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Report

Evaluating equity in European climate change mitigation pathways for the EU Scientific Advisory Board on Climate Change

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01/06/2023

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ZVR 524808900

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The authors gratefully acknowledge funding from IIASA and the National Member Organizations that support the institute (The Austrian Academy of Sciences; The Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES); The National Natural Science Foundation of China (NSFC); The Academy of Scientific Research and Technology (ASRT), Egypt; The Finnish Committee for IIASA; The Association for the Advancement of IIASA, Germany; The Technology Information, Forecasting and Assessment Council (TIFAC), India; The Indonesian National Committee for IIASA; The Iran National Science Foundation (INSF); The Israel Committee for IIASA; The Japan Committee for IIASA; The National Research Foundation of Korea (NRF); The Mexican National Committee for IIASA; The Research Council of Norway (RCN); The Russian Academy of Sciences (RAS); Ministry of Education, Science, Research and Sport, Slovakia; The National Research Foundation (NRF), South Africa; The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS); The Ukrainian Academy of Sciences; The Research Councils of the UK; The National Academy of Sciences (NAS), USA; The Vietnam Academy of Science and Technology (VAST).

Abstract

This short report presents a systematic consideration of equity in emissions pathways at the level of the European Union. The study starts from a framework of international environmental law principles that inform national fair shares and from principles that are highlighted in European Climate Law. Building from this normative position, allocation approaches that can be considered 'fair' are described and indicators that allow their operationalization are identified. The implications of the various fairness approaches for the EU are quantified and compared with stylistic European climate change mitigation pathways.

Acknowledgments

The analysis in this report was carried out in support of the European Scientific Advisory Board on Climate Change's (Advisory Board's), preparations of its advice on the EU 2030–2050 greenhouse gas budget and related emissions targets for 2040. The presented work provides independent reflection, evidence, and analysis, but does not provide advice to the EU. We gratefully acknowledge all inputs and suggestions received that helped frame the analysis and methodologies. All views expressed are those of the authors and not of IIASA or the Advisory Board.

Supporting material and citation

If citing, using, or building upon the report contents or the replication data and code, please cite:

Pelz, S., Rogelj, J., Riahi, K., 2023. Evaluating equity in European climate change mitigation pathways for the EU Scientific Advisory Board on Climate Change. International Institute for Applied Systems Analysis, Laxenburg. https://pure.iiasa.ac.at/18830

All data and code necessary to replicate the analysis is available: https://doi.org/10.5281/zenodo.7949883

Further reading

Byers, E., Brutschin, E., Sferra, F., Luderer, G., Huppmann, D., Kikstra, J., Pietzcker, R., Rodrigues, R., & Riahi, K., 2023. Scenarios processing, vetting and feasibility assessment for the EU Scientific Advisory Board on Climate Change. International Institute for Applied Systems Analysis, Laxenburg. https://pure.iiasa.ac.at/18828

Introduction

Considerations of equity feature prominently in both the UNFCCC and the Paris Agreement.

> *"The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof."* (Article 3.1, UNFCCC, 1992)

> *"This Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances."* (Article 2.2, Paris Agreement, 2015)

Klinsky et al. (2017) synthesize the recent literature, providing four lines of reasoning underpinning the continued commitment to equity in global climate change mitigation. Firstly, and as noted above, international climate treaties have an agreed obligation to consider differential impacts and how they affect human wellbeing around the world. Secondly, global cooperation is enhanced by, and likely requires, common understandings of fairness. Thirdly, understanding socio-politically relevant trade-offs that influence national political processes relating to climate mitigation requires an assessment of differential national and sub-national impacts. Finally, principled analyses of equity help mitigate the appropriation of fairness arguments hindering climate action.

There have been many approaches for operationalising equity and the intent of 'common but differentiated responsibilities and respective capabilities' (CBDR-RC) in determining nationally determined contributions (NDCs). Reflecting on the approaches used both explicitly and implicitly in submitted (intended) NDCs, Winkler et al. (2018) emphasise the need for more methodological rigour in the definitions of 'fairness' and corresponding operationalizations of equity. Specifically, they highlight the importance of seeking independent advice and understanding the consequences of normative decisions taken in one country's approach when applied to all countries. Expanding on this call for more methodological rigour, a recent critical review finds extensive unsubstantiated claims of value-neutrality across the climate change mitigate effort sharing literature (Dooley et al., 2021). The authors specifically caution against ad-hoc combinations of equity considerations in determining 'fair' allocations and provide clear guidelines in future assessment of climate change mitigation pathways with respect to principles of fairness, which we follow.

Considerations of equity are not restricted to ex-post evaluations of modelled cost-effective carbon budgets as has been done here, but can also be applied in exploring the effects of regionally differentiated strategies, such as regional carbon prices (Pye et al., 2020; Budolfson et al., 2021). Efforts to both extend modelling approaches to include considerations of equity and evaluate allocations of climate mitigation efforts should be seen as complementary and necessary in identifying feasible and fair paths to mitigate the worst of climate change.

In this short report, we present a systematic approach for how equity can be operationalised in the evaluation of proposed European climate change mitigation pathways. Our approach begins with principles highlighted in the European Climate Law and in international environmental law. We then consider peer-reviewed literature discussing mitigation effort allocation approaches from the year 2001 to 2022. Finally, we apply a selection of allocation approaches and compare the implied 'fair' emissions allocations with stylistic European climate change mitigation pathways.

Fairness principles highlighted in European Climate Law

We begin with fairness principles mentioned in the European Climate Law, the relevant excerpt of which is provided below.

> *"[…], the Union's and Member States' actions should be guided by the* ***precautionary*** *and* ***'polluter pays' principles*** *established in the Treaty on the Functioning of the European Union, and should also take into account the* ***'energy efficiency first' principle*** *of the Energy Union and the* ***'do no harm' principle*** *of the European Green Deal."* (para 9, Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), 2021, emphasis added)

The explicit references to these principles can serve as a guide to highlight emissions allocation approaches that are particularly aligned with the EU's own expressed preferences.

Principles of international environmental law

We then consider international equity and fairness principles. Rajamani et al. (2021) collate principles referenced in international law that function as a normative basis from which one can determine 'fair' allocations of climate change mitigation effort. They define four overarching principles as shown in Table 1 alongside the indicators aligned with these. This was conducted *'with a view to categorizing the indicators … that are supported by principles of international law, and those that are not.'* (Rajamani et al., 2021). Their work argues that the political position of grandfathering, alongside cost optimization and allocation using emissions per GDP are not supported as a basis for fairness and equity by the principles of international environmental law.

Table 1 – Principles of fairness referenced in international law and associated indicators (Rajamani et al., 2021)

Fairness principle	Interpretation	Associated indicators
Sustainable development	*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*	*GDP per capita, and classification as small island developing states (SIDS) or least developed countries (LDCs), those relating to 'basic needs' and the human development index.*
Special circumstances	*Requires that the special circumstances and specific needs of developing states, especially those that are least developed, and particularly vulnerable, be given priority, and/or full consideration.*	*Classification as SIDs or LDCs, and GDP per capita.*
CBDR-RC	*Recognizes that states have common but differentiated responsibilities in addressing environmental harm.*	*Historic responsibility, emissions per capita, GDP per capita, classification as SIDS or LDCs, and current and projected environmental harm.*
Equity	*A wider notion that encompasses arguments based on fairness, justice, equality (for equals), affirmative action, redistribution, and restoration.*	*Historic responsibility, emissions per capita, GDP per capita, classification as SIDS or LDCs, cumulative emissions and GDP per capita adjusted for development thresholds.*

The authors also identify two legal principles as supporting the allocation and interpretation of 'fair' shares in alignment with these fairness principles, namely *Harm prevention* and *Precaution*. These are also described in the European Climate Law. The former imposes a responsibility on states 'to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction'. The latter states that if there are 'threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation' (Rajamani et al., 2021). We discuss this further in our review of the literature.

The evolution of equity in mitigation effort literature

Our brief narrative review of the peer-reviewed literature comprises a selection of publications that reflect the recent evolution in the academic discourse and analytical approach, presented in chronological order as indicated in Figure 1.

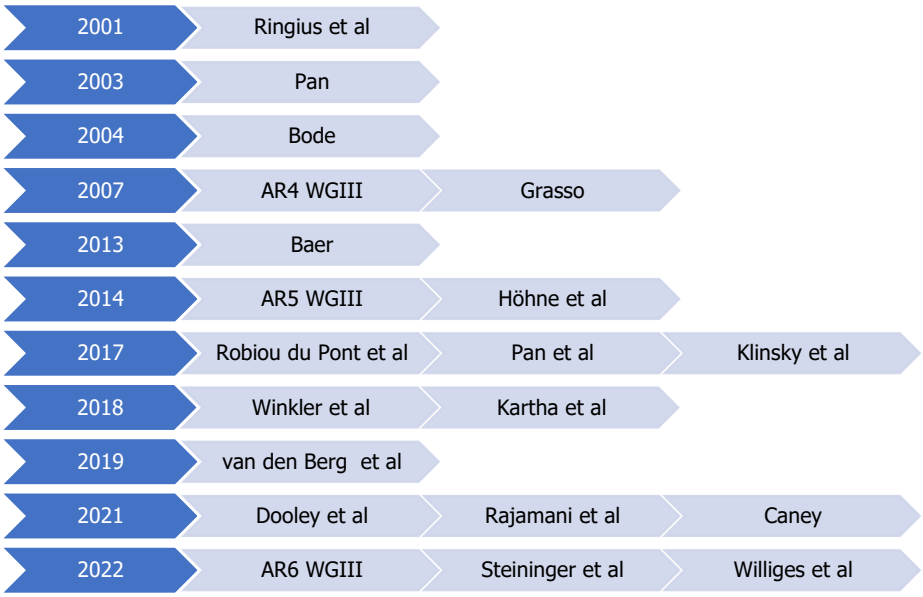


Figure 1 – The narrative review comprises a selection of peer reviewed original and synthesis articles that reflect the evolution in the academic discourse and analytical approach over the past two decades.

Ringius et al. (2001) collate and discuss fairness principles invoked in international climate negotiations prior to 2001. A summary of these is provided in Table 2. The authors synthesize three overarching substantive principles that reflect distributive fairness in this context, defined as *equality*, *equity*, and *exemption*.

- *Equality* stipulates that obligations (or allowances) associated with climate mitigation should be distributed equally across all parties. They underline that this principle has a 'firm normative basis if all parties involved are equal in all respects… [a condition] never met in global negotiations.'
- *Equity* stipulates that obligations (or allowances) associated with climate mitigation should be distributed in proportion to actor scores on a dimension considered relevant and important. Under *Equity* the authors describe the basis for the Responsibility, Capacity and Needs considerations common in contemporary literature.
- *Exemption* stipulates that the poorest countries, actors, or members of society are permitted a (temporary) exemption from climate mitigation efforts that arise from proportional effort shares determined under other principles.

The authors underline that in the absence of consensus around one unique 'trump,' effort sharing rules should combine at least two and preferably all three of the substantive equity principles. The three substantive principles are suggested to be combined and operationalised as follows. *"The principle of equality applies within groups or subsets that are considered sufficiently homogenous in important respects. The principle of equity applies where the critical differences exceed that threshold – except for the most disadvantaged parties, from whom no material contribution will be required so that they are exempted"* (Ringius et al., 2001).

Table 2 Selected fairness principles and related effort sharing rules invoked in climate negotiations (Ringius et al., 2001).

Fairness principle	Interpretation	Example of implied effort sharing rule
Egalitarian	*Every individual has an equal right to pollute or to be protected from pollution*	*Allow or reduce emissions in proportion to population*
Sovereignty	*All nations have an equal right to pollute or to be protected from pollution; current level of emissions constitutes a status quo right*	*Allow or reduce emissions proportionally across all countries to maintain relative emission levels between them*
Horizontal	*Countries with similar economic circumstances have similar emission rights and effort sharing responsibilities*	*Equalize net welfare change across countries (net cost of abatement as a proportion of GDP is equal for each country)*
Vertical	*The greater the ability to pay, the greater the economic effort*	*Net cost of abatement is directly correlated with per capita GDP*
Polluter pays	*The economic effort is proportional to emissions (eventually including historical emissions)*	*Share abatement costs across countries in proportion to emission levels*

Pan (2003) discusses the allocation of both international and intra-national emissions rights on a per capita basis. A key contribution of this work is the recognition that the poor, across all countries, must arguably be given priority in climate negotiations. The work thus critically explores the distributive justice implications of emissions trading and defines three levels or distinct 'natures' of emissions rights that scaffold considerations of equity in emissions trading approaches. The discussion of distinct characteristics of emissions rights, their assessment, transferability, and policy frameworks to operationalise these are summarised in Table 3.

Table 3 – Emissions rights and their transferability (J. Pan, 2003)

Nature of emissions rights	Assessment	Transferability	Policy framework
Basic necessity emissions rights for individuals.	*Basic needs for survival with respect to food, cooking, clothing, shelter, essential heating, and air conditioning in extreme conditions.*	*Correction of overuse/abuse of rights in the North: no repetition of wrongdoing by the South; No trading of such rights; cost-effective correction and avoidance of wrongdoing in an affordable manner.*	*Transfer of part of the unused rights from the South to the North during a transitional period in exchange for technology and financial resources.*
Individual rights but collectively managed in the name of state sovereignty and/or under state regulation.	*Claim of state sovereignty over part or all of the entitlements from a political, economic, or strategic perspective by political entities.*	*Exchangeability subject to political negotiation for both strategic and economic considerations of the political entity (state). Market may be created under political arrangement and supervision.*	*Creation of bubbles and alliances for international trading for mutual political and /or economic interest.*
Non-basic necessity emissions of individuals or groups of individuals.	*Similar to any other consumer goods, in particular, luxurious consumer goods.*	*Fully exchangeable, efficiency through market reallocation of entitlements.*	*Free market operations under "Market justice".*

Bode (2004), extends on the notion of per capita emissions rights to arrive at equal *cumulative* per capita emissions allocations. This allocation approach ensures that over a desired time period, cumulative emission per capita in all countries is equal and the annual emission per capita of all countries converges at the same level by the specified end year. This is achieved by first allocating to each country a constant per capita annual emission level aligned with the desired cumulative emissions over a desired period of allocation. This is summed over the period of allocation for each country and annualised from the desired first year of allocation using a quadratic functional form, providing an annual emissions pathway consistent with the aforementioned criteria and respecting a given starting level of annual emissions per capita in the first year of allocation. The results

are sensitive to the period of allocation and functional form of the emissions pathway, such that countries with high annual emissions per capita early in the allocation period may be allocated negative annual emissions per capita in later years.

Chapter 13 of the contribution of working group III to the IPCC's fourth assessment report (AR4) (2007) includes a summary of emissions allocation approaches evident in the literature to the date of assessment, shown in Table 4. Although the approaches are not explicitly linked to overarching principles of fairness, it is noted that several of these are linked to considerations of equity and the meeting of basic needs.

Table 4 – Overview of allocation approaches in IPCC's AR4-WGIII (Chapter 13, Table 13.2, p. 770, 2007)

Allocation approach	Description
Equal per capita allocation: Baer et al, 2000; Wicke, 2005	*All countries are allocated emission entitlements based on their population.*
Contraction and convergence: GCI, 2005	*Agreement on a global emission path that leads to an agreed long-term stabilization level for greenhouse gas concentrations ('Contraction'). Emission targets for all individual countries set so per-capita emissions converge ('Convergence').*
Basic needs or survival emissions: Aslam, 2002; Pan, 2005	*Emission entitlements based on an assessment of emissions to satisfy basic human needs.*
Adjusted per capita allocation: Gupta and Bhandari, 1999	*Allocation of equal per capita emissions with adjustments using emissions per GDP relative to Annex I average.*
Equal per capita emissions over time: Bode, 2004	*Allocation based on (1) converging per capita emissions and (2) average per capita emissions for the convergence period that are equal for all countries.*
Common but differentiated convergence: Höhne et al., 2006	*Annex I countries' per capita emissions converge to low levels within a fixed period. Non-Annex I countries converge to the same level in the same timeframe but starting when their per capita emissions reach an agreed percentage of the global average. Other countries voluntarily take on "no lose" targets.*
Grandfathering: Rose et al., 1998	*Reduction obligations based on current emissions.*
Global preference score compromise: Müller, 1999	*Countries voice preference for either per capita allocation or allocation based on current national emissions.*
Historical responsibility – the Brazilian proposal: UNFCCC, 1997b; …	*Reduction obligations between countries are differentiated in proportion to those countries' relative share of responsibility for climate change – i.e., their contribution to the increase of global-average surface temperature over a certain period of time.*
Ability to pay: Jacoby et al., 1998; Lecoq and Crassous, 2003	*Participation above welfare threshold. Emission reductions as a function of ability to pay (welfare).*
Equal mitigation costs: Rose et al., 1998; Babiker and Eckhaus, 2002	*Reduction obligations between countries are differentiated so that all participating countries have the same welfare loss.*
Triptych: Blok et al., 1997; den Elzen and Berk, 2004; Höhne et al., 2005	*National emission targets based on sectoral considerations: Electricity production and industrial production grow with equal efficiency improvements across all countries. "Domestic" sectors converge to an equal per-capita level. National sectoral aggregate levels are then adopted.*
Multi-sector convergence: Sijm et al., 2001	*Per-capita emission allowances of seven sectors converge to equal levels based on reduction opportunities in these sectors. Countries participate only when they exceed per capita threshold.*
Multi-criteria: Ringius et al., 1998; Helm and Simonis, 2001; Ringius et al., 2002	*Emission reduction obligations based on a formula that includes several variables, such as population, GDP and others.*

Grasso (2007) develops the foundations of a normative framework for the fair initial distribution of international emissions 'endowments' and exchange of these, guided by Rawls' Theory of Justice and Sen's Capabilities Approach, shown in Table 5. The work includes a detailed review of the literature and begins by defining domains of procedural and distributive justice that frame climate 'fairness'. Focussing on international climate negotiations, the author explores how principles within broader theories of justice relate to criteria of equity in the allocation and exchange of endowments. The Rawlsian *egalitarian* and *difference* principles are applied here. The former states that *"all individuals have the same right to the most extensive system of equal basic personal and political liberties, rights and duties, compatible with a similar system for all"*. The latter states that "*an injustice is tolerable only when it is necessary to avoid an even greater injustice*". Combined, these lead to similar notions of equal per capita allocations and qualifications associated with 'underserved inequalities' and with consideration to minimum basic needs as discussed by earlier scholars and in relation to the Capabilities Approach. Operationalisation of these criteria of equity must make visible what is unjust as defined by and in proportion to relevant and quantifiable attributes. Addressing what is unjust in terms of the initial allocation of endowments and historical consumption thereof – and with consideration given to differences in abatement costs – requires the exchange of endowments. This is then based on utilitarian pareto optimality which "*to be envy-free, and thus just, [requiring] … monetary compensation whereby no party prefers the emission rights and compensation payments of the others*."

Table 5 – Domains of justice and criteria of equity in climate mitigation (Grasso, 2007)

Domains of justice	Theory of justice	Criteria of equity
Initial allocation of endowments	*Rawlsian egalitarian and difference principles*	*Differentiated equality (equality considering undeserved inequalities)*
Exchange of endowments	*Utilitarian welfare economics*	*Pareto optimality supported by Envy-freeness*

Baer (2013) describes the Greenhouse Development Rights (GDRs) framework, "*a formula for global burden sharing based on a joint index of responsibility (contribution to climate change) and capacity (ability to pay),"* shown in Table 6. This approach explicitly departs from the earlier focus on (differentiated) equal per capita emissions allocations, arguing that such allocations are insufficient to enable industrialisation under precautionary carbon budgets and can lead to weakening of targets. Rather, the GDRs focus on sharing the burden of mitigation, though it is noted that these can be translated into allocations of carbon budgets using estimated business-as-usual emissions trajectories. Drawing on the principle of 'common but differentiated responsibilities and respective capabilities', the GDRs determine mitigation obligation on the basis of the individual, thus considering inequality within countries as well as that across countries. It is argued that as this attaches the 'right to development' to the individual, it moves in a principled manner beyond earlier rigid country-level analyses and associated demarcations (Annex 1 / Non-Annex I). The GDRs define capacity by summing individual incomes above a pre-determined income floor using both the GDP per capita and Gini coefficients as inputs. Responsibility is defined as the historical cumulative emissions excluding land use emissions from a specified starting year, which is similarly qualified with a pre-determined floor where the income distribution is linked with the emissions distribution for each year using an assumed elasticity of 1. Both capacity and responsibility are then determined as a share of the global aggregate. These ratios are then combined with desired weights summing to 1 and used to allocate the national burden of mitigation between a business-as-usual emissions pathway and a desired emissions trajectory. The approach is vulnerable to

uncertainties associated with a hypothetical baseline emissions pathway that remains static over time, and that starts from historical emissions in regions where targeted decarbonization may have already taken place.

Table 6 – The two allocation approaches comprising the GDRs (Baer, 2013)

Allocation name	Allocation definition	Data source
Capacity	*A country's economic wherewithal, a portion of which can reasonably be expected to be mobilized towards addressing climate change, considering the need for domestic social and economic development.*	*A country's income distribution based on the GDP and Gini coefficient in a particular year.*
Responsibility	*The degree to which a country has so far contributed to the build-up of greenhouse gases in the atmosphere.*	*Cumulative emissions from a start year up to a particular year, and annual income distributions as defined above.*

Chapter 4 of the contribution of Working Group III to the IPCC's fifth assessment report (AR5) (2014) includes a detailed summary of literature relating to the evaluation of equity in transformation pathways, drawing on the work conducted by Höhne et al. (2014). Reflecting a notable step forward, allocation approaches are explicitly grouped by overarching 'principles' of equity (namely Responsibility, Capability and Equality), and combinations of these, comprising the categories shown in Table 7. The cost-effective approach (Equal Marginal Abatement Costs) is included for reference but is not considered an equity principle in its own right.

Table 7 – Overview of allocation approaches in WGIII's contribution to the IPCC's AR5 (Chapter 4, Table 6.7, p. 458, 2014)

Categories	Description	References
Responsibility	*The concept to use historical emissions to derive emission goals was first directly proposed by Brazil in the run-up of the Kyoto negotiations (UNFCCC, 1997). Without allocations Allowances based only on this principle were quantified by only a few studies*	*Berk and den Elzen (2001)*. Den Elzen et al. (2005); Den Elzen and Lucas (2005)*
Capability	*Frequently used for allocation relating reduction goals or reduction costs to GDP or human development index (HDI). This includes also approaches that are focused exclusively on basic needs*	*Den Elzen and Lucas (2005); Knopf et al (2011); Jacoby et al (2009): Miketa and Schrattenholzer (2006): Kriegler et al (2013b) and lavoni et al (2013)*
Equality	*A multitude of studies provide allocations based on immediate or converging per capita emissions (e.g., Agarwal and Narain, 1991; Meyet 2000). Later studies refine the approach using also per capita distributions within countries (e.g., Chakravarty et al, 2009).*	*Berk and den Elzen (2001)*, Kriegler et al. (2013b) and Tavoni et al. (2013)**. Böhringer and Welsch (2006); Bows and Anderson (2008); Chakravarty et al (2009); Criqui et al. (2003); Den Elzen and Lucas (2005); Den Elzen and Meinshausen (2006); Den Elzen et al(2005, Edenhofer et al (2010); Hof et al. (2010b); Höhne and Moltmann (2008, 2009); Knopf et al(2009, 2011); Kuntsi-Reunanen and Luukkanen (2006): Nabel et al. (2011); Miketa and Schrattenholzer (2006): Peterson and Klepper (2007); Onigkeit et al (2009); Van Vuuren et al. (2009a, 2010)*
Responsibility, capability, and need	*Recent studies used responsibility and capability explicitly as a basis, e.g., Greenhouse Development Rights (Baer et al. 2008); or "Responsibility, Capability and Sustainable Development (Winkler et al. 2011)*	*Baer et al. (2008); Baer (2013): Höhne and Moltmann (2008, 2009): Winkler et al. (2011)*

Equal cumulative per capita emissions	*Several studies allocate equal cumulative per capita emission rights based on a global carbon budget (Pan, 2005, 2008). Studies diverge on how they assign the resulting budget for a country to individual years.*	*Bode (2004): Nabel et al. (2011): Jayaraman et al. (2011): Schellnhuber et al. (2009):*
Staged approaches	*A suite of studies propose or analyze approaches, where countries take differentiated commitments in various stages. Also approaches based on allocation for sectors such as the Triptych approach (Phylipsen et al, 1998) or sectoral approaches are included here. Categorization to a stage and the respective commitments are determined by indicators using all four equity principles Finally, studies using equal percentage reduction goals, also called grandfathering are also placed in this category.*	*Bosetti and Frankel (2012); Criqui et al. (2003): Den Ezzn and Lucas (2005): Den Elzen and Meinshausen (2006); Den Fizen et al (2007, 2008, 2012); Hof et al (2010a): Höhne and Moltmann (2008, 2009); Höhne et al (2005, 2006); Knopf et al (2011): Vaillancourt and Waaub (2004): Peterson and Klepper (2007); Böhringer and Welsch (2006); Knopf et al (2011) Berk and den Elzen (2001)*
Equal Marginal Abatement Costs (for reference)	*Modelling studies often use the allocations that would emerge from a global carbon price as a reference case for comparing other allocations*	*Peterson and Klepper (2007), Van Vuuren et al (2009a). Kriegler et al (2013b) and Tavon et al (2013)*

Equity evaluation after the IPCC's AR5 (WG3)

Subsequent to working group three's contribution to the IPCC's Fifth Assessment Report, the literature broadly follows the categorization it provides, operationalizing the 'principles' of Responsibility, Capability, (Need) and Equality, and their combinations, with distinct allocation approaches in different ways (Chapter 4, Table 6.7, p. 458, IPCC, 2014). We briefly examine applications of allocation approaches and criticism in the literature since AR5 below.

Robiou du Pont et al. (2017) apply five allocation approaches identified in the IPCC's AR5 (IPCC, 2014, p. 458) as shown in Table 8. The political position of 'grandfathering' evident in the operationalisation of three of the five approaches applied in this study has been criticized for privileging today's high-emitting countries when allocating future emission entitlements while providing no moral or normative basis justifying this (Kartha et al., 2018). This debate highlights the challenges faced when attempting to operationalise principles of equity and the weight of analytical decisions made in this process.

Table 8 – A selection of five distinct allocation approaches (Robiou du Pont et al., 2017).

Allocation name	IPCC category	Allocation characteristics
Capability	*Capability*	*High mitigation for countries with high GDP per capita*
Equal per capita	*Equality*	*Convergence towards equal annual emissions per person.*
Greenhouse development rights	*Responsibility / capability / need*	*High mitigation for countries with high GDP per capita and high historical per capita emissions.*
Equal cumulative per capita	*Equal cumulative per capita*	*High mitigation for countries with high historical per capita emissions.*
Constant emissions ratio	*Staged approaches*	*Maintains current emissions ratios.*

Pan et al. (2017) similarly apply a range of allocation approaches broadly aligned with the categories described in the IPCC's AR5 (IPCC, 2014, p. 458), shown in Table 9.

Table 9 – A selection of effort-sharing approaches (X. Pan et al., 2017)

Category	Approach	Allocation characteristics and main sources in literature
Responsibility	*Historical responsibility*	*Reduction burdens are allocated among participating countries based on their shares of historical responsibilities. An indicator (e.g., per capita GDP) is used to determine the participation of counties (e.g., Rive et al., 2006; Pan et al., 2014b)*
Capability	*Ability to pay*	*A bottom-up approach calculating allowances on a basis of the ability to pay often described by per capital GDP (e.g., Den Elzen and Lucas, 2005; Jacoby et al., 1999)*
	Emission intensity targets	*A bottom-up approach where allowances are calculated based on emission intensity improvements (e.g., Den Elzen et al., 2005; Miketa and Schrattenholzer, 2006 Miketa and Schrattenholzer, 2006)*
Equality	*Per capita convergence*	*Per capita emissions across countries gradually converge to the same level by a convergence date, then allowances are allocated based on equal per capita (e.g., GCI, 2005; Meyer, 2000)*
	Immediate per capita allocation	*Allocations are immediately in proportion to population (e.g., Agarwal and Narain, 1991; Baer et al., 2000)*
	One billion high emitters	*Individuals in a country reduce their luxurious emissions above a universal emission cap which is calculated based on distributions of per capita emissions (Chakravarty, 2009)*
Responsibility, capability, and need	*Greenhouse development rights*	*A burden-sharing framework considering both responsibility and capacity. The responsibility and capacity are determined by individuals above a pre-defined development threshold (Baer et al., 2009)*
	South-African approach	*A burden-sharing scheme based on both responsibility and capacity. The capacity is adjusted by human development index (components of life and education) to incorporate sustainable development needs (BASIC experts, 2011; Winkler et al., 2013)*
Equal cumulative per capita emissions	*Equal cumulative emissions per capita*	*Cumulative emissions per capita in a certain period are equal across countries (e.g., Pan et al., 2014a; Raupach et al., 2014)*
Staged approaches	*Common but differentiated convergence*	*Per capita emissions across countries converge to a common low level within a certain period. Start years of convergence are differentiated across countries by a participation threshold (Höhne et al., 2006)*
	Grandfathering rule	*Allocations are in proportion to emissions status-quo. An indicator (e.g., per capita GDP) is used to determine the participation of developing countries (e.g., Böhringer and Welsch, 2006; Robiou Du Pont et al., 2017)*
	Multi-criteria	*Allocations are based on different weights of per capita GDP, per capita emissions and emission intensity. An indicator (e.g., per capita GDP) is used to determine countries' participations (e.g., Pan et al., 2014b; Ringius et al., 1998)*
	Multi-stage	*Developing countries follow three stages to participate mitigations based on an indicator (e.g., a capacity-responsibility index): emitting as usual in the first stage; improving intensity in the second stage; absolute reducing in the third stage (e.g., Den Elzen et al., 2006; Van Ruijven et al., 2012)*

Winkler et al (2018) review 163 intended nationally determined contributions (INDCs) submitted in the lead up to the Paris Agreement. Although equity was found to be addressed almost across all of these, the quantity and quality of information provided describing how equity was operationalized varied, leaving room for improvement. Their evaluation of equity categorized the INDCs into three broad groups. An 'unsubstantiated' approach indicated that no detailed explanation was offered to support the claim that the contribution is fair; 'own analysis' indicated that the evidence was drawn entirely from analysis by in-country experts; and 'analysis by others' indicated that the evidence included analysis by experts in other countries. They found that "just over half of INDCs use own analysis, 75 are 'unsubstantiated', while only 2 (Nigeria and South Africa) refer to analysis by others." Two important recommendations can be drawn from this work. Firstly, *"increasing the rigour of information on equity … [requires that countries] … apply the principles of providing transparent, accurate, complete, comparable, and consistent information"*. Secondly, *"Neither qualitative information, nor*

quantitative indicators in themselves ensure equity … Equity lies in relative fair shares, meaning the distribution of contributions to mitigation … [across all countries].”

Van den Berg et al. (2019) apply six allocation approaches to both emissions pathways and carbon budgets, explicitly linking these with overarching principles of equity, shown in Table 10.

Table 10 – A selection of six different equitable allocation approaches and cost-effectiveness (van den Berg et al., 2019)

Allocation approach	Equity principle	Justification	Methodology for allocation
1. Grandfathering (GF)	*Sovereignty*	*Falling under the category 'acquired rights', that is justified by established custom and usage.*	*Allocations of carbon budgets based on current emission shares*
2. Immediate per capita convergence (IEPC)	*Equality*	*Based on the shared humanity and equal value of all humans, having equal claim to global collective goods.*	*Allocation of carbon budgets based entirely on average (projected) population shares in the period 2010–2100*
3. Per capita convergence (PCC)	*Sovereignty / equality*	*Combination of GF and IEPC*	*Allocation of carbon budgets based on both current emission shares and population shares*
4. Equal cumulative per capita emissions (ECPC)	*Equality / responsibility*	*A large amount of cumulative emission allowances per capita in industrialized countries has disproportionately used global emission space.*	*Allocation of carbon budgets based on cumulative emissions per capita in a certain period that is equal across countries. Incorporating historical cumulative emissions (responsibility) and based on the share of the population (equality)*
5. Ability to pay (AP)	*Capability / need*	*Based on the ability to bear the effort.*	*Carbon budget reduction targets from baseline are allocated based average GDP per capita over the period 2010–2100, taking into account increasing marginal costs with steeper reductions*
6. Greenhouse development rights (GDR)	*Responsibility / capability / need*	*Safeguarding people's right to 'reach a dignified level of sustainable human development'.*	*Considers both responsibility and capability.*
7. Cost-optimal (CO)	*Cost-effectiveness*	*Allowance according to the least-cost options from marginal abatement cost (MAC) curves.*	*Allocations of emission allowances based on mitigation potentials.*

Dooley et al. (2021) review 16 studies that evaluate equity in various climate mitigation pathways. In alignment with the critique of submitted INDCs by (Winkler et al., 2018), the authors find that "*many of these studies fail to clarify the ethical principles underlying their indicators, some mislabel approaches that favour wealthy nations as 'equity approaches' and some combine contradictory indicators into composites we call derivative benchmarks*". Particularly useful to our analysis, the authors argue that a purely equal per capita (EPC) allocation ignores differences in starting points, development needs and access to technologies. They indicate that this can be addressed through transparently justifying and combining allocations aligned with distinct principles. Here they provide direct words of caution. "*Any set of principles for equity in climate action that does not protect the vulnerable by recognizing differentiated responsibility due to different capabilities ignores both the actual history and a fundamental purpose of including equity in the assessment of climate action*". They then specifically warn against "… *equity analyses in which approaches that run contrary to this core concern, such as grandfathering or cost optimization, are treated as foundational elements.*". This work closes with three guidelines for evaluation of equity in climate mitigation pathways, which we summarize below:

- Do not claim value neutrality, be explicit about value judgements made.
- Keep losses of the poor and marginalized visible.
- Provide analytical quantification in support of but not as substitute to political debate that involves normative decisions.

Rajamani et al. (2021) collate overarching principles of fairness in international environmental law from national court decisions. They then apply two legal principles that narrow the range of allocation approaches consistent with these fairness principles, namely *Harm prevention* and *Precaution*. The authors then describe six distinct allocation approaches consistent with principles of international environmental law, shown in Table 11. This work represents a notable step forwards in justifying and selecting from the myriad of allocation approaches available in the literature on the basis of international legal precedent.

Table 11 – Allocation approaches consistent with principles of international environmental law (Rajamani et al., 2021)

Allocation name	Allocation definition
Responsibility	*Approaches in this category usually take cumulative historical emissions as an indicator for historical responsibility and assume that a country with higher historical emissions needs to reduce emissions more.*
Capability	*Approaches in this category usually use indicators such as GDP per capita or the Human Development Index and assume that states with higher values have a higher capability to reduce emissions and should do so. The 'basic needs' principle is also considered in this category because it can be considered an expression of the capability principle – least capable states could be permitted a less ambitious reduction effort to secure their basic needs.*
Responsibility, capability, and need	*Approaches in this category emphasize historical responsibility, capability and the need for sustainable development. They use a combination of the indicators listed in the previous categories.*
Equal per capita emissions	*This approach, pervasive in the quantification literature, allocates equal emission rights per person either immediately or assumes convergence over time. This approach is premised on the 'egalitarian' principle that every human being is entitled to the same atmospheric space. While it is not directly anchored in principles of international environmental law, it arguably finds support in human rights instruments and approaches.*
Equal cumulative per capita emissions	*Approaches in this category combine per capita equality with responsibility (cumulative accounting for historical emissions) to allocate emission levels based on total national carbon budgets.*
Staged approaches	*Staged approaches combine indicators to determine levels of reductions for groups of states that are staggered in time based on status or circumstances. For example, under a 'common but differentiated convergence' approach, developed states are expected to begin a transition toward equal per capita emissions before developing states. These approaches combine various elements and therefore are based on almost all of the indicators identified.*

Williges et al. (2022) allocate the remaining carbon budget from 2017 to 2050 using either equal per capita (EPC) or per-capita convergence (PCC) methods, qualifying these with the allocation approaches defined in the IPCC's AR5, as shown in Table 12.

Table 12 – Complete list of allocation approaches in IPCC's AR5 and their use in the study (Williges et al., 2022)

IPCC Category	Description	Analogue in this work
Responsibility	*Use of historical emissions to derive future reduction goals*	*Historical emissions qualification (Historical)*
Capability	*Disregarding causal and moral responsibility, approaches relating mitigation goals to capability (or capacity) to pay for – or most efficiently to contribute to – emissions reduction or approaches aiming at securing people's capability of leading a sufficiently good (decent) life.*	*Basic needs qualification (N-qualified)*
Equality	*Allocation based on equal emissions per person, applying current and/or future population projections*	*Equal per capita approach (EPC simple)*
Responsibility, capability, and need	*Includes approaches placing emphasis on historical responsibility, balanced with capability and need for sustainable development*	*Basic needs, historical emissions, and benefits qualifications (NHB-qualified); for EPC also reasonable effort limit qualification (NHBC-qualified)*

Equal cumulative per capita	*Combines equality with responsibility (cumulative accounting for historical emissions)*	*Historical emissions and benefits qualifications (HB-qualified)*
Staged approaches	*Differentiated commitments, various stages, sectoral approaches, or grandfathering approaches*	*Per capita convergence approach (PCC simple)*

Steininger et al. (2022) describe the redistribution of a European emissions budget between European countries using three principles of equity, which they defined as, capability, equality, and responsibility. Under each of these, the authors define a set of distinct interpretations or indicators specifically for the European context, as shown in Table 13.

Table 13 – Allocation approaches and corresponding indicators (Steininger et al., 2022)

Equity principle	Interpretation / indicators
Capability	*- EU implementation (2021 EU policy proposal capping countries' per capita GDP differences)* *- GDP per capita* *- Government effectiveness* *- Renewable growth capacity (Ability of countries to reduce emissions via development of RE sources)*
Equality	*- Basic needs (Emissions to meet basic needs energy demands of the population at risk of poverty)* *- ES-sector EPC convergence (Convergence to equal-per capita emissions by 2030 based on ES sectors)* *- Full-EPC convergence (Convergence to equal-per capita emissions by 2030)*
Responsibility	*- Historical emissions from 1995* *- Inherited benefits of emissions (emissions embodied in national capital stock)* *- C-budget (total emissions budget for the effort-sharing sectors, distributed by population)* *- Expansion of renewables (change in renewable share from 2005-2019 compared to the EU average)* *- Cumulative emissions per capita*

Finally, Working Group III's contribution to the IPCC's sixth assessment report includes a synthesis of contemporary literature evaluating equity considerations in climate mitigation pathways (Section 14.3.2.3, IPCC, 2022). Although discussions of equity feature throughout the report, little evolution is evident in the definition of 'principles' of equity and corresponding categorisation of allocation approaches since the previous assessment report. Rather the discussions presented suggests that as the definitions of equity as captured in AR5 are maturing, the discourse is shifting towards finding consensus on how to systematically link established principles of fairness with the most appropriate allocation approaches. Examples of this critical discussion include the contributions discussed previously in this section (Winkler et al., 2018; Dooley et al., 2021; Rajamani et al., 2021).

How do we evaluate equity?

We begin with a schematic overview of the approach followed in this report for evaluating equity in the assessment of European climate change mitigation pathways. In developing this approach we consider the reviewed literature and specifically follow the guidelines provided by Dooley et al. (2021), to not claim value neutrality (we make value judgments explicit), to keep losses of those who are marginalized visible (we show allocations across all regions), and provide analytical quantification in support but not as a substitute of a political debate that involves normative decisions (we use EU law as a guide and show implications and options).

Our approach builds on foundational principles evident in the European Climate Law and in international environmental law and treaties. We link these with four fairness principles emerging in the climate change mitigation effort sharing literature. Operationalising these principles requires the definition of corresponding allocation approaches. These allocation approaches distribute remaining carbon budgets in accordance with the overarching principles of fairness. The allocation approaches themselves select from (or combine) a set of measurable considerations. Measurable considerations in turn can be reflected by a set of indicators.

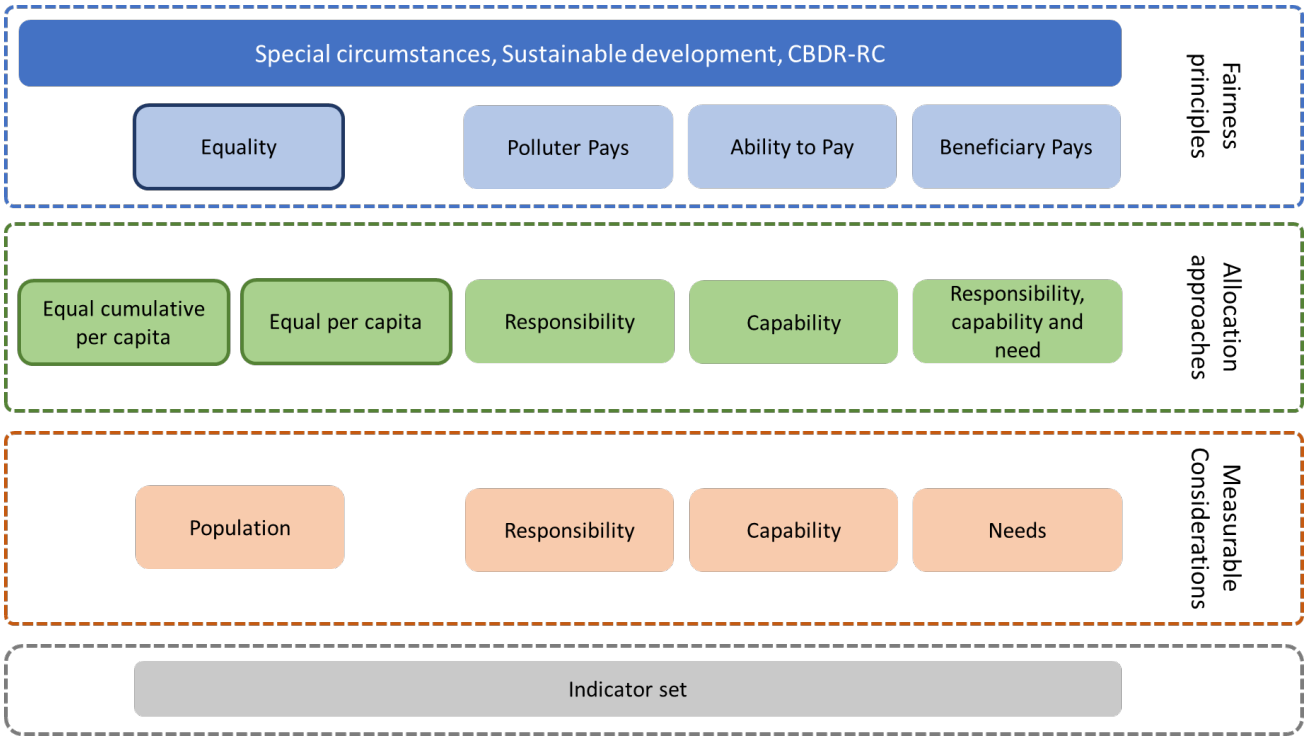


Figure 2 – Overview of our approach for operationalizing equity in evaluating European climate change mitigation pathways. To reduce cluttering, the indicators corresponding to each of the measurable considerations are not shown. Emphasis is placed on the Equality principle and associated allocation approaches, as these form the basis of our analysis.

Legal foundation

Our equity evaluation approach relies on fairness principles highlighted in the European Climate Law, as to some degree they illustrate political normative decisions about what the EU values and considers important.

The European Climate Law explicitly mentions the 'polluter pays' principle, which also features strongly in the broader equity and fairness literature. In addition, the *precautionary* and *do no harm* principles are mentioned in the Climate Law and can serve as guides for further refinement of choices. Finally, while the European Climate Law also mentions the 'energy efficiency first' principle, this would come into play at a later level only, when choices have to be made about how to translate 'fair' emissions into economy-wide mitigation strategies. This last step is not part of the scope of this report. Our equity evaluation approach also draws on a synthesis of international environmental law which discusses the principles of Sustainable development, Special circumstances, CBDR-RC, and Equity (Rajamani et al., 2021). This synthesis provides compelling evidence aiding the selection of equity considerations and leads to the exclusion of considerations that do not align with principles referenced in national court decisions. This excludes the political position of 'grandfathering' and underlines that the common implementation principle of 'cost-effectiveness' has no normative moral basis as a notion of equity or fairness.

Fairness principles

Principles of fairness provide clear reasoning underlying normative notions of 'what is fair'. We rely here on emerging principles in the climate mitigation effort sharing literature consistent with the aforementioned legal foundations. These include the Polluter Pays principle, the Ability to Pay principle, the Beneficiary Pays principle and the Equality principle (for further detail, see Caney, 2021). The original definitions of these principles describe distribution of mitigation effort, whereas our work focusses on allocation of remaining carbon budgets. We thus define how they relate to our work in Table 14; whereas the original wording can be explored in further detail in the cited literature. Operationalizing these principles requires the specification of corresponding allocation approaches, which we discuss next.

Table 14 – Principles of fairness in emissions allocation considered (modified from Caney, 2021)

Fairness principle	Definition
Equality	*Every person in all regions is allocated the same remaining carbon budget.*
Polluter Pays	*A remaining carbon budget is allocated in inverse proportion to historical emissions.*
Ability to Pay	*A remaining carbon budget is allocated in inverse proportion to the ability to pay mitigation costs.*
Beneficiary Pays	*A remaining carbon budget is allocated in inverse proportion to benefit received from past emissions.*

Allocation approaches

Allocation approaches specify how remaining carbon budgets are distributed across regions in alignment with desired fairness principles and legal foundation. We consider a selection of approaches, relying on literature which selects these on the basis of *Harm prevention* and *Precaution* (Rajamani et al., 2021). These are defined as Equal Per Capita Emissions, Equal Cumulative Per Capita Emissions, Responsibility, Capability and Responsibility-Capability-Need (Rajamani et al., 2021). Table 15 describes how we map these allocation approaches to principles of fairness. The starting allocation year refer to the year from which a remaining carbon budget is determined[1]. The final year of allocation refers to the desired year of global net zero CO_2.

Our goal is to allocate a remaining carbon budget, rather than to distribute effort. We must therefore adjust the approaches to suit our budget allocation goal. As shown in Table 15, we do this by first applying two allocation approaches as starting points, *Equal per capita* and *Equal cumulative per capita*. We then define the remaining allocation approaches as adjustments to the equal per capita and equal cumulative per capita budgets in proportion to the appropriate indicator values. This approach reflects at least two strong value judgements; first, this ensures resulting allocations correspond to the regional populations (as opposed to regions), second, the proportional adjustment discounts emissions prior to the first year of allocation (under Responsibility). By using allocations per capita as a base, rather than simply allocating proportionally by region, we are holding the overarching fairness principle of Equality as a mandatory building block in all subsequent evaluations. Our motivation to do so is to enable consistent relative allocations of a remaining carbon budget across countries with vastly different populations associated with indicators such as GDP per capita or historical emissions.

Table 15 – Allocation approaches considered (modified from Rajamani et al., 2021)

Allocation approach	Allocation definition	Aligned principles
Equal per capita	*Remaining carbon budgets are allocated equally on a per capita basis in the starting year of allocation.*	*Equality, (Polluter Pays, Beneficiary Pays)*[1]
Equal cumulative per capita	*Remaining carbon budgets are allocated equally on a cumulative per capita basis from the starting year of allocation to the final year of allocation.*	*Equality, (Polluter Pays, Beneficiary Pays)*[1]
Responsibility	*Countries with higher historical emissions are allocated proportionally lower per capita or cumulative per capita emissions.*	*Polluter Pays*
Capability	*Countries with higher economic capability are allocated proportionally lower per capita or cumulative per capita emissions.*	*Ability to Pay*
Responsibility, capability, need	*Countries with higher historical emissions, higher economic capability and higher levels of human development are allocated proportionally lower per capita or cumulative per capita emissions.*	*Beneficiary Pays*

[1]Polluter Pays and Beneficiary Pays principles are relevant here insofar as they can be considered to justify decisions made on the period over which allocation is to occur. Polluter Pays often requires establishing 'fault', in the literature, whereas Beneficiary Pays may not (Caney, 2021; Truccone-Borgogno, 2022). Shifting the year of allocation back from present day thus reflects an interpretation of the Polluter Pays or the Beneficiary Pays principle. For simplicity we do not differentiate or discuss this in the remainder of this report but note that this requires careful consideration when establishing a normative position on a region's fair share.

Measurable equity considerations

Equity considerations represent measurable characteristics of regions, countries, or populations. These are combined or used independently in the aforementioned allocation approaches. The considerations can be measured using several distinct indicators as shown in Table 16. As noted in the review of literature, there are several variations to the indicators that can have substantial weight on the resulting allocations. For instance, Responsibility and Capability indicators can be adjusted to address within-country (or within-region) inequality (Baer, 2013), and Needs can be represented as basic per capita energy or emissions allowances (J. Pan, 2003).

Table 16 Measurable considerations, corresponding indicators, and matching allocation approaches

Consideration	Indicators	Matching allocation approaches
Population	*Population* *Cumulative population*	*Equal per capita,* *Equal cumulative per capita*
Responsibility	*Historical cumulative emissions (CO2-FFCO$_2$CO2-FFI-Consumption)* *Historical cumulative per capita emissions (as above)*	*Responsibility,* *Responsibility, capability, need*
Capability	*GDP per capita* *Capital stock per capita*	*Capability,* *Responsibility, capability, need*
Needs	*Human Development Index*	*Capability,* *Responsibility, capability, need*

Regional grouping

While the goal of this report is to reflect on equity with respect to the emissions pathways of the EU27, consisting of the 27 member states of the European Union, we also provide allocations for the other regional groups as shown in Table 17.

Table 17 – Overview of the regional grouping employed in the allocation exercise

Region	Country ISO3C code
EU27	***AUT; BEL; BGR; CYP; CZE; DEU; DNK; ESP; EST; FIN; FRA; GRC; HRV; HUN; IRL; ITA; LTU; LUX; LVA; MLT; NLD; POL; PRT; ROU; SVK; SVN; SWE***
REU	*ALB; AND; BIH; CHE; FRO; GBR; GIB; GRL; IMN; ISL; LIE; MCO; MKD; MNE; NOR; SCG; SJM; SMR; SRB; TUR; VAT; YUG*
CPA	*CHN; HKG; KHM; LAO; MNG; PRK; VNM*
FSU	*ARM; AZE; BLR; GEO; KAZ; KGZ; MDA; RUS; TJK; TKM; UKR; UZB*
LAM	*ABW; AIA; ANT; ARG; ATG; BES; BHS; BLZ; BMU; BOL; BRA; BRB; CHL; COL; CRI; CUB; CUW; CYM; DMA; DOM; ECU; FLK; GLP; GRD; GTM; GUF; GUY; HND; HTI; JAM; KNA; LCA; MEX; MSR; MTQ; NIC; PAN; PER; PRY; SLV; SUR; SXM; TCA; TTO; URY; VCT; VEN; VGB*
MEA	*ARE; BHR; DZA; EGY; ESH; IRN; IRQ; ISR; JOR; KWT; LBN; LBY; MAR; OMN; PSE; QAT; SAU; SDN; SSD; SYR; TUN; YEM*
NAM	*CAN; GUM; PRI; SPM; USA; VIR*
PAS	*ASM; BRN; CCK; COK; CXR; FJI; FSM; IDN; KIR; KOR; MAC; MHL; MMR; MNP; MYS; NCL; NFK; NIU; NRU; PCI; PCN; PHL; PLW; PNG; PYF; SGP; SLB; THA; TKL; TLS; TON; TUV; TWN; VUT; WLF; WSM*
PAO	*AUS; JPN; NZL*
SAS	*AFG; BGD; BTN; IND; LKA; MDV; NPL; PAK*
AFR	*AGO; BDI; BEN; BFA; BWA; CAF; CIV; CMR; COD; COG; COM; CPV; DJI; ERI; ETH; GAB; GHA; GIN; GMB; GNB; GNQ; KEN; LBR; LSO; MDG; MLI; MOZ; MRT; MUS; MWI; MYT; NAM; NER; NGA; REU; RWA; SEN; SHN; SLE; SOM; STP; SWZ; SYC; TCD; TGO; TZA; UGA; ZAF; ZMB; ZWE*

Defining the remaining carbon budget

In allocating a *remaining* carbon budget (RCB), we must select a starting year of allocation from which point the remaining carbon budget is determined. We choose the years 1990 and 2015 as two alternatives here. 1990 is the year of the First Assessment Report of the IPCC which was the basis of the UNFCCC. 2015 is the year of the adoption of the Paris Agreement. Next, we specify the desired global temperature target with a desired likelihood. Here we choose a target of limiting global warming to 1.5°C with a likelihood of 50%. The latest

evidence available from the Intergovernmental Panel on Climate Change (IPCC) suggests that this results in a RCB_{2020} of 500 GtCO2 from the year 2020 (Canadell et al., 2021). The RCB from the two starting years of allocation (1990 and 2015) are then estimated by adding to this budget the estimated historical CO_2 emissions from 1990-2019 (1030 GtCO2) and 2015-2019 (204 GtCO2) (Friedlingstein et al., 2022). This gives us a RCB_{1990} of 1530 Gt and a RCB_{2015} of 704 Gt, starting from the years 1990 and 2015.

Allocating remaining carbon budgets – Equality

As noted earlier, we begin with two starting allocation approaches - equal per capita (EPC) and equal cumulative per capita $(ECPC)$. RCB_{EPC} allocates the $RCB_{1990,2015}$ equally across the global population (P_{PC}) in the starting year of allocation. RCB_{ECPC} allocates the RCB equally across all cumulative person-years (P_{CPC}) from the starting year of allocation to 2050. Both RCB_{EPC} and RCB_{ECPC} are global values and necessarily identical across all eleven regions (r).

$$RCB_{EPC,ECPC} = \frac{RCB_{1990,2015}}{\sum_{r}^{11}\left(P_{PC,CPC_r}\right)} \quad (1)$$

Corresponding total regional budgets $(RCB_{1990,2015_r})$ are then determined by scaling the equal global per capita budgets by the regional populations, as shown in Equation 2.

$$RCB_{1990,2015_r} = RCB_{EPC,ECPC} \times P_{PC,CPC_r} \quad (2)$$

Allocating remaining carbon budgets – Polluter Pays / Ability to Pay

From these two starting approaches, we can then determine the remaining regional per capita allocations for Responsibility, Capability and Responsibility, Capability, Needs allocation approaches by shifting the global $RCB_{EPC,ECPC}$ in proportion to specific regional indicator values corresponding to the respective allocation approach as shown in Equation 3. The intuition here is that for each region, we proportionally increase or decrease the global per capita budget $(RCB_{EPC,ECPC})$ described above in proportion to the region's historical Responsibility or current Capability relative to other regions.

$$RCB_{\widehat{PC},\ \widehat{CPC}_{i,r}} = \frac{\widehat{x_{i,r}} \times RCB_{1990,2015}}{\sum_{r}^{11}\left(\widehat{x_{i,r}} \times P_{PC,CPC_r}\right)} \quad (3)$$

This requires us to define a set of regional indicators $(x_{i,r})$ corresponding to each measurable consideration for each year of allocation. This is shown in Table 18, which lists the regional indicators used and the measurable consideration to which they correspond (See Table 16 to map these to allocation approaches and overarching fairness principles). Note that we exclude historical Land Use, Land-Use Change, and Forestry (LULUCF) CO2 emissions due both to the uncertainty in quantifying these emissions and the ongoing debate in determining

the anthropogenic fraction of these which complicates comparability. Allocation of historical CO2-FFI emissions to regions excludes those attributable to international bunkers.

Table 18 – Selected regional indicators corresponding to each measurable consideration for selected years of allocation.

Allocation Year	Regional indicator	Consideration
1990	*Population 1990*	*Population*
1990	*Cumulative Population 1990-2050*	*Population*
1990	*Cumulative CO2-FFI 1850-1989*	*Responsibility*
1990	*Cumulative per capita CO2-FFI 1850-1989*	*Responsibility*
1990	*GDP per capita 1990*	*Capability*
1990	*Capital stock per capita 1990*	*Capability*
2015	*Population 2015*	*Population*
2015	*Cumulative Population 2015-2050*	*Population*
2015	*Cumulative CO2-FFI 1850-2014*	*Responsibility*
2015	*Cumulative CO2-FFI 1990-2014*	*Responsibility*
2015	*Consumption CO2 1990-2014*	*Responsibility*
2015	*Cumulative per capita CO2-FFI 1850-2014*	*Responsibility*
2015	*Cumulative per capita CO2-FFI 1990-2014*	*Responsibility*
2015	*Cumulative per capita Consumption CO2 1990-2014*	*Responsibility*
2015	*GDP per capita 2014*	*Capability*
2015	*Capital stock per capita 2014*	*Capability*

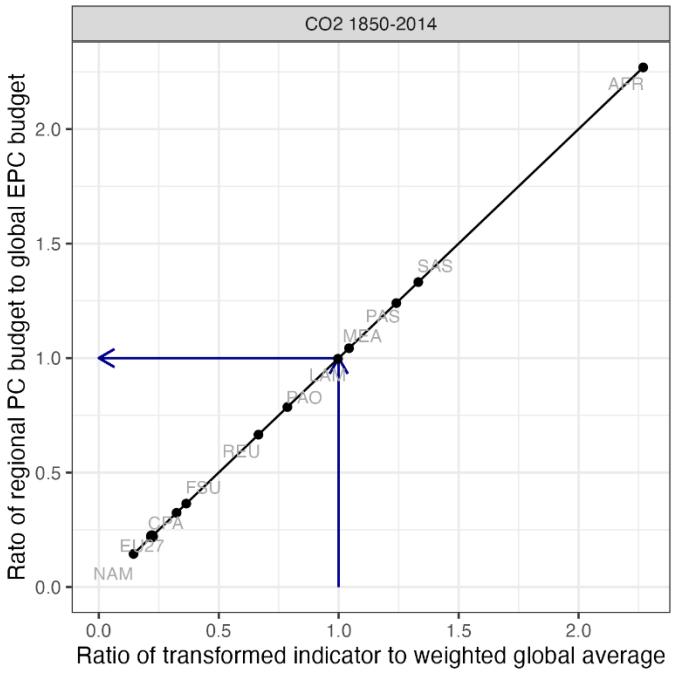


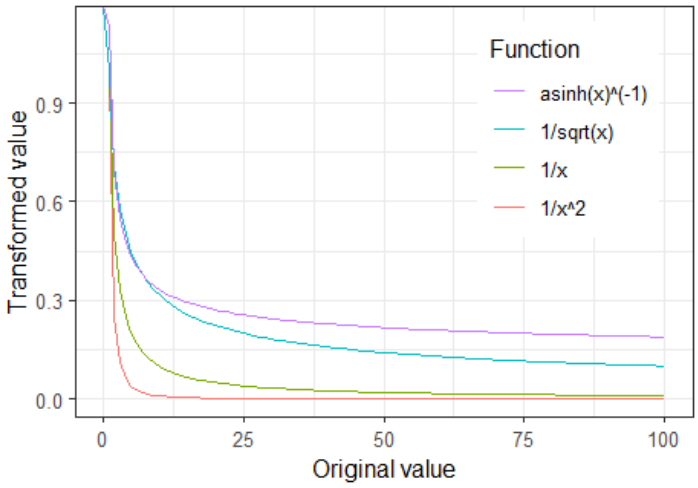
Figure 3 – Describing the direct proportional adjustment of the equal per capita budget relative to the regional transformed indicators, using the example of the Responsibility consideration indicator 'cumulative CO2-FFI 1850-2014'. While this figure shows that the allocation using the transformed indicators as described in Equation 3 reflects a direct proportional share, the transformation of indicators prior to this operation requires a value judgement.

As indicated by Equation 3 the indicators shown here must first be transformed to an inversely proportional range suitable for allocation ($\widehat{x_{i,r}}$). This transformation is discussed in the subsequent section. Before we move there, consider Figure 3 which helps provide intuition for the proportional adjustment of the RCB_{EPC} as implemented in Equation 3. Figure 3 shows the example of *Cumulative CO2-FFI 1850-2014*, which is an indicator describing the historical Responsibility from the year 1850 to the desired starting year of allocation (2015). The X-axis in Figure 3 describes the ratio of the *transformed* (see next section) *Cumulative CO2-FFI 1850-2014*, to its *transformed* global population weighted average. The Y-axis shows the ratio of the allocated PC budget relative to the global $RCB_{EPC,2015}$. This shows the desired 1:1 relation (blue arrows) of the *transformed* indicator ratio with the per capita budget ratio. Here, regions with greater historical responsibility (cumulative CO2-FFI from 1850-2014) are allocated a proportionally lower PC budget from 2015 onwards than regions with a smaller historical responsibility.

Penalty functions

Under allocation approaches using Responsibility and Capability considerations in the way we have defined these, regions with higher corresponding indicator values ($x_{i,r}$) must be assigned a smaller share of the per capita RCB. The transformation of the Responsibility and Capability consideration indicators thus requires the use of a decreasing function that transforms the indicators to an inversely proportional range as per the wording of the allocation approaches where they are employed. This is itself a strongly normative procedure which we explore in detail below. Table 19 describes the original indicator values and corresponding indicative ranges for all considerations.

Table 19 - Overview of transformations applied to Responsibility, Capability and Needs indicators.

Indicator	Original indicator range	Penalty function
Historical cumulative emissions	*10-600 GtCO2*	
Historical cumulative per capita emissions	*0.1-20 tCO2 / capita / year*	
GDP per capita	*1500-60000 USD_{PPP} / capita*	
Capital stock per capita	*3000-253000 USD_{PPP} / capita*	

We apply a set of penalty functions to transform the Responsibility and Capability consideration indicators. The penalty functions are ordered in terms of severity, where $F(x) = \frac{1}{x^2}$ penalises wealthier and higher emitting regions most and $F(x) = asin(x)^{-1}$ penalises wealthier and higher emitting regions least. We now conduct

allocations requiring the Responsibility and Capability consideration indicators using all four functional forms. Figure 4 describes the ratio of Responsibility and Capability allocations to the global average per capita RCB, relative to the ratio of the original consideration indicator value to the global population weighted average. This figure can be interpreted as describing the severity of penalty (i.e., a deviation downwards on the Y-axis away from 1 relative to the severity of inequity (i.e., a deviation to the right on the X). It is intuitive that $F(x) = asin(x)^{-1}$ does very little to change allocations for indicators with large maximums, and on this basis can be excluded from any further consideration.

Conversely, the $F(x) = \frac{1}{x^2}$ penalises the majority of the regions so severely as to raise the question of whether it is indeed 'fair' that the region with the highest historical emissions (four times the population weighted global average) and the region near the average should be allocated an almost identical per capita RCB. For the remainder of this report, we apply two functional forms F(x)=1/x and F(x)=1/√x and provide both results.

As we have already noted, these results do not reflect all possible ranges in the application of these allocation approaches. Care must be therefore taken in interpreting the allocations.

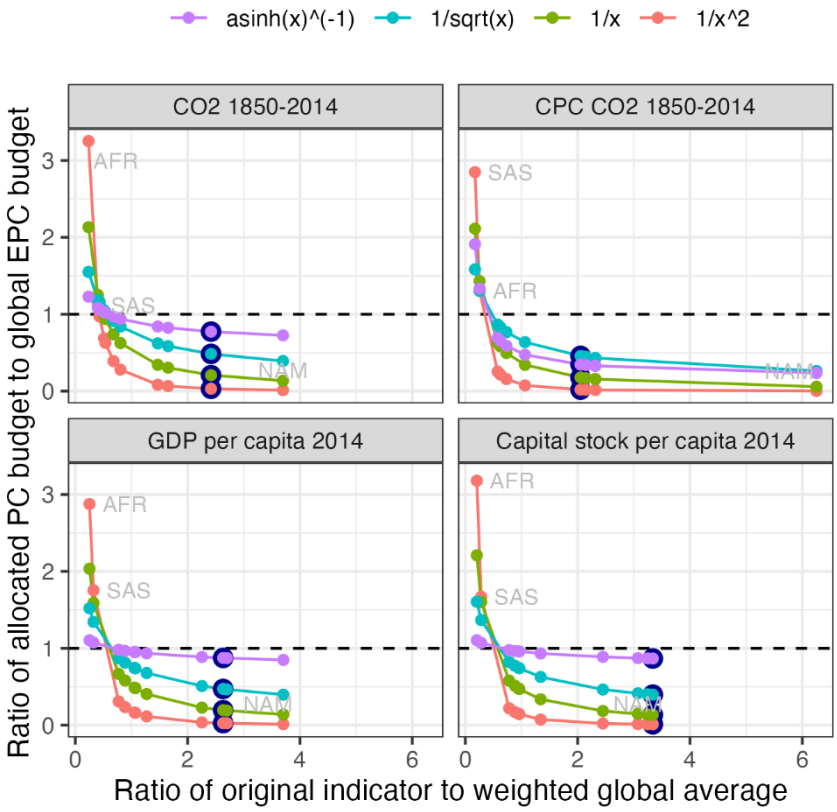


Figure 4 – The influence of penalty functions on Responsibility and Capability considerations. Ratios of the 'fair' regional per capita allocations of RCB_{2015} to the global average, relative to the ratio of the original indicator values to the global population weighted average. Both using selected indicators corresponding to the considerations of Responsibility and Capability, themselves applied in the allocation approaches Responsibility and Capability and corresponding to the principles of Polluter Pays and Ability to Pay. The black circles indicate the ratios for the EU27. Allocations for AFR, SAS and NAM are highlighted with grey text for the $1/x^2$ function.

Allocating remaining carbon budgets – Combinations

The allocation approach of Responsibility, Capability, Needs requires the combination and aggregation of the distinct equity considerations prior to the allocation. This approach is aligned somewhat with the principle of Beneficiary Pays, the intuition being that it is not only necessary to have emitted in the past, but also to have benefitted from these with respect to wealth and human wellbeing. This can be operationalised by combining Responsibility, Capability and Needs consideration indicators, and weighting them appropriately. We do not provide calculations using this allocation approach given the large solution space when weighting the composite allocation approaches. This exclusion is not intended to be a value judgement, but effectively functions as one. Allocations using combinations of considerations would be within the bounds of the extreme distributions we show and require further discussion with respect to the weighting scheme necessary to combine these.

Comparing resulting 'fair' EU27 allocations to known recent CO2-FFI emissions

Figures 5 and 6 describe 'fair' remaining carbon budgets allocated to the EU27 corresponding to the principles of Equality, Polluter Pays and Ability to Pay from the years 1990 and 2015. Allocations are shown both as ratios of per capita budgets to the global equal per capita budgets (upper panels), and as absolute total remaining budgets in GtCO2 (lower panels).

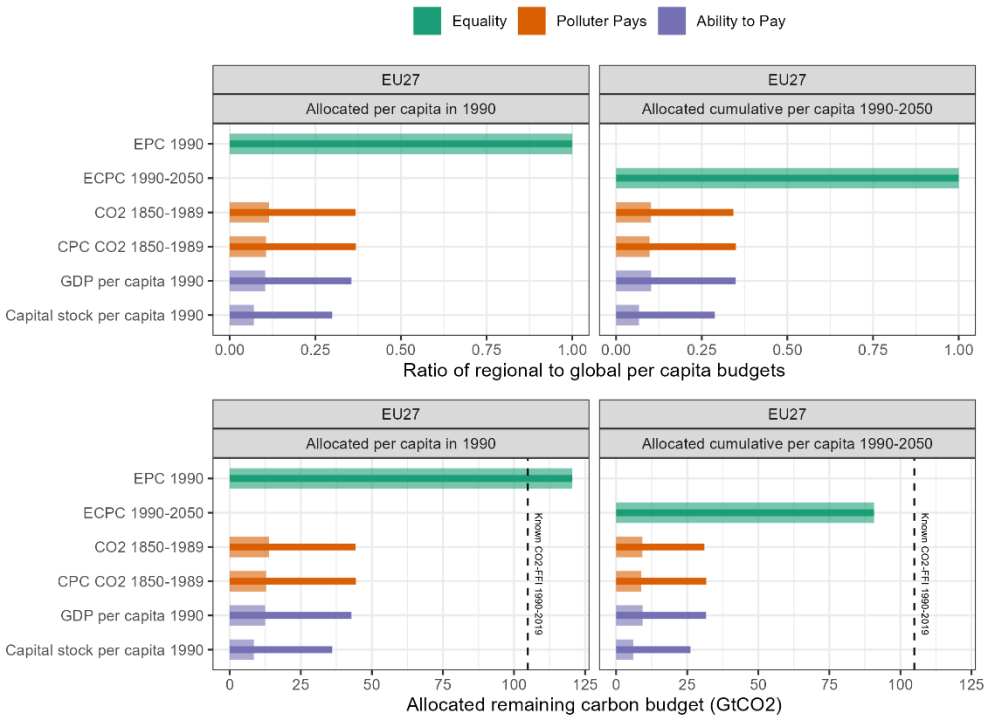


Figure 5 – 'Fair' remaining carbon budgets allocated to the EU27 corresponding to the fairness principles of Equality, Polluter Pays and Ability to Pay from the year 1990 against the known CO2-FFI emissions from 1990-2019. Two functional

forms F(x)=1/x (thicker bars, less lenient) and F(x)=1/√x (thinner bars, more lenient) are used to transform the original values of Responsibility and Capability considerations.

Known CO2-FFI emissions from the starting year of allocation in each case up to the year 2020 are shown by the dashed lines. These known emissions indicate how much of the allocated budget is estimated to have been consumed before the year 2020. Two functional forms F(x)=1/x (thicker bars, less lenient) and F(x)=1/√x (thinner bars, more lenient) are used to transform the original values of Responsibility and Capability considerations to an inversely proportional range appropriate for allocation as discussed in the previous section. It is important to note again that this is a value judgement as different functional forms will result in different allocations.

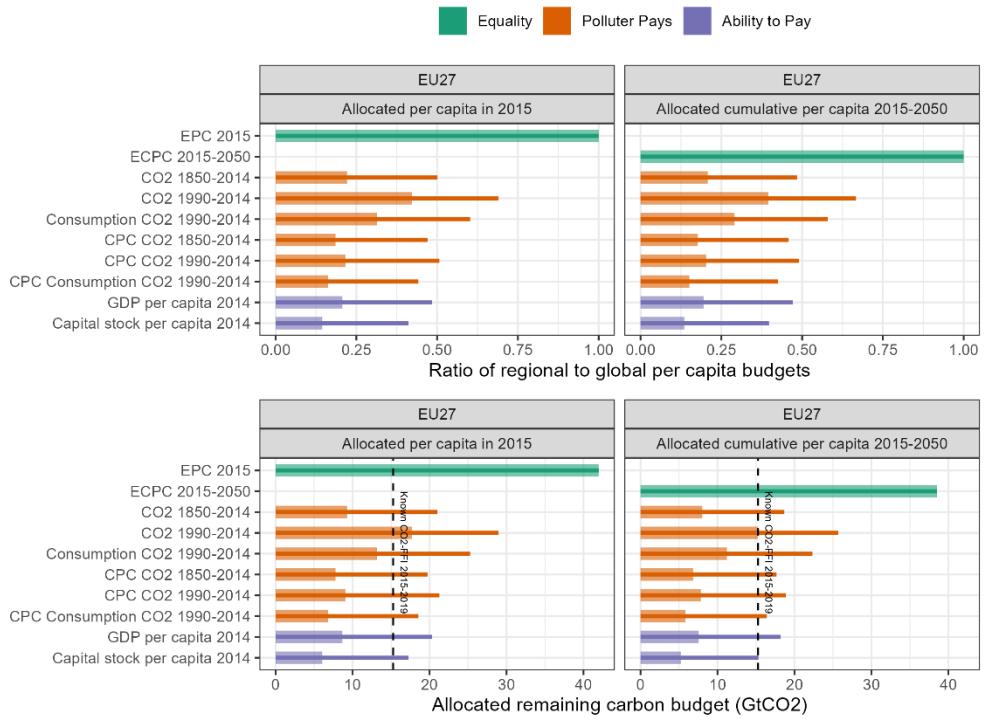


Figure 6 – 'Fair' remaining carbon budgets allocated to the EU27 corresponding to the fairness principles of Equality, Polluter Pays and Ability to Pay from the year 2015 against the known CO2-FFI emissions from 2015-2019. Two functional forms F(x)=1/x (thicker bars, less lenient) and F(x)=1/√x (thinner bars, more lenient) are used to transform the original values of Responsibility and Capability considerations.

Comparing 'fair' allocations with stylistic pathways for EU27

This report continues by considering two stylistic mitigation pathways reflecting a linear reduction in per capita annual emissions from 2020 to a global net zero year of 2050 or 2040, for the EU27.

- The stylistic pathway reflecting a global net zero year of 2050 requires an approximate 55% reduction in emissions from 1990 levels for the EU27.
- The stylistic pathway reflecting a global net zero year of 2040 requires an approximate 65% reduction in emissions from 1990 levels for the EU27.

These stylistic pathways provide an example for when and by how much the EU27 would exceed their 'fair' share under these hypothetical mitigation scenarios. For this exercise, allocations shown reflect alternatives under an Equal Per Capita (EPC) starting allocation.

Comparing 'fair' allocations with stylistic pathways, allocated in 1990

Figures 7 and 8 compare 'fair' allocations with a stylistic mitigation pathway beginning in 2020 and allocating remaining carbon budgets from the year 1990.

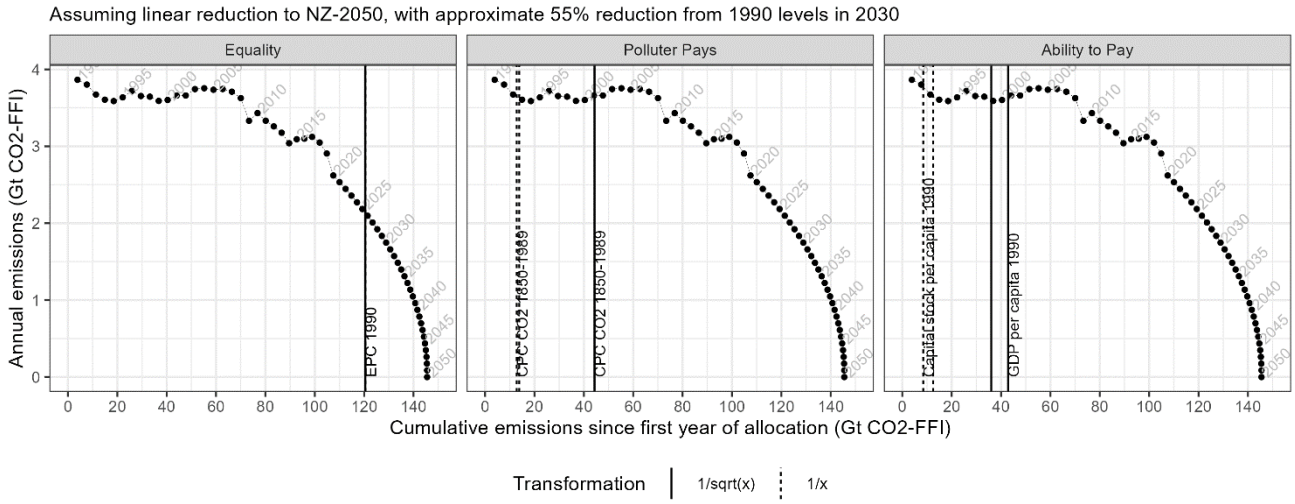


Figure 7 – Total regional allocations from 1990 on the basis of EPC against a stylistic mitigation pathway achieving net zero in 2050 (NZ-2050). Only the maximum and minimum allocations within each fairness principle are labelled for clarity.

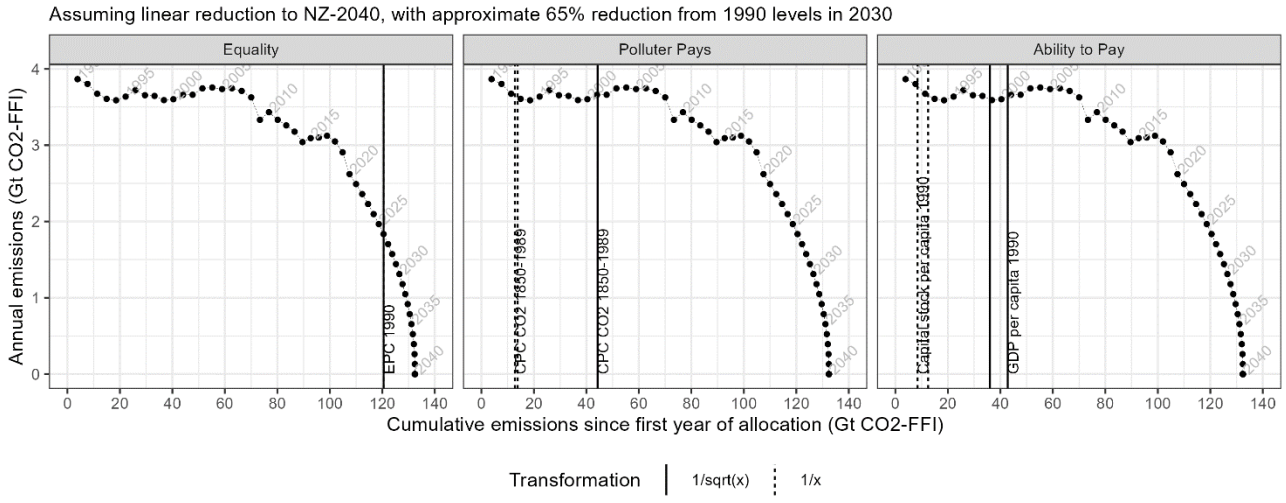


Figure 8 – Total regional allocations from 1990 on the basis of EPC against a stylistic mitigation pathway achieving net zero in 2040 (NZ-2040). Only the maximum and minimum allocations within each fairness principle are labelled for clarity.

Comparing 'fair' allocations with stylistic pathways, allocated in 2015

Figures 9 and 10 compare 'fair' allocations with a stylistic mitigation pathway beginning in 2020 and allocating remaining carbon budgets from the year 2015.

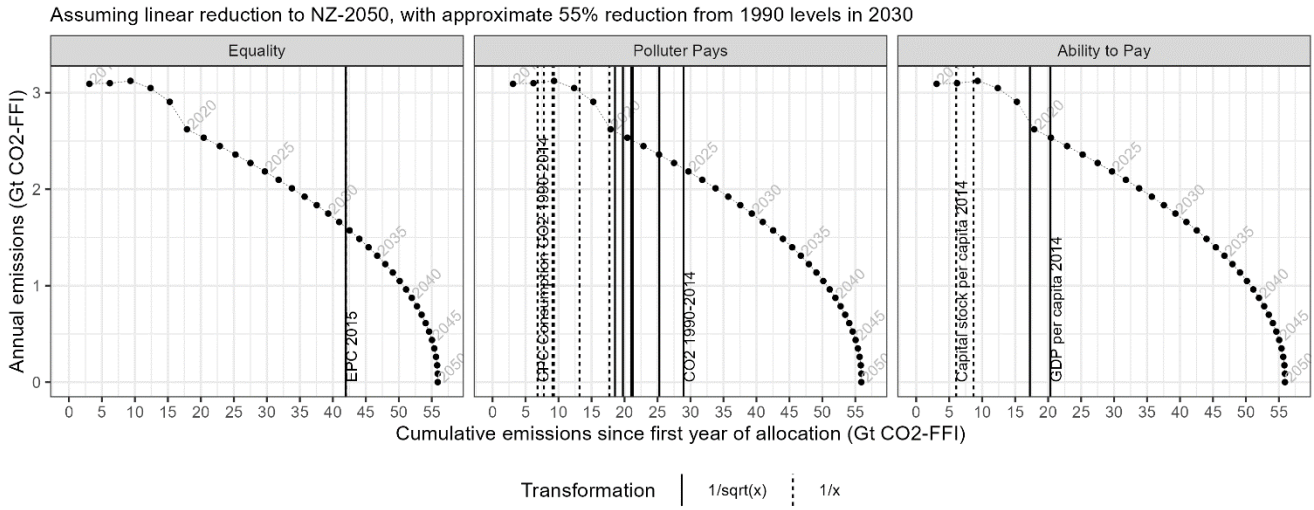


Figure 9 – Total regional allocations from 2015 on the basis of EPC against a stylistic mitigation pathway achieving net zero in 2050 (NZ-2050). Only the maximum and minimum allocations within each fairness principle are labelled for clarity.

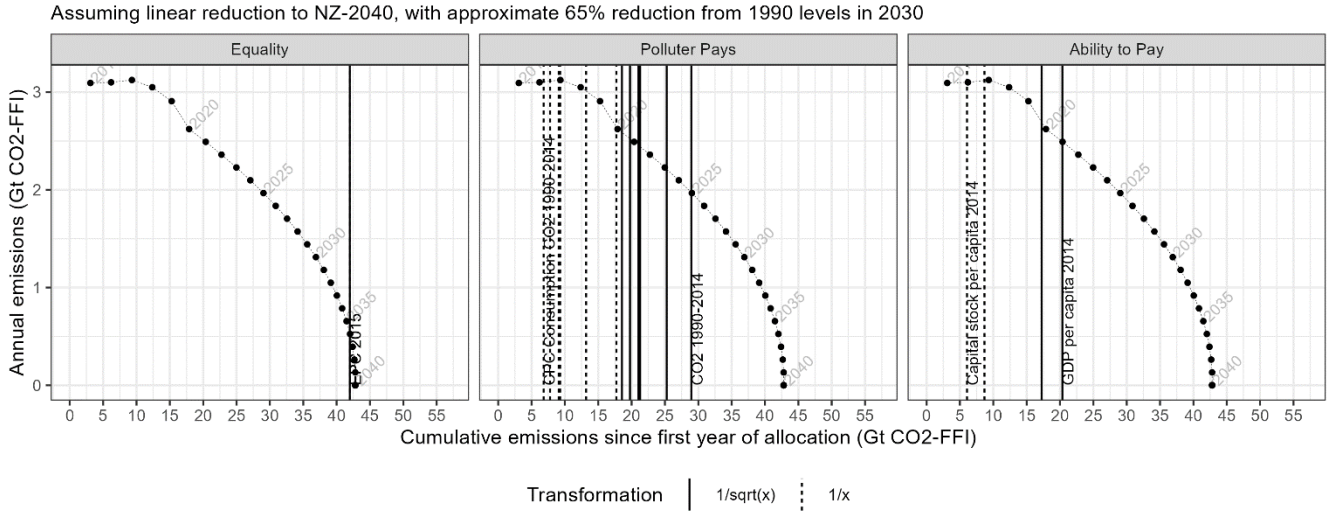


Figure 10 – Total regional allocations from 2015 on the basis of EPC against a stylistic mitigation pathway achieving net zero in 2040 (NZ-2040). Only the maximum and minimum allocations within each fairness principle are labelled for clarity.

Comparing allocations across all other regions

Figures 11 and 12 show allocations across all other regions corresponding to the principles of Equality, Polluter Pays and Ability to Pay from the years 1990 and 2015. For this exercise, allocations reflect alternatives under an Equal Per Capita (EPC) starting allocation.

Allocations are shown both as ratios of per capita budgets to the global equal per capita budgets (top panel), and as absolute total remaining budgets in GtCO2 (bottom panel). Known CO2-FFI emissions from the starting year of allocation in each case up to the year 2020 are shown by a cross. These known emissions indicate how much of the allocated budget is estimated to have been consumed by CO2-FFI emissions before the year 2020.

Figure 11 – Fair' remaining carbon budgets corresponding to the fairness principles of Equality, Polluter Pays and Ability to Pay from the year 1990 against the known CO2-FFI emissions from 1990-2019 (cross). Allocations for Beneficiary Pays are not shown as noted in the text of the report. Two functional forms F(x)=1/x (thicker bars, less lenient) and F(x)=1/√x (thinner bars, more lenient) are used to transform the original values of Responsibility and Capability considerations.

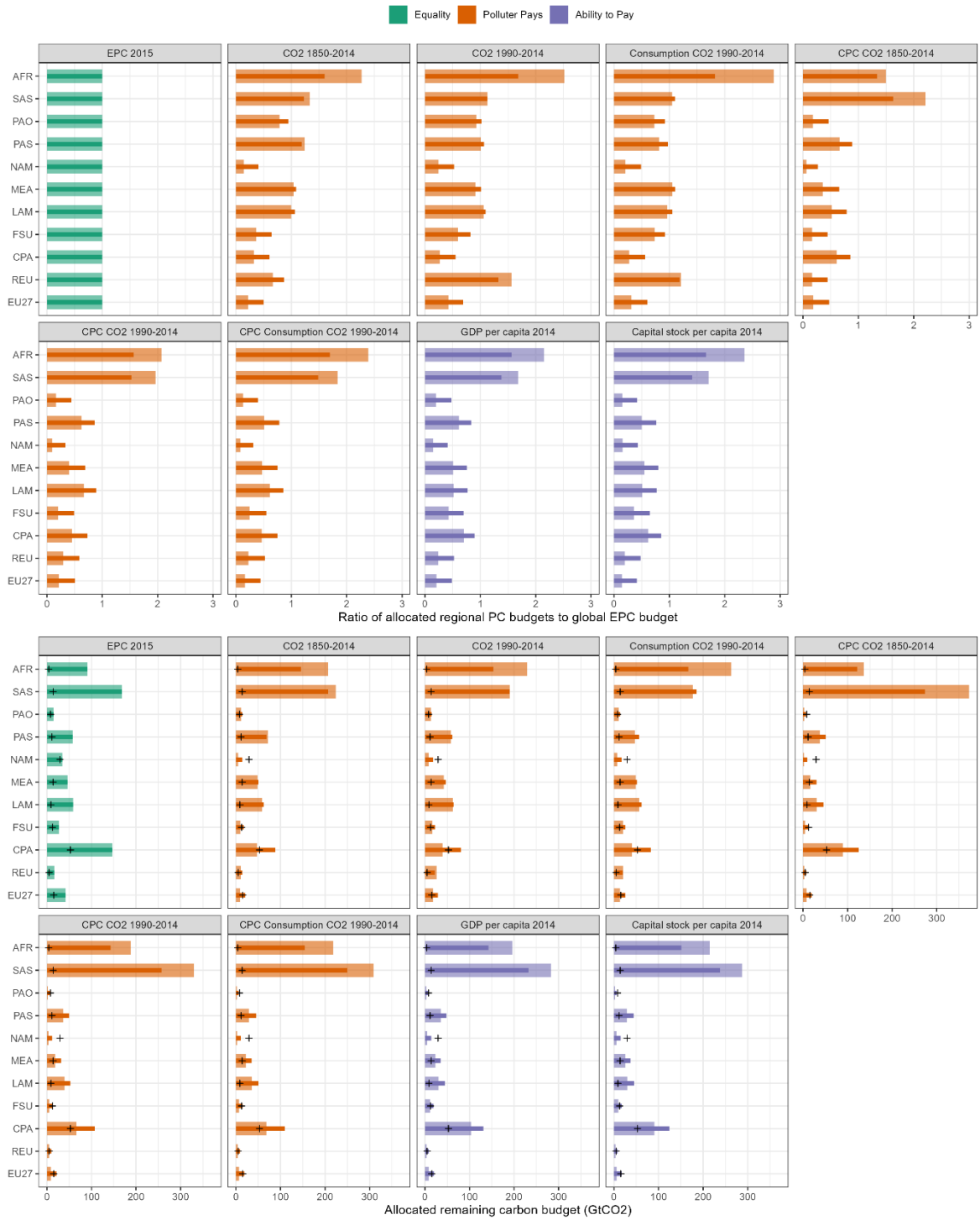


Figure 12 – Fair' remaining carbon budgets corresponding to the fairness principles of Equality, Polluter Pays and Ability to Pay from the year 2015 against the known CO2-FFI emissions from 2015-2019 (cross). Allocations for Beneficiary Pays are not shown as noted in the text of the report. Two functional forms F(x)=1/x (thicker bars, less lenient) and F(x)=1/√x (thinner bars, more lenient) are used to transform the original values of Responsibility and Capability considerations.

Consideration of GHG emissions, LULUCF and International Bunkers

The primary focus of this study is to evaluate equity in carbon budgets based on existing literature. The literature currently shows gaps on fair sectoral emissions floors (e.g., in the agricultural sector) and how to include warming contributions of non-CO2 GHGs (in particular, when they have lifespans shorter than CO2). This complex topic is subject to active scientific discussion and warrants a comprehensive report in its own right, extending beyond the scope of this study (Cain et al., 2021; Rogelj & Schleussner, 2019, 2021; Reisinger et al., 2021; Meinshausen & Nicholls, 2022; Dhakal et al., 2022). While our literature review acknowledges the existence of 'fair-shares' studies employing the Global Warming Potential (GWP) metric to include non-CO2 GHGs, the evolving debate surrounding this issue cautions against relying on this for long-term fairness calculations. It is also crucial to note that the primary objective of this study is to contextualize the fairness of transitions, rather than setting a quantitative GHG budget. Consequently, we concentrate solely on historical and remaining CO2 budgets, where the literature is more established. In alignment with this approach and as noted above Table 18, we exclude historical Land Use, Land-Use Change, and Forestry (LULUCF) CO2 emissions from our analysis. This decision is based on the uncertainty in quantifying and attributing historical anthropogenic CO2-LULUCF emissions, which remains subject to active discussion. Finally, the allocation of historical CO2-FFI emissions to regions excludes those attributable to international bunkers as provided by the authors of the Global Carbon Budget used as a basis for this analysis.

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