiency and sufficiency levels and estimate the emissions that would be generated from the production of manufactured assets by 2050 under those different scenarios. To assess the sustainability and equity of each scenario, I then compare the emissions to the global RCB as well as to regional fair shares, calculated on the basis of responsibility and capability. I further describe the approach and methodology in the *Methods* section. I then provide the *Results* from both scenario emissions estimates and their comparison to RCB on a global and regional level, and analyse their implications in the *Discussion*. In the *Conclusion*, I also provide an outlook for future policies and research.

Methods

I perform a scenario analysis to estimate the future emissions caused by the production of the manufactured capital stock between 2020 and 2050, both on a global and regional level. These estimations are based on the LEF methodology (18) and take efficiency and sufficiency as parameters. To all for comparison, I additionally select a relevant range for RCB and further quantify responsibility- and capability-based regional shares using simplified approaches

Parameters

The parameters decomposing LEF reflect the two sets of emission-reducing strategies put forward in the literature: efficiency and sufficiency. Here, *efficiency* is the emission efficiency associated to the accumulation of manufactured capital stock, including emission intensity and economic productivity in asset production. *Sufficiency* reflects the size of the economy measured as the gross value added (GVA) of productive activities. In addition, seeing as the *global population* will be changing by 2050, and that it will affect emissions, I included it as an additional parameter. LEF can thus be understood as the resulting product of the amount of assets required to sustain the lifestyle of a population of a certain size in a given year, and of the emissions generated when producing those assets.

The LEF equation therefore reads as follows:

$$LEF_{i,t} = E_{i,t} * \ GVA\_pp_{i,t} * pop_{i,t}$$

(1)

where LEF comprises only its greenhouse gas emissions component. $LEF_{i,t}$ is the amount of emissions generated from the production of manufactured assets accumulated in country *i* in target year *t*. $E_{i,t}$ is the emission efficiency in asset accumulation per unit of GVA, $GVA\_pp_{i,t}$ is the gross value added per capita, and $pop_{i,t}$ is the size of the population.

To have results that fully estimate the emissions linked to manufactured capital accumulation that will be additionally generated after the base year of 2019 and by the target year of 2050, I correct the $LEF_{i,t}$ obtained using the equation above to exclude emissions that would have been generated prior to 2020 while also considering the emissions linked to assets that would have been produced and retired between 2020 and 2050. This additional LEF ($a\_LEF_{i,t}$) therefore results from the following:

$$a\_LEF_{i,t} = \ LEF_{i,t} - r\_LEF_t^{2019} * (1 + rr_{(t-2019)years})$$

(2)

where $r\_LEF_t^{2019}$ is the emissions embodied in the capital stock that is remaining from before 2020 in the year t. It is calculated by following the assets available in 2019 and using their respective retirement curves (18) to establish how much remains in 2050. $rr_{(t-2019)years}$ is the ratio between retirement and net accumulation over a period of *t-2019* years, calculated backwards from 2019. I here therefore assume that the future ratio is the same as the one calculated on the basis of historical retirement and accumulation trends. I floor the results of this equation to 0 as the subtracted emissions of $r\_LEF_t^{2019}$ have already been generated and can therefore not be removed without additional efforts.

Scenarios

To set the *efficiency* and *sufficiency* parameters in the equation, I define four different scenarios. These scenarios are compared to a reference one and differ in their parameter settings as follows:

Table 1. Scenario parameters.

Scenario		Efficiency (E)	Sufficiency (GVA_pp)
Reference (no change)		= 2019 levels	= 2019 levels
Developed world		= 2019 levels	≥ DE average
Efficient world	2% impr.	= 2019 + 2% yr. improvement	≥ DE average
	Full ef.	≥ DE average + 2% yr. improvement	≥ DE average
Sufficient world	High limit	= 2019 levels	= avg. of HDI≥0.8 countries
	Low limit	= 2019 levels	= HDI=0.8
Sustainable world	High limit	≥ DE average + 2% yr. improvement	= avg. of HDI≥0.8 countries
	Low limit	≥ DE average + 2% yr. improvement	= HDI=0.8

Further information regarding the specific parameter values is provided in *Appendix B*.

The reference scenario is one in which both emission efficiencies of asset production and sizes of countries' economies remain the same as they are in 2019. The only parameter that differs is population size as it accounts for the expected population growth from 7.5 to 9 billion people by 2050. This population growth is applied to all other scenarios.

The *Developed World* scenario describes a society where all countries have had the right and the opportunity to develop their economy, at the minimum, to the average size of that of developed countries in 2019. Countries that had per capita GVA levels higher than that amount in 2019 keep their above-average level, without additional growth.

In the *Efficient World* scenario, not only were all countries allowed to develop, they also benefitted from the best technologies, capabilities, and practices while doing so. This scenario thus includes the same sufficiency levels as in the *Developed World*, and improved efficiency levels. To show a first stage of efficiency improvement, I apply a yearly improvement rate of 2%. This is based on the fact that historical trends have shown a yearly improvement in energy intensity rates, with 2% being the current rate in 2022 and the expected minimum one in the future (50). I additionally model the global sharing of technology and knowledge by having all countries reach, at the minimum, the average efficiency levels of the developed countries in 2019. Here again, countries that had efficiency levels higher than the average one keep those.

The *Sufficient World* scenarios show societies that have capped their economy sizes at a certain level, having applied limits to their economic growth, as argued for by proponents of sufficiency as a strategy for sustainable development within planetary boundaries. A widely used method to set sufficiency thresholds is to apply a top-down approach linking the researched impact to the Human Development Index (HDI), which is the most common measure for human well-being (45, 51). I here rely on the strong relationship between per capita GVA and HDI (*Appendix B*) and set two different maximum levels of per capita GVA that would still allow, globally, for a very high level of human well-being (HDI ≥ 0.8). In the *Sufficient World (high)* scenario, everyone's per capita GVA is equal to the average level of countries that have a HDI ≥ 0.8 in 2019. In the *Sufficient World (low)* scenario, it equals the level of per capita GVA corresponding to a HDI score of 0.8.

The *Sustainable World* scenarios combine both efficiency improvements as described in the *Efficient World* and sufficiency limits to economic growth. The distinction between limits to growth corresponds to the one made between the two *Sustainable World (high)* and *(low)* scenarios.

Remaining carbon budget shares

RCB estimates vary on the basis of global warming limit, probability of success, and additional variations and geophysical uncertainties. For the global comparisons, I use IPCC's estimate ranges (52) counting from 2020 onwards for a likelihood between 33% and 67% of keeping global warming below 1.5˚C (400-650 $GtCO_2e$) and 2˚C (1150-1700 $GtCO_2e$). As a basis for the calculation of countries' fair shares, I more specifically use their estimate for a global warming of 1.5˚C, with a success probability of 50%, which amounts to 500 $GtCO_2e$. To this RCB, I apply simple effort-sharing approaches based on responsibility and capability. As the right to development is part of the scenario analysis, I do not include it additionally in the approaches.

For responsibility, in accordance with the purpose of this thesis focusing on the importance of manufactured assets within the production-consumption system, I propose to use LEF as a new proxy. Although LEF takes into consideration emissions released throughout the assets' supply chains, within and outside national territorial boundaries, it is not strictly a consumption-based accounting method as the environmental impacts are attributed to the capital-using production activities in a given year, rather than to the final consumption in each country; it is rather an accounting method that takes an ownership (of the assets) perspective when considering which country to attribute emissions to. Thus, using this footprint means that I consider that, in 2019, countries are responsible for the emissions that were generated in order to produce the manufactured assets that compose their capital stock in that year. For capability, I use GVA and HDI as indicators to get both perspectives of economic size on the one hand and human well-being on the other.

I use the same reasoning for all effort-sharing calculations in order to assign shares of the RCB that would be inversely proportional to countries' responsibility or capability. Hereunder, I present an example using LEF. For the other proxies, LEF should be replaced with GVA and HDI, respectively. As HDI is given as an index per country, and to account for effects of population size, I first weight it by population before using it in the equations as presented hereunder.

The weighting of HDI to HDI_w is done as follows:

$$HDI\_w_{i,2019} = HDI_{i,2019} * pop_{i,2019}$$

(3)

where $HDI\_w_{i,2019}$ is the weighted HDI of country *i* in 2019, $HDI_{i,2019}$ is that country's HDI level in 2019 and $pop_{i,2019}$ its population.

The effort-sharing approach for all proxies follows two steps. Firstly, I take the ratio of global average LEF per capita to the country's LEF per capita in 2019. This ratio is then multiplied by the population in 2050 to ensure that the RCB is divided in proportion to population, as advised in Wei et al. (53):

$$R\_ratio_{i,t} = \frac{LEF_{2019}/POP_{2019}}{LEF_{i,2019}/pop_{i,2019}} * pop_{i,t}$$

(4)

where $R\_ratio_{i,t}$ is the ratio of responsibility of country *i* in the target year t. $LEF_{i,2019}$ is country *i*'s LEF in 2019 and LEF_{2019} is the sum of all countries' LEF in 2019. Similarly, $pop_{i,2019}$ is country *i*'s population in 2019 and POP_{2019} is the sum of the population sizes of all countries in 2019. $pop_{i,t}$ is the population of country *i* in target year *t*.

To get the final share of RCB per country, I then rescale the ratio for target year *t* so that the new ratios sum to 1, and multiply it with the global RCB, as follows:

$$R\_rcb_{i,t} = \frac{R\_ratio_{i,t}}{\sum_j R\_ratio_{j,t}} * RCB$$

(5)

where $R\_rcb_{i,t}$ is the RCB share of country *i* in target year t, and RCB is the global remaining carbon budget.

Data sources

I gathered the LEF and GVA data from the Legacy Environmental Footprints of Manufactured Capital dataset (54). The LEF dataset comprises resource use and other environmental impacts embodied in capital stock for the years 1995 to 2019, and includes those from 1970 onwards. For this thesis, only the information regarding GHG emissions was used. The GHGs included carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), as well as fluorinated GHGs (HFC, PFC, SF_6). As the LEF dataset is built using the EXIOBASE3 multiregional input-output (MRIO) database, the same spatial and sectoral specification also apply. The LEF and GVA data is therefore available for 44 countries as well as five addition rest-of-the-world (RoW) regions. I aggregated these countries/regions into two or eleven regions when I present the results (*Appendix C*). The LEF and GVA data can also be detailed by production activity, which there are 200 of. It should be noted that, as in Wang et al. (18), I adjusted the GVA values for price differences between countries using the power parity rate (PPP) provided in the LEF database.

For HDI, I used the dataset that is maintained by the United Nations Development Programme (UNDP) and that shows the HDI level of 191 countries for the years 1990-2021 (55). And for population, I used two different datasets: the EXIOBASE3 dataset for the population sizes in 2019 (56), and the SPP2 data from the SSP Public Database (Version 2.0) for those in 2050 (57–59). The latter provides population projections for 193 countries from 2010 to 2100 with 5-year increments.

I aggregated all the datasets to the spatial groups specifications of the LEF data to make the data comparable. One of the countries individually specified in the LEF dataset was missing from the SSP database (Taiwan) and I therefore removed it from all datasets. The results are thus provided for 48 countries/regions.

Results

The results from the different scenarios and from the sharing of RCB following the three different effort-sharing approaches are provided in this section, with details to be found in *Appendix D*.

The impact of universal development by 2050

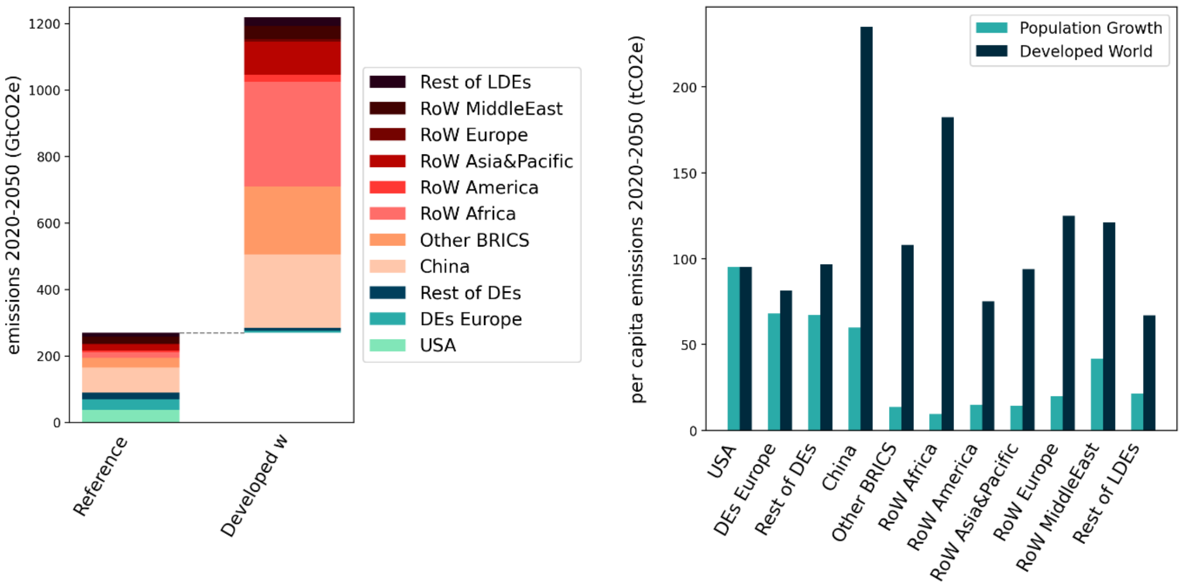

Figure 1. Future emissions 2020-2050 for the reference and the Developed World scenarios, per region total (left, in GtCO2e) and per capita (right, in tCO2e).

Under the reference scenario (*Figure 1*), accounting for the projected population growth, the additional emissions embodied in capital stock by 2050 are of 270 $GtCO_2e$, with China (76 $GtCO_2e$) and the developed regions (89 $GtCO_2e$) accounting for more than half of those. The developed regions are also those with the highest per capita emissions (67-95 tCO_2e/pp), followed closely by China (60 tCO_2e/pp) and the Rest of the World (RoW) region of Middle East (42 tCO_2e/pp). All the other less developed regions have per capita emissions below the global average of 29 tCO_2e/pp, with RoW Africa emitting the least with 10 tCO_2e/pp.

The development increase described in the *Developed World* scenario not only comes with a significant rise in global emissions, which shoot up to 1220 $GtCO_2e$, it also leads to somewhat of an inversion in the regional contributions to those (*Figure 1*). Indeed, the less-developed regions that emitted considerably less than the developed regions in the reference scenario experience a large increase in their emissions. This is especially the case for RoW Africa, which has the lowest GVA per capita by far. Its emissions (333 $GtCO_2e$) make up almost a fourth of the global amount while those of other less-developed regions also grow 3 to 8 times, with the largest increases taking place in the Other BRICS countries (234 $GtCO_2e$), RoW Asia&Pacific (117 $GtCO_2e$), and RoW Europe (9 $GtCO_2e$). The two former become some of the largest contributors to global emissions behind RoW Africa and China. China, which already was a significant emitter, remains one in this scenario, with the second largest contribution to global emissions (297 $GtCO_2e$) and the most emissions per capita (235 tCO_2e/pp). On a per capita level, it is followed by RoW Africa (182 tCO_2e/pp), and RoW Europe and RoW MiddleEast, which generate 120-125 tCO_2e/pp. Developed regions' contributions barely increase and become much less significant in comparison, with them generating 90 $GtCO_2e$ together. On a per capita level they also emit much less than the global average of 133 tCO_2e/pp, with 80-95 tCO_2e/pp each. The Rest of LDEs and RoW America have the lowest emissions per capita, with 67 and 75 tCO_2e/pp, respectively.

Efficiency improvement potentials

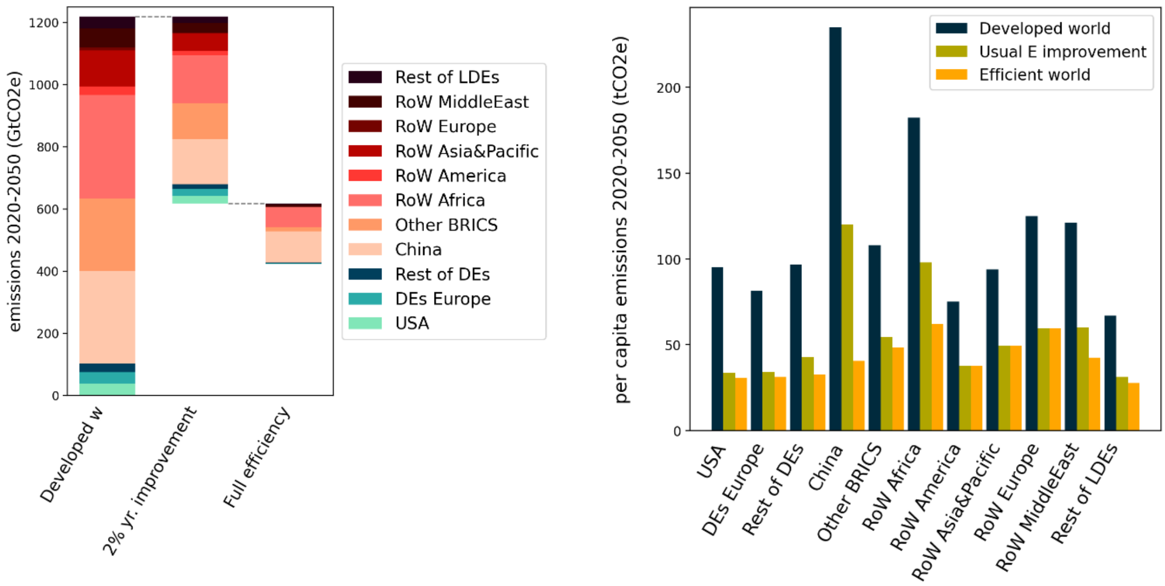

Figure 2. Future emissions 2020-2050 for the Developed World and the Efficient World scenarios, per region total (left, in $GtCO_2e$) and per capita (right, in tCO_2e).

In the *Efficient World* scenario (*Figure 2*), the expected minimum yearly emission efficiency improvement rate of 2% already contributes to bringing the future global emissions down to about their half (618 $GtCO_2e$). The shares of these emissions remain similar between the regions, with the largest decreases in emissions taking place in the regions that generate them the most. As such, RoW Africa, China, Other BRICS and RoW Asia&Pacific generate 179, 152, 118, and 62 $GtCO_2e$ respectively, while RoW Europe only generates 4$GtCO_2e$. On a per capita basis, the global per capita emission average is also reduced by half to 67 tCO_2e/pp. Similarly, the most important improvements also happen in the regions that generate the most emissions per capita, bringing the contributions of China and RoW Africa to 120 and 98 tCO_2e/pp each. All other regions generate less emissions than the average. The Other BRICS, although being one of the regions contributing the most to global emissions is amongst those, with 54 tCO_2e/pp, just behind RoW MiddleEast and RoW Europe, which both emit 60 tCO_2e/pp. The smallest per capita emissions generated are from DEs Europe, the USA, and the Rest of LDEs, and are all under half the global average.

Additionally bringing the efficiency levels of all countries to the 2019 average level of the developed countries, at the minimum, further reduces the additional emissions by a third to equal 423 $GtCO_2e$. Globally, the Other BRICS region (105 $GtCO_2e$) surpasses China (51 $GtCO_2e$), becoming the second largest contributor after RoW Africa (113 $GtCO_2e$). This is explained by the fact that China's emissions are reduced threefold, which is double to triple the reduction ratio of any other region. The smallest contribution to emissions comes again from RoW Europe with an unchanged amount of 4 $GtCO_2e$. This stagnation is due to its efficiency level already being better than the 2019 average level in developed regions. The same reason explains the unchanged emissions from RoW America and RoW Asia&Pacific, which remain at 14 and 62 $GtCO_2e$, respectively. The global average per capita emissions is also reduced by a third to 46 tCO_2e/pp. China's emissions drop to be some of the lowest per capita ones, with 40 tCO_2e/pp. The largest contributors on the per capita level are now RoW Africa (62 tCO_2e/pp), RoW Europe with its unchanged amount (60 tCO_2e/pp), Other BRICS (48 tCO_2e/pp), and RoW MiddleEast (43 tCO_2e/pp). The developed regions and the Rest of LDEs are those that generate the least amount of emissions per capita (27-32 tCO_2e/pp).

Sufficiency considerations

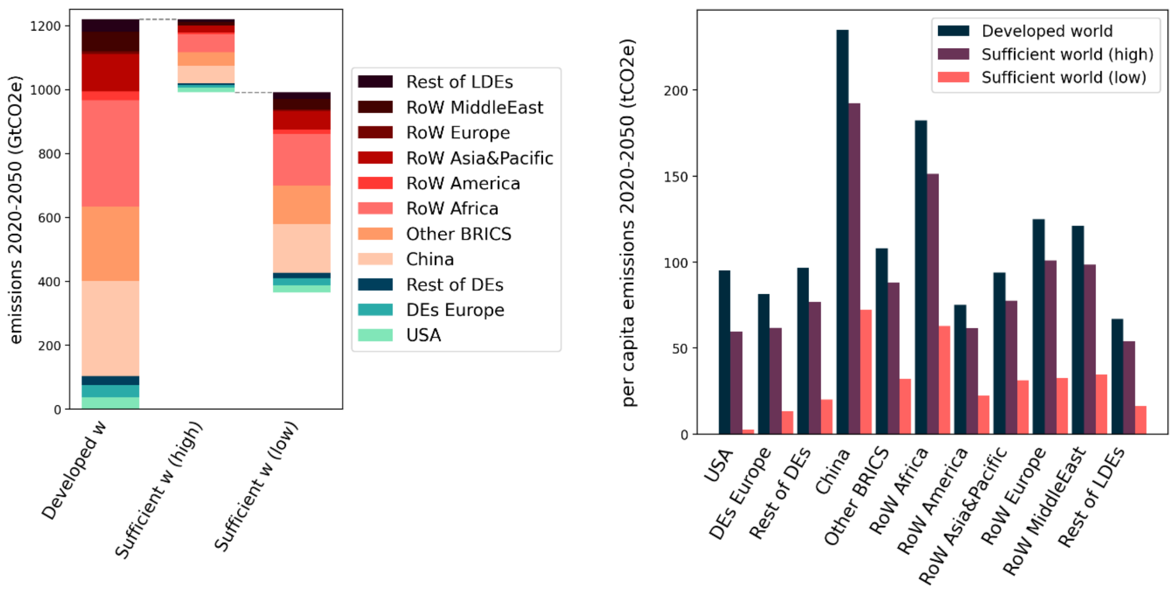

Figure 3. Future emissions 2020-2050 for the Developed World and the Sufficient World scenarios, per region total (left, in $GtCO_2e$) and per capita (right, in tCO_2e).

Figures 3 shows the reductions of emissions in both *Sufficient World* scenarios in comparison to the emissions generated under the *Developed World* scenario. Limiting per capita GVA to still allow all to reach a HDI score ≥0.8 brings a small reduction of global emissions to 992 $GtCO_2e$ in the *Sufficient World (high)* scenario. Limiting it further to HDI=0.8 significantly reduces those to 365 $GtCO_2e$ in the *Sufficient World (low)*.

In both *Sufficient World* scenarios, the largest reduction ratios are in developed countries, which currently have the highest GVA levels per capita. In the *high* scenario, those average

1.5, with other regions all experiencing decreases closer to the order of 1.25. In that scenario, RoW Africa remains the region that contributes the most to global emissions, with 276 $GtCO_2e$. China (243 $GtCO_2e$), Other BRICS (191 $GtCO_2e$), and RoW Asia&Pacific (97 $GtCO_2e$) follow as the largest emitters. The lowest contributions come once again from the developed regions, RoW America, and RoW Europe, with their emissions being under 30 $GtCO_2e$ each. Looking at the emissions per capita, China still generates the largest amount, with 193 tCO_2e/pp. It is followed by RoW Africa (151 tCO_2e/pp) as the only other region above the global average of 108 tCO_2e/pp. Although being the other largest contributors globally, Other BRICS' (88 tCO_2e/pp) and RoW Asia&Pacific's (78 tCO_2e/pp) per capita emissions are lower than RoW Europe's (101 tCO_2e/pp) and RoW MiddleEast's (99 tCO_2e/pp). The smallest per capita emissions are not significantly lower, with the Rest of LDEs' at 54 tCO_2e/pp.

In the *Sufficient World (low)* scenario, the USA experiences a large decrease, with its emissions dropping to 1 $GtCO_2e$. The other developed regions, the Rest of the LDEs, and RoW Europe have emissions decreasing 4-6 times in comparison to the *Developed World* scenario. Along with those of RoW America, these are all under 10 $GtCO_2e$. The emissions in other regions decrease about 3 times. RoW Africa is still the largest contributor to global emissions, almost emitting half of those (115 $GtCO_2e$). The other half is mostly coming from China (91 $GtCO_2e$), Other BRICS (69 $GtCO_2e$), and RoW Asia&Pacific (40 $GtCO_2e$). Per capita, China (72 tCO_2e/pp) is still the leading region, followed by RoW Africa (63 tCO_2e/pp). All other regions generate less than the global average of 40 tCO_2e/pp. RoW MiddleEast, RoW Europe, Other BRICS, and RoW Asia&Pacific all have per capita emissions of 30-35 tCO_2e/pp. The lowest contribution comes from the USA, with 3 tCO_2e/pp.

Combining strategies for a sustainable world

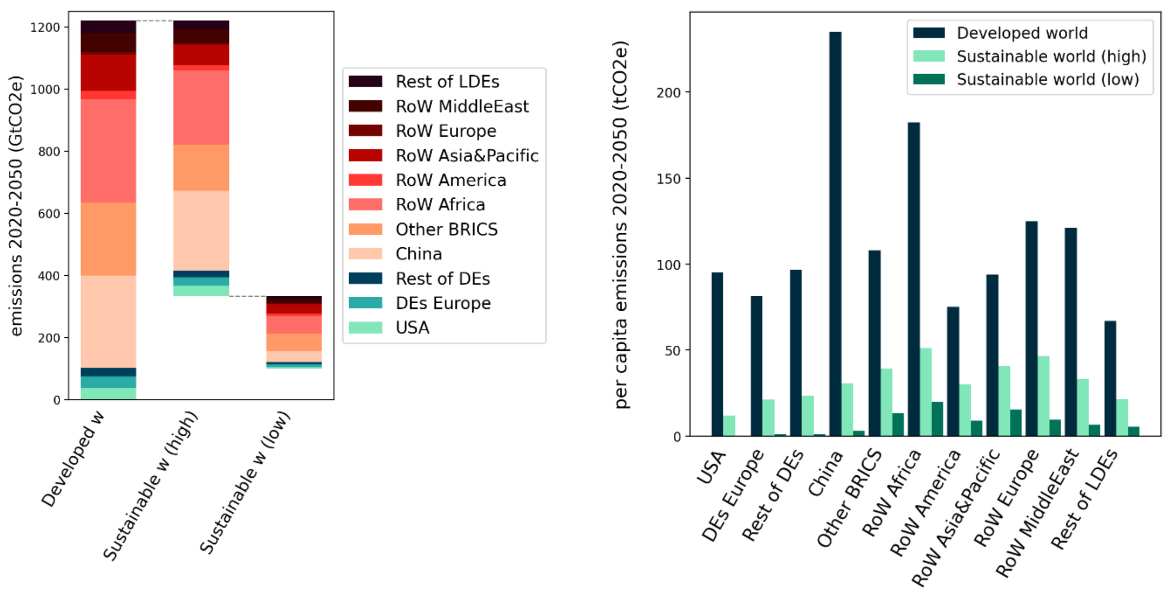

Figure 4. Future emissions 2020-2050 for the Developed World and the Sustainable World scenarios, per region total (left, in $GtCO_2e$) and per capita (right, in tCO_2e).

With both efficiency improvements and sufficient limits combined in the *Sustainable World* scenarios, the global emissions drop to 333 $GtCO_2e$ in the *high* scenario, and to 100 $GtCO_2e$ in the *low* one (*Figure 4*).

In the *Sustainable World (high)* scenario, the regions that experience the highest combined reductions in their emissions are the USA and China, with those being about 8 times lower than in the *Developed World* scenario. The Rest of DEs, DEs Europe, RoW MiddleEast, and RoW Africa have reduction ratios around 4, while other regions have their emissions reduced by 2.5-3 times total. The largest contributor to global emissions in this scenario is again RoW Africa, with 93 $GtCO_2e$. It is followed by the Other BRICS (85 $GtCO_2e$), RoW Asia&Pacific (51 $GtCO_2e$), and China (39 $GtCO_2e$). The lowest contributions are from developed regions and RoW Europe (3 $GtCO_2e$), with the USA (5 $GtCO_2e$) dropping to the second to last position. On a per capital level, the differences between regions are the smallest in this scenario. RoW Africa is now the largest contributor at that level, with 51 tCO_2e/pp, while China's contributions are some of the lowest again, after those of the developed regions and the Rest of LDEs. The USA (12 tCO_2e/pp) has the lowest per capita emissions. RoW Europe (47 tCO_2e/pp), RoW Asia&Pacific (41 tCO_2e/pp), and the Other BRICS (39 tCO_2e/pp) have per capita emissions that are higher than the average of 36 tCO_2e/pp.

In this *Sustainable World (low)* scenario, the USA does not emit any additional emissions, while those of other developed regions and of RoW_Europe are under 1 $GtCO_2e$. Most of the emissions come from RoW_Africa (36 $GtCO_2e$), BRICS_Rest (29 $GtCO_2e$), and RoW_Asia&Pacific (19 $GtCO_2e$). These three regions also have the largest per capita emissions, with 20, 13, and 16 tCO_2e/pp, respectively. The other regions all have per capita emissions lower than the global average of 11 tCO_2e/pp. The smallest contributions, besides the null one from the USA, come from DE_Europe and DE_Rest, with about 1 tCO_2e/pp.

Global comparison to RCB

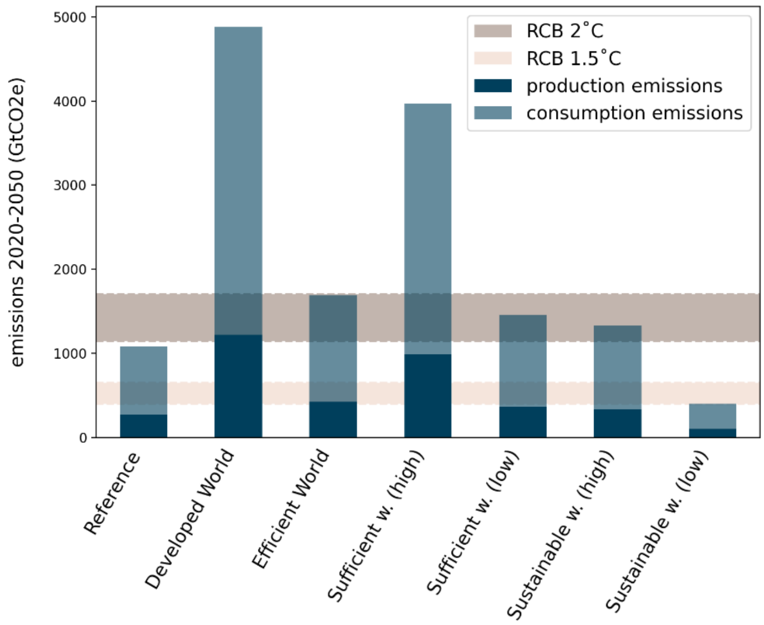

Figure 5. Comparison of global RCB ranges (for 1.5˚C & 2˚C warming) with future global emission estimates based on different scenarios, in $GtCO_2e$.

While comparing the future emissions as estimated in the different scenarios to the remaining carbon budget, one should keep in mind that LEF only covers emissions caused by the production of manufactured capital. These only account for 25-40% of the global amount (19, 20), with the rest of emissions being associated with the final consumption of goods and services enabled by the assets. To ease the comparison, a visual representation of the total global emissions, with consumption emissions accounting for 75% of those, is included in *Figure 5*.

Taking this into account, emissions from both the *Developed World* (1220 $GtCO_2e$) and the *Sufficient World (high)* (992 $GtCO_2e$) scenarios would far surpass the limit for a global warming of 2˚C. Only more significant emission reductions linked to efficiency and/or a lower limit on economic growth can contribute to keeping global warming below 2˚C. The *Efficient World* scenario (423 $GtCO_2e$) would bring emissions from the production of manufactured assets just to the higher limit for a global warming of 2˚C (67% likelihood). The other scenarios would reduce these even more to stay at the lower limit, giving an higher likelihood to stay below 2˚C warming, with the *Sufficient World (low)* scenario reaching 365 $GtCO_2e$ and the *Sustainable World (high)* scenario amounting to 333 $GtCO_2e$. The *Sustainable World (low)* *(*100 $GtCO_2e$) is the only scenario that would ensure a global warming below 1.5 ˚C.

Regional comparison to RCB fair shares

Sharing the global RCB using different approaches provides insight into the equity implications of regional emissions. Using the responsibility-based effort-sharing approach, the largest shares of an RCB of 500 $GtCO_2e$ are distributed to RoW Africa (172 $GtCO_2e$) and the Other BRICS countries (153 $GtCO_2e$). RoW Asia&Pacific, the Rest of LDEs, RoW America, and China are allowed 81, 29, 20, and 18 GtCO_2e, respectively. All other regions can only emit less than 10 GtCO_2e, with the smallest shares going to the developed regions and RoW Europe. The per capita results clearly reflect responsibility with regions that emitted the least emissions in the past having the larger RCB shares per capita. This is the case of RoW Africa, which has the largest one with 95 tCO_2e/pp. Other BRICS and RoW Asia&Pacific follow with 70 and 65 tCO_2e/pp each. RoW America, the Rest of LDEs, and RoW Europe all get about 50 tCO_2e/pp. The other regions have less than 20 tCO_2e/pp, with developed regions and China receiving the lowest shares, especially the USA, with 9 tCO_2e/pp.

Under the capability-based effort-sharing approaches, RoW Africa and Other BRICS are again the recipients of the largest shares, with 226 and 128 GtCO_2e each when GVA per capita is used as proxy, and an equal division of each 124 GtCO_2e when HDI is the proxy. With both approaches, the developed regions also receive the smallest shares, and China now differs from them, getting comparatively bigger shares. With the GVA-based approach, RoW Asia&Pacific, China, and the Rest of LDEs are given allowances of 58, 35, and 17 GtCO_2e each, while all other regions have shares around or under 10 GtCO_2e. The developed regions and RoW Europe once again have the lowest shares. The differences between regional shares are smaller with the HDI-based approach. It results in RoW Asia&Pacific and China receiving about 65 GtCO_2e. They are followed by the Rest of LDEs (29 GtCO_2e), RoW MiddleEast (25 GtCO_2e), DEs Europe (19 GtCO_2e), RoW America (18 GtCO_2e), the USA (17 GtCO_2e), the Rest of DEs (12 GtCO_2e), and RoW Europe (3 GtCO_2e). Looking at the per capita RCB shares, RoW Africa and Other BRICS again get the largest ones, with 124 and 59 tCO_2e/pp with the GVA-based approach, and with 68 and 57 tCO_2e/pp with the HDI-based approach. Using the GVA-based approach, RoW Asia&Pacific follows with 47 tCO_2e/pp. Other regions have shares around 30 tCO_2e/pp, while RoW MiddleEast gets 21 tCO_2e/pp and developed regions receive 8-12 tCO_2e/pp, with the USA being on the lowest end. With the HDI-based approach, the per capita shares are very close together, ranging from 41 tCO_2e for both the USA and DEs Europe, to 57 tCO_2e/pp for Other BRICS and 68 tCO_2e/pp for RoW Africa. All other regions have shares between 42 and 54 tCO_2e/pp.

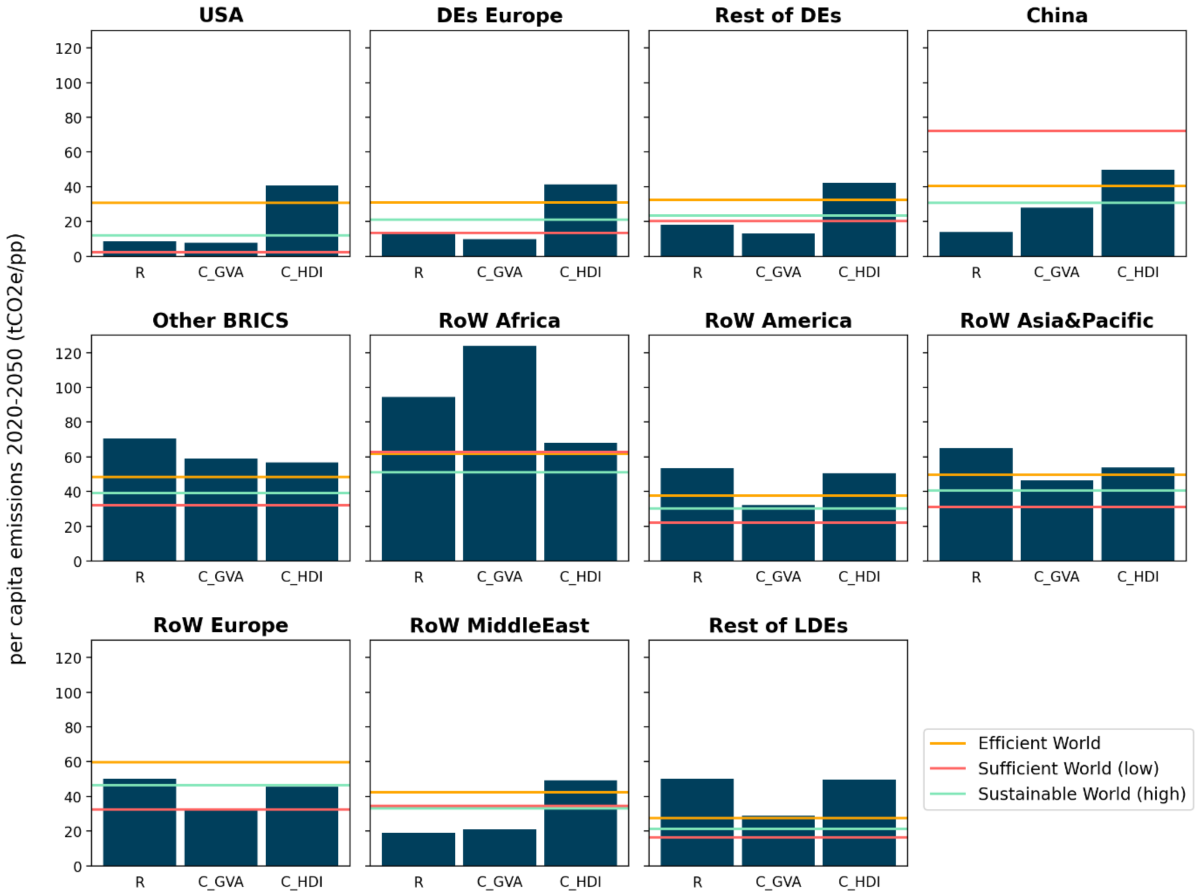

Figure 6. Comparison of per capita RCB fair shares based on responsibility (R) and capability (using GVA per capita as proxy (C_GVA) & using HDI as proxy (C_HDI) (bars) with per capita future emission estimates based on different scenarios for 2020-2050, per region, in tCO_2e/pp.

Comparing the regional RCB shares to the estimated future assets production emissions under the different scenarios, it can be observed that all regions are above their shares in both the *Developed World* and the *Sufficient World (high)* scenarios, and all are under their shares in the *Sustainable World (low)* scenario, whatever the effort-sharing approach used. *Figure 5* shows the compared results of the per capita RCB shares to the emissions of the other scenarios, namely the *Efficient World*, the *Sufficient World (low)*, and the *Sustainable World (high)*. It should be kept in mind that emissions associated with the final consumption of goods and services are excluded in this part of the analysis.

With fair shares calculated on the basis of responsibility, whatever the scenario, China is the region that emits the most emissions per capita above its share, with those equalling 27, 58, and 168 tCO_2e/pp for the *Efficient World*, *Sufficient World (low)*, and the *Sustainable World (high)*, respectively. The developed regions, RoW Europe and RoW MiddleEast are the other regions that also go over their fair shares. All of those do so in the *Efficient World* scenario, RoW Europe does not in the *Sustainable World (high)* scenario, and nor do the DEs Europe nor the USA in the *Sufficient World (low)* scenario. All other regions emit less than their fair shares, with RoW Africa and Other BRICS having the least emissions in comparison to their shares in both the *Efficient World* and the *Sustainable World (high)* scenarios, and Other

BRICS, RoW Asia&Pacific, and the Rest of LDEs being those with the least relative emissions in the *Sufficient World (low)* scenario.

When the fair shares are defined on the basis of capability, with GVA per capita as proxy, RoW Africa is the one region that remains significantly below its share in all scenarios, with a difference of 60-70 tCO_2e/pp. In the *Efficient World* scenario, only Other BRICS and the Rest of LDEs also remain under their fair shares. In the other two scenarios, so do RoW America and RoW Asia&Pacific, and in the *Sufficient World (low)* one, the USA also emits less emissions that it would be allowed to. The regions that consistently generate more emissions that fairly allowed are China, DEs Europe, the Rest of DEs, RoW Europe, and RoW MiddleEast. It should be noted that China does so significantly more than the other regions in the *Sufficient World (low)* scenario.

When the RCB shares are calculated based on HDI, most regions remain under their fair share, whatever the scenario. The only exceptions are RoW Europe in the *Efficient World* scenario, with 14 tCO_2e/pp generated above its threshold, and China in the *Sufficient World (low)* scenario, with an additional 22 tCO_2e/pp emitted. The Rest of LDEs is the region that emits the least compared to its fair share in the *Efficient World* scenario, but the USA takes over that position in the other two scenarios. The differences between regional performance relative to their fair shares is lowest in the *Sustainable World (high)* scenario.

Discussion

The LEF-based scenarios estimating future emissions associated to capital formation between 2020 and 2050 show that giving an equal right to development to all regions leads to a large increase in global emissions, mostly from regions that are currently less developed – corresponding to the trends observed in past research (15, 20, 23, 24). Depending on the level of development and emission efficiency of the accumulation of assets, the amounts of additional GHG emissions however vastly differ, both on a global and regional level. The results highlight the effectiveness of both efficiency and sufficiency strategies in reducing emissions.

Improving efficiency in the production of manufactured assets requires both production- and consumption-side interventions. The majority of the emissions generated are linked to infrastructure (18), which is one of the sectors that is hardest to decarbonize. Indeed, their reliance on carbon-intensive materials, such as steel and cement, means that, in addition to energy efficiency, material efficiency also plays a significant role (60). Policies supporting a reduced use of those highly-emitting materials are therefore important. Effective strategies include light design, better circularity, and also the use of emerging alternative materials that have lower environmental impacts, such as wood (24, 60–62). The *Efficient World* scenario in this thesis shows that a highly-efficient world could actually reduce global emissions by two-thirds. This shows even more potential than findings relating to efficiency of production for building materials, which were set to half (24). Currently, less efficient practices are however still predominant, especially in developing regions (24). Here, the results also show that the potential for efficiency improvement is higher in developing regions, and particularly in China and RoW Africa. As these regions are some of the top contributors both on a regional and per capita level in all scenarios, supporting a fast-paced realization of that potential is especially critical. Globally, the sharing of technology and best-practices will be crucial in achieving sustainable development.

Limiting economic growth to specific levels is a strategy that can effectively help achieve sustainable development but that is also less politically acceptable, and hence implementable (63). The results of this study show that, to sufficiently and fairly reduce emissions, this would furthermore imply some degrowth from developed regions. The current inequality of development between regions, and the disproportionately high level of GVA per capita in developed regions, demands a reduction in their inhabitants' affluence. On the other hand, this would leave space for regions that currently need it the most (RoW Africa, RoW Asia&Pacific, and Other BRICS – mostly India) to develop without global emissions reaching an unsustainable level. The fact that sufficiency does not equate less well-being should be reiterated, as literature has shown that the latter does not increase further with more economic growth (*see Introduction*). For a switch towards sufficiency, a change in focus from economic growth to human well-being instead is thus needed. With that in mind, practices to achieve a very high level of human well-being while using less and differently can be successfully introduced. These have even been found to actually positively contribute to enhancing well-being (38) and include reducing living space and transport, renting instead of owning, extending product life, and (re)using those more intensively (24, 35, 60, 64). The importance of the latter two is also reflected through *Equation 2* in this thesis. The effects of short assets' longevity can particularly be seen in the drastically higher estimates of per capita emissions in RoW Europe in comparison to RoW America, which otherwise has similar efficiency and GVA per capital levels.

Unsurprisingly, the results further show that combining both efficiency and sufficiency strategies is the most effective, with the *Sustainable World* scenarios leading to the lowest amount of global emissions. The necessity of their combination is even more compelling when considering that sufficiency can counter the rebound risks associated with efficiency improvements (65) and also minimize the feasibility risks that come with solely relying on technology, such as those from large-scale carbon dioxide removal (CDR) deployment and rapid production transformations (33).

The future emission estimates only comprise the emissions associated with the production of manufactured assets, leaving aside those caused by their use. Assuming that the latter would represent 75% of the total emissions, the resulting global emission estimates for worlds with high economic activity – the *Developed world* – and with more than a sufficient very high level of human well-being – the *Sufficient world (high)* – would vastly surpass the remaining carbon budget for a 2˚C warming. Assuming the basic 2% yearly improvement rate to efficiency, the resulting emissions for high development are actually consistent with those from studies estimating emissions resulting from a convergence of per capita material stocks (20) and from a near-universal very high level of human well-being level (15). Supporting the points hereabove, the introduction of additional efficiency and sufficiency measures can bring the total global emissions down to amounts congruous with a global warming of 2˚C, and only their combination can have them reach a level enabling the world to stay below 1.5˚C warming.

The large proportion of consumption emissions that need to be additionally taken into consideration when discussing the impacts of manufactured capital on global warming not only not only highlights the importance of implementing both efficiency and sufficiency strategies, but furthermore to invest strategically in sustainability-compatible assets, both from a production and in-use perspective. Taking into consideration the usual long-life of most assets (e.g., infrastructure), this could further prevent locking societies into resource-intensive practices and lifestyles (22). Potential trade-offs between the two should furthermore be kept in mind. Two relevant sets of assets can be further explored to illustrate these points. The first concerns energy infrastructure. There currently already is a lock-in from the existing fossil-fuel power plants, which are expected to generate 500 $GtCO_2e$ should they be used until the end of their lifetime (66, 67). This would effectively prevent keeping global warming below 1.5˚C. Retiring those early to be replaced by renewable energy infrastructure is therefore necessary but will also lead to additional emissions caused by the production of the new infrastructure (68). Preventing lock-in would be more effective. This is especially relevant for another set of assets: urban areas, and especially the nascent ones in developing regions such as Africa and Asia, where a large part of upcoming assets is expected to be produced. Through planning for compact infrastructure, as well as accessible public transport, not only would production emissions be reduced as less material would be needed, it would also ensure a sustainable lifestyle requiring less travel, that could be fully done without relying on personal cars (25, 69). Should the planning also include the construction of energy-efficient buildings to reduce in-use emissions though, a trade-off could still come from needing additional material in comparison to less efficient dwellings (24). All these considerations are extremely relevant when assessing emissions associated with manufactured assets. They are however lacking in this particular research as I did not account for consumption emissions, trade-off effects, nor additional emissions due to precocious asset retirement. I also did not consider any impact from the potential CDR infrastructure that many of the low-global warming scenarios rely on (70), whether from their production or effect reducing atmospheric GHGs.

When comparing the regional emission estimates to the RCB shares obtained using the different effort-sharing approaches, the same limitation of only a portion of emissions being accounted for applies. Unsurprisingly, and consistently with other research that considers responsibility and capability principles in climate mitigation (71–73), developing regions are due the larger per capita shares. The use of the novel LEF as proxy for responsibility results in a higher accountability for developed regions and China. Whatever the sharing approach, combining efficiency and sufficiency here also prove to more effectively ensure that regions do not emit more emissions than their fair shares. Looking at the intermediate scenarios that result in global emissions below the 500 $GtCO_2e$ threshold, but that still see some regions either above or under their shares, the HDI-based sharing approach is the one that would lead to the least amount of international compensations or transfers. Under this effort-sharing approach, the great majority of regions indeed all stay below their fair shares. While the consumption emissions are once indeed omitted in this part of the analysis, the results still point to HDI being the most equitable proxy for sharing RCB to enable sustainable development for all. This should be taken into consideration in international climate mitigation negotiations when discussing the quantifiability of the ‘common but differentiated responsibilities and respective capabilities’ clause. Especially as finding a suitable equity sharing principle is essential to convincing all Parties of each other’s fair effort and to thus muster the needed cooperation to solve this commons problem (17).

Some additional limitations to this research should be pointed out. The scenario modelling is simple, only giving nuance for the sufficiency considerations. As the parameter settings are idealistic rather than following realistic trends, the results offer a wide range of possible future emissions in a world committed to the right to development. The parameters are furthermore fixed throughout the 2020-2050 period, thus neglecting the effects of the more accurate gradual change in both efficiency and production levels. This would affect the results with them being an underestimation compared to more realistic efficiency improvements. On the other hand, the effects of a gradual change in economy size would probably lead to lower emission estimates as the larger percentage of the population is in less developed economies that still need to grow their manufactured capital. Regarding both parameters, emissions would furthermore depend on the pathways of change.

Conclusion & Outlook

Whether sustainable development can be achieved significantly depends on the compatibility of future investments in manufactured assets. Combining efficiency and sufficiency strategies to reduce emissions associated with the production of those assets is essential to minimize risks and keep global warming a low as possible by 2050. There therefore is a need to immediately switch from focusing on economic growth to enabling human well-being instead. This could additionally be supported in international climate negotiations by using HDI as a proxy to share RCB. Further, seeing as a large proportion of the upcoming capital formation will take place in Africa and Asia, there is an urgency to share both technology and best practices to ensure efficient infrastructure planning that enables a sustainably very high level of well-being and avoids undesirable lock-ins.

To better understand the implications of the sustainability of future manufactured assets for achieving global human well-being within planetary boundaries, research should be done on both production and consumption-based environmental impacts of capital. For the production-side, this could be partially based on the LEF data, which includes material extractions and health impacts. Other environmental impacts, such as water use, could be added. Future research should further incorporate the trade-off effects between production and in-use impacts, such as those associated with early retirement of unsustainable infrastructure, and with the deployment of CDR technology. Regarding mitigation solutions, seeing the necessity of sufficiency measures, research should be done to pave pathways to improve their realistic feasibility.

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Appendices

Appendix A. Equity principles and effort-sharing approaches.

Responsibility relates to the ‘polluter pays’ principle where those that contributed more to climate change have to make more efforts (47). It is calculated (as a debt) proportional to both present and past emissions (72). These emissions can include different emission sources (e.g., only energy, including land-use related emissions or not, …) and can be measured from various starting dates, usually 1850 representing the start of the industrial revolution, or 1990 as the year of the first International Panel on Climate Change (IPCC) assessment report (48), which proves knowledge of the harm induced (17). Emissions can also be calculated using different accounting methods, with the main discussion being whether to use a production perspective (i.e., accounting for all emissions generated within the territorial boundaries of the jurisdiction of interest) or a consumption-based one (i.e., a carbon footprint that considers all GHG emissions embodied in the goods and services consumed within said jurisdiction, wherever these emissions were released along the supply chains) (17).

Capability reflects the ‘ability to pay’ principle where those that can afford to contribute more should do so. It is often measured using GDP. However, following arguments similar to those mentioned above regarding the fact that a country’s capability is not solely determined by the state of its economy, HDI has also been used as an alternative proxy (72, 74).

Equality is based on the universal equality of human rights. This has either been understood as an equal right to emit, or as resources having to be shared equally while compensations between different goods would be allowed (47, 49, 72). Equality has been criticized for not taking into consideration the existing inequalities between countries (47), which is why it can also be merged with responsibility and/or capability with the understanding of equality meaning equal sacrifices in regards to one’s responsibility or capability (75).

The **right to development** relates directly to sustainable development, with needing to allow all to reach a certain level of economic growth and/or well-being. It is usually simply included as a threshold under which its contribution to global warming and/or its income/HDI level is not taken into consideration in calculations of a country’s capability or responsibility(17). This reflects the fact that less capable countries are allowed to contribute less to the global response to climate change (49).

Other types of effort-sharing approaches exist. A number of those combine the considerations of some or all principles, others take a staged approach where the countries’ commitments enter into force in various stages, and some are based on cost-effectiveness rather than equity principles (49).

Appendix B. Parameter values and additional regional data.

Parameter levels that are "= 2019 levels" are the same as in 2019, for each country. For E, this means it is $E_{i,2019}$ and for GVA_pp, this means it is $GVA\_pp_{i,2019}$.

To determine the E and GVA_pp levels to select in order to model an improvement of their levels, I first performed a comparison between the average levels for developed economies on the one hand and for less-developed economies on the other hand. The results are shown in *Table A.1.*

Table A.1. Average parameter levels per development-based regional groupings, in 2019.

	E (tCO_2e/million €)	**GVA_pp** (million €/pp)
Developed economies	1652	0.0501
Less-developed economies	2037	0.0358

As a lower E value reflects the desired efficiency improvement, and as a higher GVA_pp value shows a larger economy, the average of developed economies was selected for both parameters. In the scenarios, all parameter values that are under those averages are made to equal them while values that are above remain the same. The additional 2% yearly improvement rate is then only added for efficiency, on the basis of literature.

In the *Sufficient World* and *Sustainable World* scenarios, GVA_pp values are set following a top-down approach, where the level of sufficiency is based on the HDI level desired. In those scenarios, all countries are set to have the same value, whether it is a lower or a higher one than their 2019-level. For the "average of HDI≥0.8 countries", the average GVA_pp values of all countries that have an HDI level of 0.8 or above is taken. This value equals 0.0426 million €/pp. For the "HDI=0.8", the GVA_pp value is obtained using a semi-logarithmic least square fit (*Figure A.1.*). This function type has been regularly used in literature to represent the relationship between energy use per capita and HDI (40, 41). I use it here to determine the relationship between GVA per capita and HDI with a high goodness-of-fit value (R^2=0.900); and apply the resulting equation to find GVA_pp for an HDI level of 0.8. This value equals 0.0191 million €/pp.

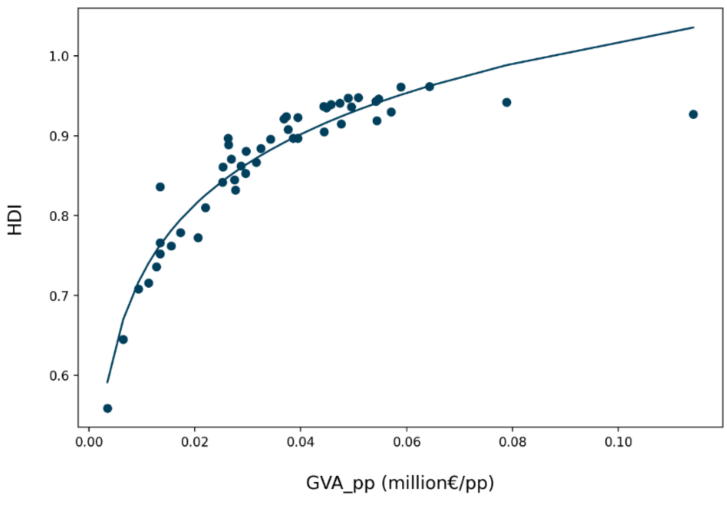

Figure A.1. Semi-logarithmic least square fit between HDI and gross value-added per capita, in 2019.

The parameter values can be seen alongside their regional 2019 levels in *Figures A.2. & A.3.* hereunder.

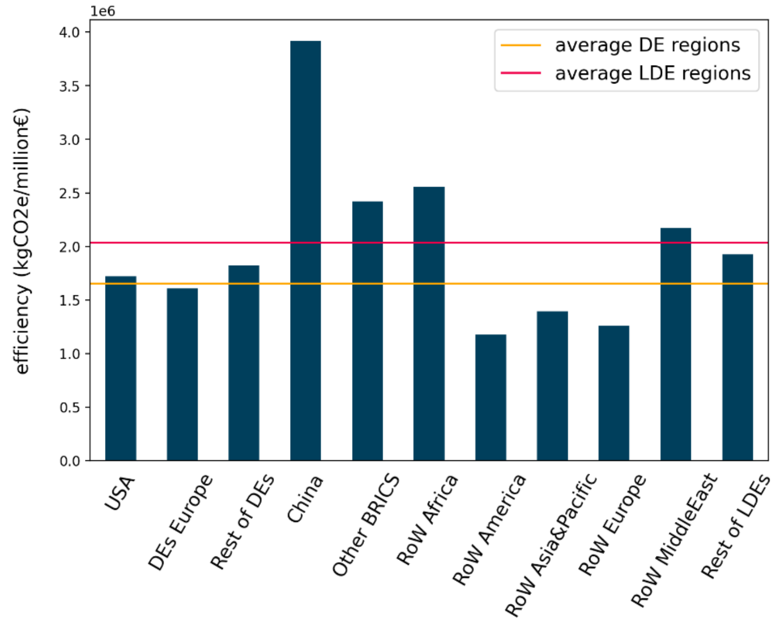

Figure A.2. Efficiency levels in 2019, per region, in kgCO$_2$e/million€.

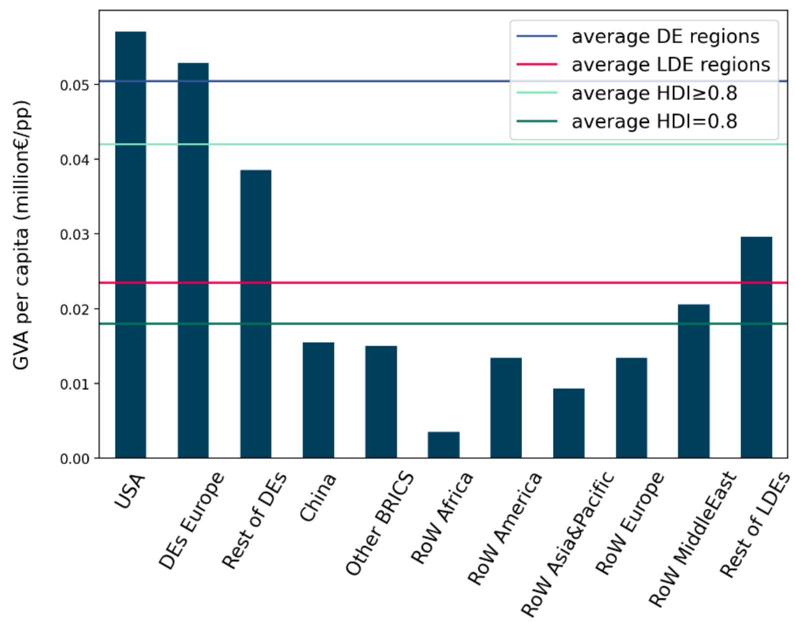

Figure A.3. Sufficiency levels in 2019, per region, measured as GVA per capita, in million€/pp.

For reference, the regional population sizes in 2019 and 2050 are given in *Table A.2.*, along with HDI levels in 2019.

Table A.2. Population size in 2019 and 2050, and average HDI score in 2019, per region.

	Population		HDI (2019)
	2019	2050	
BRICS_Rest	1.7E+09	2.2E+09	0.748
China	1.4E+09	1.3E+09	0.762
DE_Europe	4.2E+08	4.6E+08	0.927706
DE_Rest	2.7E+08	2.9E+08	0.911
LDE_Rest	5.5E+08	5.8E+08	0.862375
RoW_Africa	1.2E+09	1.8E+09	0.558706
RoW_America	3.1E+08	3.7E+08	0.751935
RoW_Asia&Pacific	9.7E+08	1.2E+09	0.708282
RoW_Europe	7.4E+07	6.9E+07	0.836417
RoW_MiddleEast	3.2E+08	5E+08	0.772733
USA	3.4E+08	4E+08	0.93
TOTAL	7.5E+09	9.2E+09	NA

Table A.3. also provides additional information relating to equation (2): the LEF linked to the 2019 capital stock that still remains in 2050 with both regional total and per capita values, and the retirement to net accumulation ratio for a period of 30 years, calculated backwards from 2019.

Table A.3. Amount of LEF from 2019 remaining in 2050, per region, total and per capita, in kgCO_2e; and retirement to net accumulation ratio for a 30-year period (1989-2019).

	2019 LEF remaining in 2050 (kgCO_2e)		Retirement/Net accumulation (30-year period, 1989-2019)
	total	per capita	
BRICS_Rest	1.6028E+13	7401.999	0.479577
China	1.7423E+13	13793.45	0.276757
DE_Europe	7.575E+12	16543.19	0.388787
DE_Rest	4.524E+12	15702.5	0.420705
LDE_Rest	5.5485E+12	9535.587	0.244443
RoW_Africa	4.2965E+12	2356.183	0.439669
RoW_America	1.8522E+12	5072.78	0.383714
RoW_Asia&Pacific	3.0687E+12	2464.548	0.380186
RoW_Europe	5.5994E+11	8123.123	1.256342
RoW_MiddleEast	5.4258E+12	10762.72	0.226739
USA	1.1706E+13	29097.4	0.377217

Appendix C. Regional classification.

The regional classification is similar to the one in the LEF paper by Wang et al. (2023), except that the Rest of the World regions are kept separate. Moreover, Taiwan was removed from the list as the SSP data used did not include it.

Table B.1. Two regional classifications.

Two regions	Developed economies (DE)[a]	Austria, Belgium, Germany, Denmark, Spain, Finland, France, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Sweden, United Kingdom, United States, Japan, Canada, Australia, Switzerland, Turkey, and Norway
	Less-developed economies (LDE)	Bulgaria, Cyprus, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovenia, Slovakia, China, South Korea, Brazil, India, Mexico, Russia, Indonesia, South Africa, RoW Asia and Pacific[b], RoW America[b], RoW Europe[b], RoW Africa[b], and RoW Middle East[b]
Eleven regions	United States	United States
	DE_Europe	Austria, Belgium, Germany, Denmark, Spain, Finland, France, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Sweden, United Kingdom, Switzerland, and Norway
	Rest of DE	Japan, Canada, Australia, and Turkey
	China	China
	Rest of BRICS	Brazil, India, Russia, and South Africa
	Rest of LDE	Bulgaria, Cyprus, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Latvia, Malta, Poland, Romania, Slovenia, Slovakia, South Korea, Mexico, Indonesia
	5 distinct Rest of the World (RoW) regions[b]	Rest of Asia and Pacific[b], Rest of America[b], Rest of Europe[b], Rest of Africa[b], and Rest of Middle East[b]

[a] DE includes countries that joined the Organisation for Economic Co-operation and Development (OECD) by 1990. OECD-1990 includes the 20 founding countries of OECD and Japan, Finland, Australia, and New Zealand. We consider the later members that joined during OECD's enlargement to Central Europe (e.g., Poland, Czech Republic, and Estonia), Latin America (e.g., Chile and Mexico), and Asia (e.g., South Korea) as LDE in this analysis.

[b] countries not individually specified in Exiobase 3.

Appendix D. Detailed results.

Table C.1. Future emissions (2020-2050) by 11 regions, and globally, in $GtCO_2e$.

	2019	BAU	Dev_w	2% ef.	Ef_w	Suf_h	Suf_l	Sust_h	Sust_l
BRICS_Rest	33.2	29.4	234.0	117.7	105.0	191.1	69.4	85.1	28.7
China	82.4	75.7	296.6	151.7	51.1	243.2	91.4	38.8	3.9
DE_Eur.	27.4	31.1	37.3	15.6	14.3	28.3	6.2	9.7	0.5
DE_Rest	17.0	19.4	27.8	12.3	9.4	22.1	5.8	6.8	0.3
LDE_Rest	15.9	12.6	39.0	18.2	16.1	31.4	9.6	12.5	3.2
RoW_Afr.	10.5	17.3	332.7	178.7	113.2	276.0	114.7	93.2	36.4
RoW_Am.	4.9	5.4	27.5	13.8	13.8	22.4	8.1	11.1	3.3
RoW_A&P	12.6	18.1	116.9	61.8	61.8	96.6	38.9	50.8	19.3
RoW_Eur.	1.3	1.4	8.6	4.1	4.1	7.0	2.3	3.2	0.7
RoW_ME	14.2	21.0	61.1	30.3	21.5	49.7	17.5	16.8	3.4
USA	33.0	38.3	38.3	13.6	12.4	24.0	1.1	4.9	0.0
TOTAL	252.4	269.8	1219.8	617.8	422.7	991.8	364.9	332.8	99.7

Table C.2. Future per capita emissions (2020-2050) by 11 regions, and their global average, in $kgCO_2e/pp$.

	2019	BAU	Dev_w	2% ef.	Ef_w	Suf_h	Suf_l	Sust_h	Sust_l
BRICS_Rest	19111	13559	108051	54356	48468	88270	32035	39291	13261
China	60710	59901	234807	120079	40459	192543	72387	30736	3094
DE_Eur.	65890	68000	81383	34049	31276	61898	13496	21243	1128
DE_Rest	63174	67315	96628	42675	32661	76753	20247	23496	1194
LDE_Rest	28790	21646	67103	31323	27698	53922	16449	21444	5474
RoW_Afr.	8961	9508	182466	97990	62088	151346	62875	51124	19954
RoW_Am.	15824	14877	75245	37855	37855	61471	22312	30341	8980
RoW_A&P	13025	14576	93846	49646	49646	77563	31272	40764	15512
RoW_Eur.	16916	19839	124826	59760	59760	100856	32712	46685	9514
RoW_ME	44700	41632	121135	60076	42592	98642	34694	33250	6690
USA	98294	95299	95299	33770	30746	59614	2618	12078	0
AVERAGE	33594	29432	133083	67405	46121	108215	39815	36307	10875

Table C.3. Emission reduction ratios between scenarios, per region.

	Dev_w[a]	2% ef.[b]	Ef_w[c]	Ef_w[b]	Suf_h[b]	Suf_l[d]	Suf_l[b]	Sust_h[b]	Sust_l[b]
BRICS_Rest	8.0	2.0	1.1	2.2	1.2	2.8	3.4	2.8	8.1
China	3.9	2.0	3.0	5.8	1.2	2.7	3.2	7.6	75.9
DE_Eur.	1.2	2.4	1.1	2.6	1.3	4.6	6.0	3.8	72.2
DE_Rest	1.4	2.3	1.3	3.0	1.3	3.8	4.8	4.1	80.9
LDE_Rest	3.1	2.1	1.1	2.4	1.2	3.3	4.1	3.1	12.3
RoW_Afr.	19.2	1.9	1.6	2.9	1.2	2.4	2.9	3.6	9.1
RoW_Am.	5.1	2.0	1.0	2.0	1.2	2.8	3.4	2.5	8.4
RoW_A&P	6.4	1.9	1.0	1.9	1.2	2.5	3.0	2.3	6.0
RoW_Eur.	6.3	2.1	1.0	2.1	1.2	3.1	3.8	2.7	13.1
RoW_ME	2.9	2.0	1.4	2.8	1.2	2.8	3.5	3.6	18.1
USA	1.0	2.8	1.1	3.1	1.6	22.8	36.4	7.9	N/A

[a] in relation to the *BAU* scenario; [b] in relation to the *Developed World* scenario; [c] in relation to the first stage of 2% yearly improvement in the Efficient World scenario; [d] in relation to the high *Sufficient World* scenario

Table C.4. Equity-based shares of RCB (500 $GtCO_2e$) per region, in $GtCO_2e$; and per capita in each region, in $kgCO_2e$.

	Responsibility		**Capability (GVA_pp)**		**Capability (HDI)**	
	Total ($GtCO_2e$)	pp ($kgCO_2e$)	Total ($GtCO_2e$)	pp ($kgCO_2e$)	Total ($GtCO_2e$)	pp ($kgCO_2e$)
BRICS_Rest	152.5	70405	128.0	59124	123.2	56882
China	17.6	13949	35.4	28005	63.1	49918
DE_Eur.	6.3	13866	4.5	9813	18.9	41245
DE_Rest	5.1	17858	3.7	12887	12.2	42313
LDE_Rest	29.1	50084	16.8	28938	28.8	49510
RoW_Afr.	172.3	94505	225.9	123898	124.1	68081
RoW_Am.	19.5	53515	11.8	32309	18.5	50586
RoW_A&P	81.0	65014	57.9	46520	66.9	53704
RoW_Eur.	3.5	50062	2.2	32255	3.1	45477
RoW_ME	9.6	18945	10.6	21068	24.8	49224
USA	3.5	8615	3.1	7606	16.5	40900