Brief Communication

The 'Global Stocktake' and the remaining carbon budgets for G20 countries to limit global temperature rise to +1.5 °C

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Abstract

The G20 brings together the world's major economies. Its members represent 85% of global GDP, 75% of international trade, and two-thirds of the world's population. According to the Intergovernmental Panel on Climate Change, the total remaining global carbon budget required to limit the world's temperature increase to 1.5 °C (with 67% likelihood) is 400 $GtCO_2$, decreasing to 50% likelihood if emissions reach 500 $GtCO_2$ between 2020 and 2050. The UNFCCC's 'Global Stocktake' addresses the distribution of the remaining carbon budget to countries and industry sectors, to assess the technical, financial, and policy measures required for decarbonization and the national and international responsibilities involved. In this paper, the decarbonization pathways for all G20 member countries with high technical resolution, are broken down into key industry sectors. The energy-related national carbon budgets necessary to maintain the remaining global carbon budget between 400 $GtCO_2$ and 500 $GtCO_2$ are calculated and a new methodology how a fair distribution can be achieved, considering the historical emissions and economic situations of all G20 countries is presented.

Article Highlights

- 1.5 °C sectoral pathways for all G20 countries with high technical reasolution.
- Breakdown global carbon budget to remain under 1.5 °C for all G20 countries and assessment of delayed implemtation.
- Introduction of 'Per Capita Carbon Index' as benchmark to determine fair carbon budget distribution for global stocktake.

Keywords Global Stocktake · Carbon budget · G20 country · Science-based target setting · Net-zero

1 Introduction

Achieving the goals of the Paris Climate Agreement (2015) will require the total decarbonization of the global energy system by 2050, with an emissions peak between 2020 and 2025 [1] and a drastic reduction in non-energy-related greenhouse gases (GHGs), including land-use-related emissions [2]. Based on the Agreement, countries have agreed to regularly report their GHG emissions and submit their 'Nationally Determined Contributions' (NDC),

The UN-convened Net Zero Asset Owner Alliance (the Alliance) is a Principles for Responsible Investment (PRI)- and UNEP FI-supported initiative, which commissioned the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS) to utilize their 1.5 °C One Earth Climate Model (OECM) (Teske et al., 2019) to derive decarbonization pathways.

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describing their planned measures to reduce GHG emissions. In 2021, the 'Global Stocktake' process began to collect the latest data on emissions and assess future developments based on NDCs already commenced. According to the United Nations Framework Convention on Climate Change (UNFCCC), the Global Stocktake '*enables countries and other stakeholders to see where they're collectively making progress toward meeting the goals of the Paris Agreement—and where they're not. It's like taking inventory*' [3].

This paper documents the decarbonization pathways for all G20 member countries,[1] broken down into key industry sectors and the energy-related national carbon budgets required to achieve the remaining global carbon budget of between 400 $GtCO_2$ and 500 $GtCO_2$ are calculated. The historic CO_2 emissions for all G20 countries are also considered in determining the overall carbon budget until 2050, as a basis for the allocation of national carbon budgets and a contribution to the UNFCCC's 'Global Stocktake' process. Additionally, a sensitivity analysis examines the impact of the delayed implementation of the 1.5 °C decarbonization scenarios on the global carbon budget.

2 Methodology

The decarbonization pathways for all G20 countries, and the global scenario, were developed with the One Earth Climate Model (OECM), noting that the overall remaining carbon budget cannot exceed 500 $GtCO_2$ between 2020 and 2050 if we are to limit the mean global temperature rise to + 1.5 °C with a likelihood of 50%. The OECM is an integrated energy assessment model that covers the entire energy system of a country or region, broken down into 16 industry-specific sectors. The methodology was developed by the Institute for Sustainable Futures at the University of Technology Sydney, with the support of the Institute of Networked Energy Systems and Energy Systems Analysis of the German Aerospace Center and in close co-operation with the finance sector of the Net-Zero Asset Owners Alliance and the United Nations Principles for Responsible Investment.

The methodology of the OECM provides high technical resolution and has been extensively documented in the scientific literature [4–7]. The sectorial breakdown is based on the Global Industry Classification Standard (GICS) (MSCI, 2020) and defines the system boundaries for the sector-specific decarbonization scenarios (Teske and Guerrero, 2022). The term 'technical resolution' refers to the level of detail with which the model captures specific technical processes, such as steel, aluminium, and cement production, transport modes, and vehicle types, and the energy-generation technologies used for power, (process) heat, and fuel supply [8].

The existing national industry sectors are calculated bottom up as part of the national energy scenario development. It is assumed that global market shares of national industry sectors will remain constant between 2020 and 2050. If a country produces 50% of the global steel in 2020, it is assumed that this global market share will remain constant until 2050. This assumption was applied to all analysed branches of industry in the manufacturing sector and raw material extraction.

The annual energy-related CO_2 emissions between 2020 and 2050 of all country-specific OECM 1.5 °C scenarios have been combined to calculate the total G20 carbon emissions. The accumulated carbon emissions for all industries, by country and globally, are also calculated. The results for all G20 countries are compared with the global emissions—both on national and sectorial levels. The historic emissions [9] of all G20 countries are included in the overall emissions balance. The total emissions—historic plus the projected energy-related CO_2 emissions until 2050 under the OECM 1.5 °C scenarios—are then divided by the countries' populations in 2020 to determine a per capita carbon emission index. Finally, we calculate the additional emissions for each sector and country if implementation is delayed by 5 or 7 years, assuming that a delay freezes emission at the 2022 levels for the period of the delay.

3 Remaining carbon budgets for G20 countries

In this study, we compare the calculated energy-related CO_2 emissions of all G20 countries with the global scenario under a defined carbon budget limit. The details of all countries' scenarios—in terms of energy demand and supply pathways and the assumed market and/or demand developments for 16 industry sectors (outlined in Table 1)—are documented in a separate open-access paper, which allows the input and output of data (Teske et al., 2023). Figure 1 shows the historic cumulative energy-related CO_2 emissions in 1750–2019, as previously documented, and the calculated CO_2 emissions under the OECM 1.5 °C pathways in 2020–2050. The historic and projected energy-related CO_2 emissions in 2020–2050 for each G20 country are divided by the current population to determine the country-specific emission index. The Per Capita Carbon Index (PCCI) is introduced as a benchmark with which to compare cumulative historic and projected

[1] G20 member countries—Canada, USA, Mexico, Brazil, Argentina, Germany, France, Italy, United Kingdom, Turkey, Russian Federation, Saudi Arabia, South Africa, Indonesia, India, China, Japan, South Korea, and Australia.

Table 1 Cumulative energy-related CO_2 emissions by sector (2020–2050) for all G20 OECM 1.5 °C pathways compared with the global remaining budget and the remaining carbon budgets for other countries

Sector	Industry	G20	G20 shares	Rest of the World (ROW)	ROW shares	Global
Cement (process heat, fuels, & electricity)	Industry	8554	89%	1102	11%	9657
Steel (process heat, fuels, & electricity)	Industry	27,421	98%	430	2%	27,851
Chemical Industry (process heat, fuels & electricity)	Industry	19,080	97%	509	3%	19,589
Textiles & Leather (process heat, fuels, & electricity)	Industry	3877	84%	746	16%	4623
Aluminium (process heat, fuels, & electricity)	Industry	5108	92%	450	8%	5558
Buildings, commercial, residential, & construction (heat, fuels, & electricity)	Services	57,803	91%	5565	9%	63,368
Fisheries (fuels & electricity)	Services	415	68%	200	32%	614
Agriculture & Food Processing (heat, fuels, & electricity)	Services	13,558	100%	49	0%	13,607
Forestry & Wood (heat, fuels, & electricity)	Services	8442	94%	550	6%	8993
Water Utilities (heat, fuels, & electricity)	Services	305	69%	134	30%	439
Aviation—Transport Services	Transport	6163	35%	11,580	65%	17,743
Aviation Industry Direct (fuels & electricity)	Transport	342	23%	1129	77%	1471
Navigation Transport Services	Transport	2079	16%	10,575	84%	12,653
Navigation Industry Direct (fuels & electricity)	Transport	484	27%	1285	73%	1770
Road Transport—Transport Services	Transport	56,100	76%	18,106	24%	74,205
Road Transport Industry Direct (fuels & electricity)	Transport	2936	63%	1737	37%	4673
All Other Sectors	Other	158,230	99%	1735	1%	159,965
Total cumulative CO_2 2020–2050	[$MtCO_2$]	370,897	87%	55,882	13%	426,779
Total cumulative CO_2 1750–2020		1,198,388		102,092		1,664,542
Total CO_2 budget beginning to end of fossil fuel era		1,569,286		157,974		2,091,321
2020–2050 carbon budget per capita (2020 population)		92		15		55
Carbon budget (1750–2050) per capita index (based on 2020 population)	[tCO_2/capita 1750–2050]	390		42		269
Regional CO_2 share	[%]	86.90%		13.10%		100.00%
Population share	[%]	51.80%		48.20%		100.00%
Population in 2020	[million]	4,022		3740		7762

emissions. However, the PCCI is a simplified calculation because historic and future population developments are not included. Therefore, the index is only an indication. The global OECM 1.5˚C pathway calculation in this analysis resulted in a total cumulative energy-related CO_2 emission of 426 $GtCO_2$ (2020–2050). The maximum value of 500 $GtCO_2$ was deliberately undercut in order to maximize the probability of achieving the 1.5 °C target.

3.1 Carbon budgets

Historic (1750–2019) and 1.5 °C pathway emissions (2020–2050) will lead to the total global emission of 2091 $GtCO_2$, 75% (1570 $GtCO_2$) of which will be emitted by the G20 countries. In terms of overall emissions, the USA is by far the greatest emitter, with 471 $GtCO_2$—87% are historic emissions and the future emissions allowance under the OECM pathway is 58.9 $GtCO_2$. The second greatest emitter is the 27 countries of the European Union (EU27), with 286 $GtCO_2$ of historic emissions, 30% less than the USA.

Under the OECM 1.5 °C pathway, the EU27 will decarbonize with a total remaining carbon budget of 32.9 $GtCO_2$, 44% less than the USA, even though the EU27 population is 448 million, 26% larger than the USA. The European economy is significantly more energy efficient than the USA economy, and the renewable energy share (final energy) in 2020 was 28%, more than twice that of the USA (11%). Therefore, the faster decarbonization of Europe's energy system is assumed. China is the third greatest emitter, with 227 $GtCO_2$ of historic emissions and a projected remaining carbon budget of 151 $GtCO_2$.

The USA, EU27, and China represent 28% of the global population (in 2020) and are responsible for 56% of historic emissions (926 $GtCO_2$). The 1.5 °C OECM decarbonization pathways for these three regions lead to a remaining carbon budget of 243 $GtCO_2$, 57% of the total

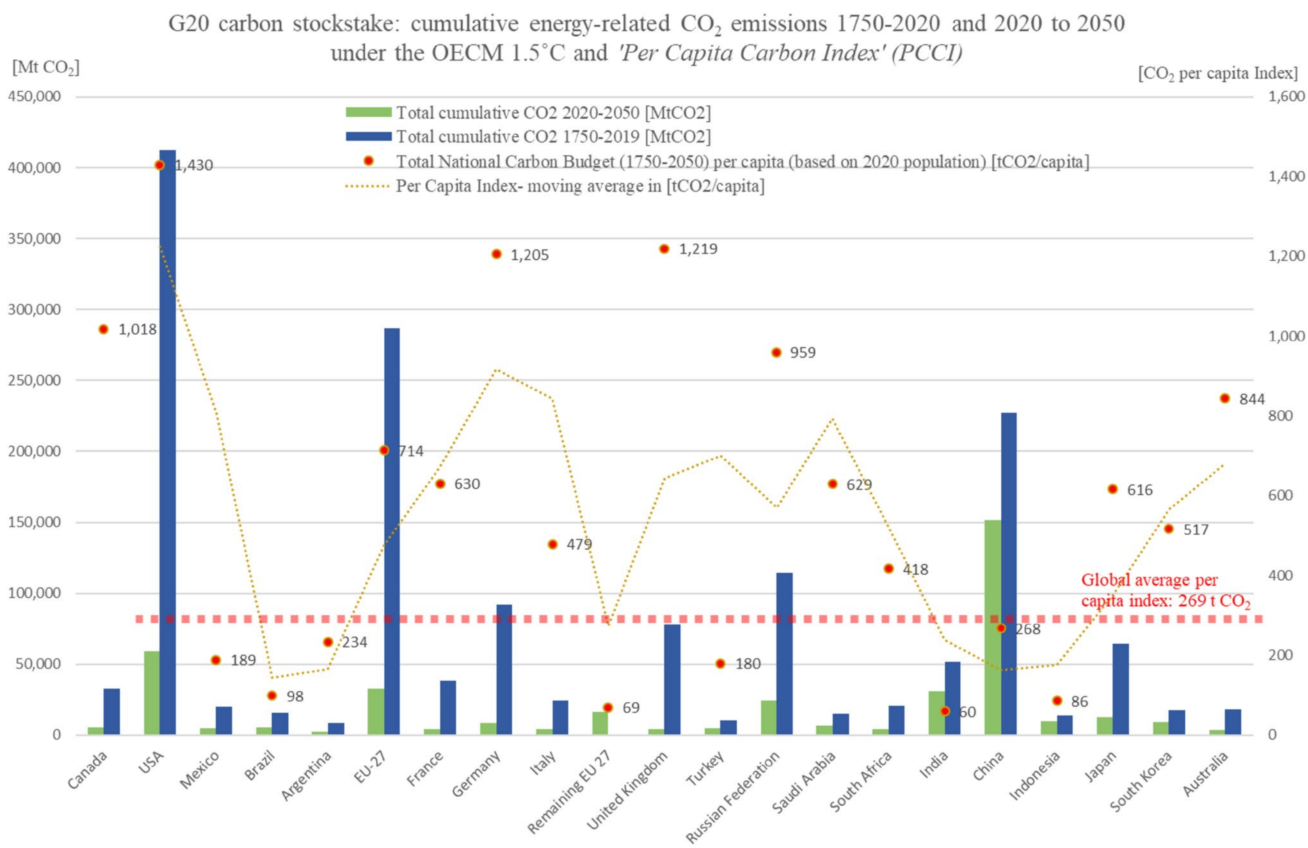

Fig. 1 G20 carbon stocktake: cumulative energy-related CO_2 emissions 1750–2020 and 2020–2050 under the OECM 1.5 °C pathways and Per Capita Carbon Index (PCCI)

global carbon budget of 426 $GtCO_2$. China is assumed to require the largest carbon budget to reach decarbonization. Under the national OECM 1.5 °C decarbonization pathway, China—with a population of 1.4 billion people, compared with 0.8 billion for the EU27 and USA combined—will cumulatively emit 151 $GtCO_2$ in 2020–2050, more than 1.5 times the remaining carbon budget of the EU27 and USA combined.

In terms of total combined historic and projected emissions, the fourth largest emitter is Russia, with 138.2 $GtCO_2$, followed by Germany (100.3 $GtCO_2$). All other G20 countries—including populous India—have significantly lower cumulative emissions, although some had significantly higher per capita emissions in 2020.

3.2 Per capita carbon index

The total carbon emitted determines the increase in global temperature, so an increase in global CO_2 emissions, and consequently the global carbon budget, will inevitably cause us to miss the 1.5 °C target. Therefore, increasing in the carbon budgets of countries with low historic emissions is not possible. To still determine fair CO_2 budgets for developing countries with little responsibility for climate change, the *Per Capita Carbon Index* (PCCI) is introduced. The historic emissions and future emissions under the OECM 1.5 °C pathway for each G20 member are divided by each country's population in 2020. The '*historic PCCI*' shows the level of responsibility and the '*1.5 °C PCCI*' provides a way to compare the remaining carbon budgets. In combination, the total PCCI provides a way to compare emissions, as required in the *Global Stocktake*. The overall PCCI for each country is compared with the global PCCI under the global OECM 1.5 °C scenario plus global historic emissions.

G20 countries are the world's major economies, representing 85% of global GDP, 75% of international trade, and two-thirds of the global population [10]. However, the national historic emissions of the G20 member countries vary significantly, and their individual PCCIs differ greatly: India has the lowest, with only 60 tCO_2/capita, whereas the USA has the highest, with 1430 tCO_2/capita—almost 24 times higher. The United Kingdom, Germany, and Canada have PCCIs > 1000 tCO_2/per capita. The global average PCCI is calculated to be 269 tCO_2/per capita—almost exactly the PCCI of China (268

Table 2 Total cumulative energy-related CO_2 emissions (2020–2050) for the G20, global, and 'rest of the world' if implementation of the 1.5 °C pathway is delayed by 5 or 7 years

Total cumulative energy-related CO_2 emissions (2020–2050) by G20, global, and 'rest of the world' (ROW) with a 5-year or 7-year delay in implementing the 1.5 °C pathway [$MtCO_2$]	5-year delay			7-year delay		
Sector	G20	ROW	Global	G20	ROW	Global
Cement	12,320	1502	13,821	13,826	1661	15,487
Steel	35,145	564	35,709	38,234	618	38,852
Chemical Industry	25,479	1090	26,569	28,038	1323	29,361
Textiles & Leather	5439	882	6321	6064	936	7000
Aluminium	7933	446	8380	9063	445	9508
Buildings—commercial, residential, & construction	85,257	9135	94,391	96,238	10,562	106,801
Fisheries	521	256	777	563	279	842
Agriculture & Food processing	19,891	304	20,195	22,424	406	22,830
Forestry & Wood	12,165	948	13,113	13,654	1107	14,761
Water Utilities	454	217	671	513	250	763
Aviation—Transport Services	8518	15,280	23,799	9460	16,761	26,221
Aviation Industry Direct	422	1107	1529	454	1098	1552
Navigation—Transport Services	2747	14,068	16,815	3014	15,466	18,479
Navigation Industry Direct	589	1258	1847	631	1247	1878
Road Transport—Transport Services	77,641	25,454	103,095	86,257	28,394	114,651
Road Transport Industry Direct	3935	1415	5350	4335	1286	5622
All Other Sectors	210,366	2862	213,228	231,220	3313	234,533
Total cumulative energy-related CO_2 emissions (2020–2050)	508,822	76,788	585,610	563,991	85,151	649,142

tCO_2/per capita). The results for all other developing countries are below the global average.

3.3 Carbon budget by sector

The 1.5 °C carbon budgets (2020–2050) for all 16 industry sectors analysed are shown in Table 1. Each sectorial carbon budget is presented as the sum for G20 member countries and compared with the results for the global pathway. The difference between the global and G20 emissions represents the carbon budget for all remaining countries. The OECM 1.5 °C pathways for all G20 countries reflect the current distribution of industry sectors. The G20 steel industry, for example, represents almost 90% of the current production capacity of the global steel industry, and is assumed to remain so until 2050.

3.4 Impact of implementation delay of the 1.5 °C OECM pathways

The total remaining global carbon budget required to limit the temperature increase to 1.5 °C (with 67% likelihood) is 400 $GtCO_2$. An increased carbon budget of 500 $GtCO_2$ will decrease the likelihood to 50%, and one of 650 $GtCO_2$ will reduce it to only 33%, according to the Intergovernmental Panel on Climate Change [1]. The impacts of delaying the implementation of the 1.5 °C pathways by 5 or 7 years are shown, by sector, in Table 2. A delay of 5 years—across all sectors and countries—will increase global carbon emissions from 426 $GtCO_2$ under the 1.5 °C OECM scenario to 585 $GtCO_2$, and the likelihood of meeting the + 1.5 °C target will decrease to < 50%. A delay of 7 years will increase the total emissions to 649 $GtCO_2$ in 2020–2050, reducing the likelihood of achieving the target to 33%.

A closer look at the development of sector-specific emissions and the increase in emissions if implementation is delayed shows that those of the transport sector and building sector will be significant. A 7-year delay in the road transport sector alone will increase emissions in in 2020–2050 by 39 $GtCO_2$.

4 Discussion and conclusion

It will be essential to remain within a global carbon budget well under 500 $GtCO_2$ if we are to meet the Paris Climate Agreement target of maintaining '*the global temperature rise this century well below 2 degrees Celsius above pre-industrial levels*' [11]. 'The IPCC 6th Assessment

Report (AR6) [1] highlighted that a global temperature rise of 1.5 °C would already lead to significant climate impacts. Therefore, the One Earth Climate Model (OECM) pathways aim to stay within a carbon budget to limit global temperature rise to 1.5 °C with a probability of 50% or more.'

The OECM 1.5 °C decarbonization scenarios were developed for countries, regions, and the world to provide possible mitigation pathways with high technical resolution and system boundaries that reflect the sector definitions used by the global finance industry. In this research, individual scenarios for all G20 countries have been created to assess how countries can decarbonize as quickly as possible while maintaining economic growth. Decarbonization pathways differ significantly because the demand and supply structures of each country are very specific. The level of industrialization, the dominant industry sectors, and the level of private consumption define their current emissions. Restructuring the energy sector to decarbonize a country's economy is possible in all OECM 1.5 °C pathways, but the national requirements for a carbon budget that allows decarbonization differ. Therefore, a fair distribution of the remaining carbon budget must consider the technical and economic situations of each country, and their historic emissions, in total and per capita, are also important factors. Although the remaining global carbon budget required to remain well under + 2 °C is fixed and cannot be negotiated, the Global Stocktake must go beyond defining national carbon budgets. It must include financial and technical support from those countries with the highest historical emissions to countries that have minor historical emissions but still require energy for economic development.

The *Per Capita Carbon Index* is one possible tool with which to develop such a global support mechanism. For instance, if a line is drawn at the global average PCCI of 269 tCO2/capita, all countries above that value must provide financial and technical support to those countries below that value. The higher the PCCI, the greater the responsibility to actively invest in decarbonization beyond a country's national borders. The determination of the carbon budget including the PCCI supports low and middle-income countries (LMIC) in particular in the allocation of funds for climate change adaptation as well as climate mitigation measures.

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Author contributions I am the single author of this manuscript. This article is a 'Brief Communication' and suggested a new methodology to define national carbon budget. This work is based on my own research only.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The author has no conflict of interests to declare.

Ethical approval This research involved no human participant or animal.

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