



Modelling carbon mitigation pathways by 2050: Insights from the Global Calculator

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ABSTRACT

The Global Calculator (GC) can be used to assess a wide range of climate change mitigation pathways. The GC is an accessible integrated model which calculates the cumulative emissions of a basket of the main greenhouse gases that result from a set of technological and lifestyle choices made at the global level and as defined by the user within a single system dynamics tool. Using the GC, we simulated ambitious scenarios against business as usual trends in order to stay below 2 °C and 1.5 °C of maximum temperature change by the end of this century and carried out a sensitivity analysis of the entire GC model option space. We show that the calculator is useful for making broad simulations for energy, carbon and land use dynamics, and demonstrate how combined and sustained mitigation efforts across different sectors are urgently needed to meet climate targets.

1. Introduction

The Global Calculator¹ (GC) is a pioneering initiative aimed at informing the climate debate at the international level, by providing a relatively simple and highly accessible systems tool for policy makers, business leaders, NGOs and researchers. This initiative builds on the successful experience of the UK 2050 Calculator, launched 2011, which inspired several nations to prepare their own national calculators,² including Australia, Austria, Bangladesh, Belgium, Brazil, China, Colombia, Czech Republic, Ecuador, India, Indonesia, Ireland, Japan, Mauritius, Mexico, New Zealand, Nigeria, South Africa, South East Europe, South Korea, Switzerland, Taiwan, Thailand, and Vietnam, in addition to other ongoing national calculators. Among the several potential uses of these calculators, some nations used them for preparing

their Intended Nationally Determined Contributions for the United Nations Framework Convention on Climate Change (UNFCCC), which latterly became their respective Nationally Determined Contributions (NDCs). The GC can also be used as a communication tool in policy discussions and in science education. Similarly, based on the Global Calculator, the *Financial Times* (FT) [1] prepared a climate change calculator³ to assess the impacts of major greenhouse gas (GHG) emitting countries on meeting global temperature targets, by simulating the implementation of their respective INDCs at different levels in the context of the UNFCCC's 21st Conference of the Parties (COP21, Paris).

In this paper, we provide a brief description and assessment of the GC (version 23) by running a range of representative scenarios and a sensitivity analysis, in order to demonstrate and discuss the utility of this tool. The calculator is a fully open access model, which was subject to

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¹ The full model, supporting documents and web tool are available at: <http://tool.globalcalculator.org>. Some authors of this article (A. Strapasson, J. Woods, M. Cornet, J. Pestiaux and R. Chaturvedi) participated in the development of the Global Calculator, among several other colleagues involved in the project.

² The UK 2050 Calculator and the list of all other existing national calculators are available at: <https://bit.ly/2050Calculators>.

³ The FT Climate Change Calculator is available at: <http://ig.ft.com/sites/climate-change-calculator>. Some authors of this article (J. Woods, R. Chaturvedi and A. Strapasson) along with Nicole Kalas (ETH Zurich) participated in the development of this calculator for the Financial Times.

several stakeholders' consultations, peer-reviewing process, and two public calls for evidence before its final launch in a high-level ceremony at the UK Royal Society in 2015. Since then, it has been presented in several international events, including in recent UNFCCC Conference of the Parties meetings. Its use has extended beyond its original target audience and is now being widely used as a template and reference for the development of other similar systems models, such as the recently published European Calculator (EUCalc).⁴

The novelty of the GC is to offer a highly accessible and relatively simple tool that can be used by non-specialists in modelling the impacts of a wide range of technology and lifestyle choices on global emissions and temperature through to 2100. Its dynamic and near instant responses to different choices available help inform decision makers about climate change mitigation strategies through a user-friendly web tool based on robust systems science. Thus, users can reflect on different carbon mitigation pathways and build their own scenarios for informing their government's policies towards sustainable long-term strategies. To this end, it is fundamental to have a model that is transparent, simple, affordable and credible, and preferably developed by a group of institutions and experts with interdisciplinary backgrounds, which was the case of the Global Calculator. The GC is a complementary model to other integrated assessment and sector-specific econometric models, and does not aim at substituting these more complex, detailed and dedicated models, but instead offering some alternative perspectives, as a user-accessible and relatively simple whole-system model.

The GC project was led by the former UK Department of Energy and Climate Change (DECC), currently Department for Business, Energy & Industrial Strategy (BEIS), funded by its International Climate Fund and co-funded by Climate Knowledge and Innovation Community (Climate-KIC) of the European Union. Several institutions were involved in the project, leading the development of the different sectors in the global model, such as: land use, food, bioenergy and greenhouse gas removals, led by Imperial College London; the transport sector by the World Resources Institute (WRI) in the United States and Climact in Belgium; manufacturing sector by Climact; energy sector by E&Y in India; and commercial and residential sector by the Energy Research Institute (ERI) in China. The climate science approach was led by the Grantham Institute for Climate Change at the London School of Economics in collaboration with the UK Met Office. The Climate Media Factory at PIK-Potsdam (Germany) was responsible for developing the web interface of the calculator. Many other institutions have also contributed with the model's calibration, including the International Energy Agency (IEA).

2. Methods

The GC is a system dynamics model. It was firstly built in an MS Excel spreadsheet, integrating different modelling approaches to the main sectors of the global economy (i.e. manufacturing, energy, transport, land/food/bioenergy, residential and commercial) into a single operating model. The spreadsheet was then converted into C language in order to reduce the calculation time by more than 1000 times. Finally, a Ruby multi-paradigm language was then used as interface to support the online publication as a user-friendly dynamic web tool. The spreadsheet data, calculation and the supporting documentation are available in the public domain and are owned by the UK BEIS under an Open Government Licence, whereas the web tool is owned by Climate-KIC and published in open access under the Creative Commons Licence attribution, non-commercial.

The earlier mentioned website of the GC includes a large amount of

documentation related to the methodology, assumptions and references used to calibrate the model, as well as the limitations of the calculator, and the spreadsheet used with all detailed equations and calculations, including IEA energy data, the University College London's (UCL) TIAM model (for cost estimates), and data from the UN Food and Agricultural Organization (FAO) for land use and food (see more in Appendix). In addition to the supporting documentation, the GC was reviewed in some recent publications, such as, for assessing the global limits of bioenergy and land use for climate change mitigation by Strapasson et al. [2] and on global transport initiatives by Cooper et al. [3]. An analogous methodology was also described and used for the preparation of a land use futures model for the European Union [4]. A general briefing note on the calculator and some key insights can be found in DECC [5].

The GC combines all sectors of the global economy into a single system dynamics model by deriving interconnecting variables between the different sectors over time, as represented in Fig. 1. It works as an engineering model of stocks and flows, aimed at providing broad simulations of system dynamics at global scale; it does not attempt to be an econometric model or a profit-optimisation model. Optimisation functionality is instead passed to the user who makes combinations of choices and is immediately shown the impacts arising from that set of choices (a pathway). The calculator also provides a novel approach to assess energy demand and supply dynamics. The user begins by defining or setting levels of core 'activities' (e.g., the amount of protein-rich food eaten, the distance travelled, the level of heating and cooling needed for residential and commercial buildings) and then chooses (and sets) the food, transport and building solutions that enable those activities (or services) to be provided. For example, once these choices are made, the overall demand for food is calculated and defines the impacts on land resources given the set of technological choices for the provision of the food as made by the end-user (or as default settings under a given pre-defined pathway). All the pathways available will be defined by the set of services (activities) demanded and the associated products (fertilisers, cars, houses, and windmills) needed to supply those services, which in turn are manufactured with associated demand for resources (fuels, minerals, biomass, etc.) calculated. All activities, services and product provision use energy which needs to be produced, transported and stored. Finally, both energy demand and supply use fuel resources. This enables the model to be used to assess the impact of both behavioural (e.g., eating and heating habits, modal switching in transport) and technological changes (e.g., electric vehicles, renewable energy (wind, PV, hydro, marine, geothermal, and biomass) and product innovation).

To become operational, the calculator deploys a number of representative levers, which are all interconnected as a broad integrated system that may vary over time. A lever is an issue that may substantially affect greenhouse gas emissions, for example, changes in the dietary patterns, changes in cement manufacturing, the expansion of solar energy or wind power, changes in crop yields, among other levers. Each lever allows a choice to be made between four levels of ambition for climate change mitigation. The levels of ambition are defined by the technical and behavioural settings rather than the choice of economic or policy parameters, as follows: level 1 – no ambition, pessimist scenario; level 2 – moderate ambition; level 3 – highly ambitious; level 4 – extremely ambitious, but still technically possible (Fig. 2). The calculator can also simulate intermediate decimal levels of ambition, such as levels 1.1, 1.2, 1.3 and so forth, by using interpolation between whole levels. Some few levels do not have this type of growing levels of carbon mitigation effort; instead, they vary from levels A to D, given that this variation may not necessarily reduce or increase emissions comparatively to each other, this would depend on the broad scenario. For example, the GC has a lever about bioenergy provision, which can be offered as either liquid or solid biofuels (note: biogas is a consequential energy from anaerobic digestion) and, hence, the emissions would depend on how they are integrated in their respective commodity chains across the other sectors of the calculator. Further explanations about the levers' levels of all sectors and how they were calibrated can be found in

⁴ The EUCalc is available at: www.european-calculator.eu. Some authors of this article (J. Woods, A. Strapasson, M. Cornet and J. Pestioux) have also participated in the development of the EUCalc, among other colleagues involved in this project, which was supported by the EU Horizon 2020 Programme.

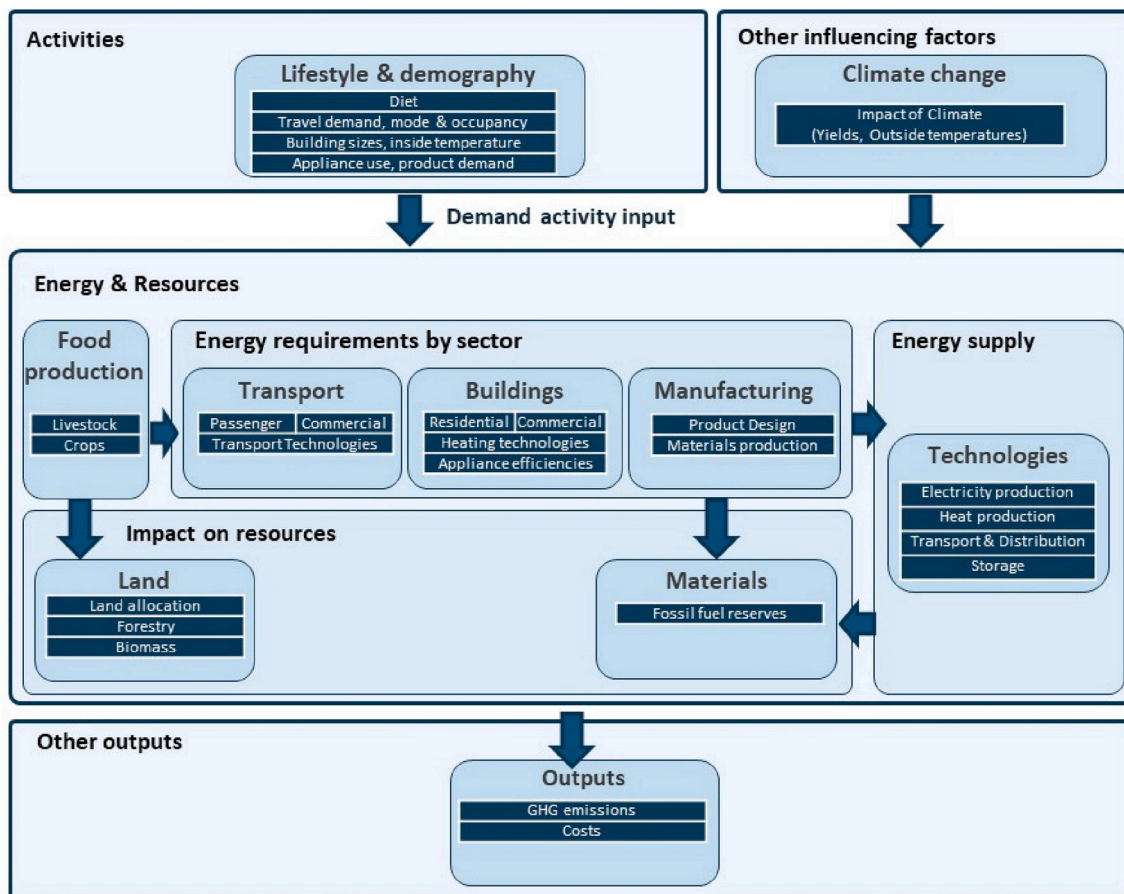


Fig. 1. Global Calculator's basic modelling structure. Source: Prepared by the authors, based on Global Calculator.



Fig. 2. Four growing levels of carbon mitigation effort by 2050 used for each lever of the Global Calculator. Source: Prepared by the authors, based on the Global Calculator.

the supporting documentation available on the GC website. A brief explanation about the levers' calibration is also available on dedicated pages, by clicking on the information icon beside each lever on the calculator's web tool.

The focus of this paper is to run some selected scenarios and a sensitivity analysis of the entire model, similarly to the assessment carried out by Elizondo et al. [6] for the Mexico 2050 Calculator. For the global version, however, there is a much higher number of levers' levels interactions than any other national calculator published so far. The GC also carries out approximate cost simulations by using the UCL TIAM model, and includes an original land use sub-model [2]. Another important difference between the global and national versions is that the global model allows us to estimate the expected temperature change by 2100, providing a visual thermometer with a distribution bar on the web tool, as well as a bar graph which displays the cumulative emissions and the 50% chance to stay below 2 °C or 1.5 °C target. To estimate temperature potentials, the calculator uses the projected cumulative emissions obtained from the model, and uses the methodology of the

International Panel on Climate Change (IPCC) [7], as derived from several climate simulation models for temperature change (see the climate tab of the GC web tool and its supporting online documentation). Moreover, as an innovation based on the GC model, linking the lever ambitions to economics was recently assessed in the European Calculator, whereas linking the lever ambitions to policies has been assessed by Climact and NewClimate for the European Climate Change Foundation within the Climate Transparency Initiative.

2.1. Description of the selected scenarios and pathways

For our evaluation of the GC we have used the pre-defined 'distributed effort' example pathway ('2D') which spreads the effort required to meet the 2 °C target evenly across all the levers, and developed a further, more ambitious distributed effort pathway that reaches the 1.5 °C target. This new 'ambitious distributed effort' pathway ('1.5D') aims to exemplify the level of effort that would be required to hold the increase in global temperature 'to well-below 2 °C, and pursuing efforts to limit it to 1.5 °C' by 2100, as stated in Article 2 of the Paris Agreement [8]. The temperature change calculated is for the year 2100 and represents a 50% chance of keeping temperature below 2 °C and 1.5 °C, respectively, based on the GHG abatement contributions and energy use by 2050, extrapolated to 2100. These scenarios are compared with a Business-as-Usual (BAU) pathway, as described below. Further information on the assumptions underpinning each of the lever levels is available from the GC web tool.

2.1.1. Business as usual 6 °C

Our baseline 6 °C scenario ('BAU') is the default pathway set in the GC. It simulates a low mitigation pathway by 2050 and is similar to the scenario provided by the IEA [9] that would lead to a global temperature

increase of 6 °C (its 'IEA6DS' example pathway). The approximate representation of this scenario in the calculator was developed in collaboration with IEA staff. Despite the BAU being considered as a pessimistic scenario, it still contains some level of low mitigation efforts and technology improvements, including limited residential building sizes as well as some improvements in home energy use efficiency, particularly in lighting and appliances and, from the land-use side, agricultural and livestock practices such as the management and use of agricultural residues. The rest of the levers are set with moderate level of mitigation ambition with the lowest ambition being placed in commercial building efficiency as well as in carbon capture and storage technologies.

2.1.2. Distributed effort 2 °C

In the 2 °C scenario (2D), also called 'Distributed Effort' in the GC, mitigation efforts are balanced across all sectors of the economy, rather than focused on a single sector or the advancement of a single specific technology. This distributed pathway was originally developed by DECC et al. [5], not to be confused with the 'IEA2DS' example pathway that is also available in the GC. There is an increased ambition from both sides of energy markets, demand and supply, when compared to the BAU case. In addition to energy, land is used with more efficient land use techniques, regenerating forests and grasslands, and leaving part of the freed-up lands available by 2050 for the expansion of energy crops. Cities undergo transformations in their structure and transportation, and citizens modify lifestyle habits related to transport and energy consumption. Manufacturing of products (including product design and lifetime, and materials required) is more efficient and renewables play an important role in providing low carbon energy. Technologies such as nuclear and Carbon Capture and Storage (CCS) also contribute to reach a 2 °C pathway. On the other hand, dietary patterns of the global population remain the same as the BAU pathway.

2.1.3. Distributed effort 1.5 °C

The third scenario is a new simulation that represents an even higher mitigation effort that is required to meet the 1.5 °C target of maximum global mean surface temperature change (1.5D pathway). It intensifies the level of mitigation effort in 2D until a 1.5 °C temperature change is approximately achieved in 2100. The 1.5D pathway includes a particularly ambitious set of actions on the demand side, placing a higher ambition effort on cities and transport than 2D, and results in a substantial reduction in fossil fuel use, and a large increase in energy efficiency in buildings, transport and manufacturing. Given the emphasis on energy efficiency, 1.5D uses renewables approximately as intensively as 2D. On the other hand, the 1.5D pathway generates a significant amount of bioenergy, as land resources are freed up due to the significant gains in crop and livestock yields assumed; therefore, allowing to increase afforestation/reforestation and the expansion of energy crops. This does not lead to food security issues (or deforestation) as food demand is always met by default in the model and the expansion area for dedicated energy crops is conditioned to the availability of land resources which were once used for agricultural or livestock production (i.e., a freed-up land, aka 'surplus' land).

2.1.4. Assumptions on demography and emissions trajectory

The GC simulates mitigation scenarios by 2050. However, in order to estimate the expected cumulative emissions and temperature change by 2100, the GC provides the option of choosing the emissions trajectory for extrapolating GHG emissions after 2050 up to 2100 by setting the level of the 'Emissions After 2050' lever. The three pathways assessed here have restricted this lever's setting to between levels 2 and 3, as further detailed in the next section. This setting means that the post-2050 emissions trajectory changes every year by between one third and two thirds of the average yearly change for the previous 15-year period, with a slight increase in the mitigation ambition from the BAU scenario to the two distributed-effort scenarios.

In terms of demography, all three pathways assume that the global population will rise from the current 7.3 billion to 9.6 billion people in 2050, as projected in the UN's medium variant scenario [10], with 66% of the population living in urban areas. The GC's users can also simulate other demographical trends to assess the potential impacts of a wider range of global population scenarios.

2.1.5. Replicating the simulations online

In order to replicate these three proposed simulations (i.e., BAU, 1.5D and 2D) directly on the web tool, Table 1 provides the levels of effort used here for simulating each of the three pathways according to the assessed scenario. It is worth noting that the calculator is able to show a large number of mitigation pathways, resulting from the combinatorics of all levers' levels (and intermediate levels) and, therefore, these three chosen scenarios were selected to demonstrate the functionality of the calculator. There are a number of other example pathways available on the web tool, including scenarios proposed by businesses and NGOs. In addition, the GC offers an approximate

Table 1
Levels of effort by lever and selected scenario of the Global Calculator.

SECTOR	LEVER	Simulation Pathways and Lever's Levels		
		BAU	2D	1.5D
Travel	Passenger distance	2.7	2.7	3.0
	Freight distance	1.5	1.5	1.8
	Mode of transport	2.4	2.4	2.7
	Occupancy and load	1.4	1.4	1.7
	Car own or hire	2.0	2.0	2.3
Homes	Building size	3.0	3.0	3.2
	Temperature and hot water	1.1	1.1	1.4
	Lighting and appliance use	1.4	1.4	1.6
Diet	Product lifespan and demand	1.0	1.0	1.3
	Calories consumed	2.0	2.0	2.3
	Quantity of meat	2.0	2.0	2.3
Transport	Type of meat	2.0	2.0	2.3
	Transport efficiency	1.4	2.8	3.1
Buildings	Electric and hydrogen	1.0	2.8	3.5
	Building insulation	1.0	2.8	3.1
Manufacturing	Temperature and cooking technology	1.0	2.8	3.5
	Appliance efficiency	1.0	2.8	3.1
	Design materials & recycling	1.2	2.8	3.1
	Iron, steel & aluminium	2.0	2.8	3.1
	Chemicals	1.2	2.8	3.0
CCS	Paper & other	2.0	2.8	3.1
	Cement	1.2	2.8	3.1
Bioenergy	CCS in manufacturing	1.0	2.8	2.8
	CCS in electricity	1.0	2.8	2.8
Fossil Fuels	Bioenergy yields	3.0	2.8	2.7
	Solid or liquid	3.0	2.8	2.7
Nuclear	Coal, oil & gas	2.3	2.8	3.1
	Fossil fuel efficiency	3.0	2.8	3.1
Renewables	Nuclear	1.7	2.8	2.7
	Wind	1.5	2.8	2.7
	Hydroelectric	1.9	2.8	2.7
	Marine	1.3	2.8	2.7
	Solar	1.2	2.8	2.7
Food	Geothermal	1.4	2.8	2.7
	Storage and demand shipping	1.5	2.8	2.7
	Crop yields	1.7	2.8	3.1
	Livestock (grain/residues fed)	2.0	2.8	3.1
	Livestock (pasture fed)	3.0	2.8	3.1
Land use	Water and residues	1.5	2.8	3.0
	Surplus land (forest & bioenergy)	2.0	2.8	2.7
Demographics	Land-use efficiency	2.5	2.8	3.0
	Global population	2.0	2.0	2.0
Emissions after 2050	Urbanisation	2.0	2.0	2.0
	Emissions trajectory	2.3	2.7	2.7

Source: Prepared by the authors, using the Global Calculator.

representation of the IPCC Representative Concentration Pathways⁵ (RCPs) for 2.6, 6.0 and 8.5 W/m² of radiative forcing⁶ in the year 2100 relative to pre-industrial levels, whilst these radiative forcing levels are derived from different GHG concentration trajectories [7]. Although the representation of RCPs in the GC was not assessed in this article, they are also available in the list of example pathways shown on the GC's web tool.

2.2. Sensitivity analysis

The sensitivity analysis was carried out by firstly setting the GC to its default IEA6DS pathway (our BAU pathway). Then, each lever was individually set in-turn to its mitigation levels 1, 2, 3 and 4, with the changes to total greenhouse emissions by 2050 at each level recorded. Each lever was tested one at a time, moving back to the default IEA6DS example pathway after the changes were made to a lever's settings. Thus, it was possible to assess the potential impact of each individual lever and its respective four levels of effort. This is important to reflect on the significance of each individual climate change driver and highlight key areas for reducing carbon emissions. However, it is worth noting that the GC operates as a system dynamics model, i.e. all levers are integrated and affect each other. Therefore, if the individual impact of each lever is summed up, the result in terms of GHG emissions and energy balance may have a different value than when considered aggregately as a new pathway.

3. Results and discussion

The results and discussion are split into three sub-sections: firstly, the modelling simulations, providing a comparative analysis of the three assessed carbon mitigation pathways; secondly, the results from the sensitivity analysis; and thirdly, some additional considerations.

3.1. Results from the modelling simulations

The 6 °C scenario (BAU pathway) yields total annual emissions of 84.3 GtCO₂eq in 2050 with cumulative emissions reaching 7693 GtCO₂eq in the atmosphere by 2100. Many consider a 6 °C increase in global mean surface temperature by 2100 as catastrophic for human development and potentially incompatible with viable ecosystem functioning. In terms of costs, this scenario is considered used as a baseline for the economy. The 2 °C scenario, instead, considers a trajectory that results in the generation of 18.5 GtCO₂eq per year in 2050 with an abatement of 65.8 GtCO₂eq (c.f. BAU) and which costs the global economy 2.59% of global GDP, compared to the BAU scenario, leading to less than 3000 GtCO₂eq of cumulative emissions by 2100. Finally, the 1.5 °C scenario reaches 8.7 GtCO₂eq per year in 2050, reducing emissions by approximately 75.6 GtCO₂eq (c.f. BAU) and costing 0.75% of global GDP, restricting cumulative emissions to 2260 GtCO₂eq by 2100.

Comparing scenarios in terms of efficiency, the 2 °C scenario reduces energy demand by 28% by 2050, going from 610 EJ to 434 EJ (Fig. 3). When increasing the target ambition to limiting temperature increase to 1.5 °C, energy demand reduces by 39% (370 EJ in 2050). Hence, energy supply declines by 30% and 37%, respectively, and is able to reduce considerably the dependence on hydrocarbons, such as oil, natural gas

⁵ The IPCC Fifth Assessment Report (AR5) provides a number of Representative Concentration Pathways (RCPs) for assessing ranges of potential global warming scenarios. Each RCP represents an equivalent radiative forcing effect in the year 2100 relative to pre-industrial levels, such as, +2.6, +4.5, +6.0, and +8.5 W/m², globally.

⁶ The term *radiative forcing* has been used by the IPCC to represent a perturbation in the radiative energy balance of the Earth's climate system, for example, due to an increase in the concentration of greenhouse gases in the atmosphere.

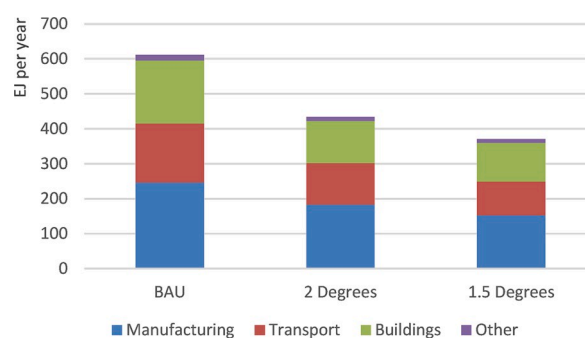


Fig. 3. Energy demand in EJ (exa-Joules) by different GHG mitigation scenarios in 2050. Source: Prepared by the authors, using the Global Calculator.

and coal. At sectorial level, the manufacturing industry is the main energy consumer by 2050 in both the 2 °C and 1.5 °C scenarios, whereas energy requirements among sectors remain approximately the same for both scenarios. Energy used for transportation and buildings accounts for the remaining demand, with a slightly larger share used for lighting, heating, cooling and cooking, in buildings.

On the supply side, both alternative scenarios (2 °C and 1.5 °C) decrease the use of non-renewable sources from more than 80% in the 6 °C scenario to around 40% in the 2 °C and less than 30% in the 1.5 °C scenarios (Fig. 4), in 2050. Accordingly, renewable sources and nuclear fission together increase their share from 20% of the energy sources in the BAU to 60–70% in the alternative scenarios. The global economy is then able to meet 20–30% of its energy requirements with bioenergy and waste, according to its climate ambition. Other renewable sources also show a remarkable increase when moving from the 6 °C to the 2 °C scenario. Solar, wind, wave and tidal energy increase substantially, from 2% of the energy supply to 17%. Nevertheless, augmenting the ambition to the 1.5-degree pathway target does not change their share substantially, except for bioenergy, with a significant increase in the global energy mix. This pathway requires dietary changes of the global population, reducing the need for agricultural and pasturelands to meet global food demand by 2050 and, therefore, freeing up more lands for the expansion of energy crops, without challenging food security.

The GC also provides a Sankey diagram for energy flows between supply and demand, as shown in Fig. 5, Fig. 6 and Fig. 7, respectively for the BAU, 2D and 1.5D simulation pathways. More detailed Sankey diagrams are also available on the GC's web tool, showing some intra-sector variations for each pathway.

In terms of emissions' trajectories, emissions in both the 2 °C and the 1.5 °C scenarios decline starting in 2015 until 2050 (Fig. 8). Deferrals in these very substantial GHG reductions in the short term then exacerbate

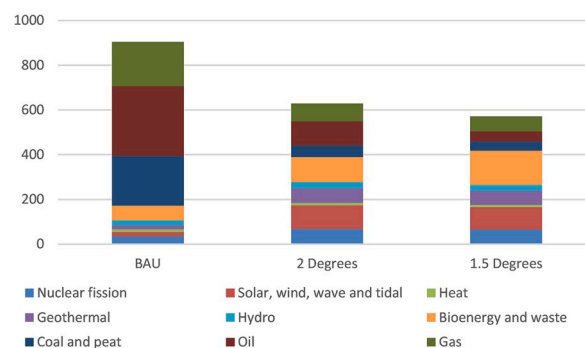


Fig. 4. Global energy supply in EJ (exa-Joules) by different GHG mitigation scenarios in 2050. Note: Approximate share of renewable energies in total primary energy supply for each simulation pathway in 2050: BAU, 14% out of 905 EJ in total; 2D, 49% out of 628 EJ in total; and 1.5D, 60% out of 572 EJ. Source: Prepared by the authors, using the Global Calculator.

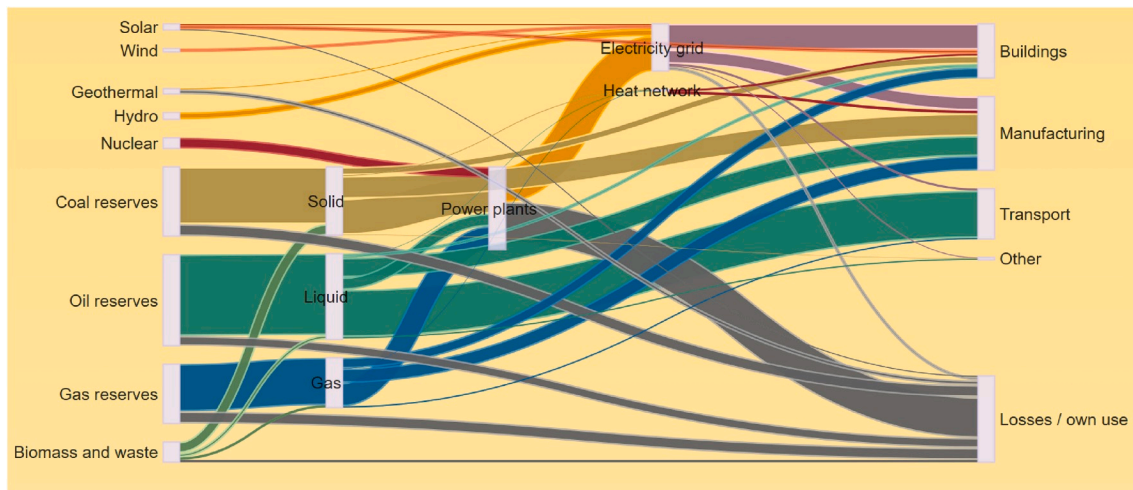


Fig. 5. Energy flows under the GC's BAU pathway. Source: Simulated by the authors, using the Global Calculator.

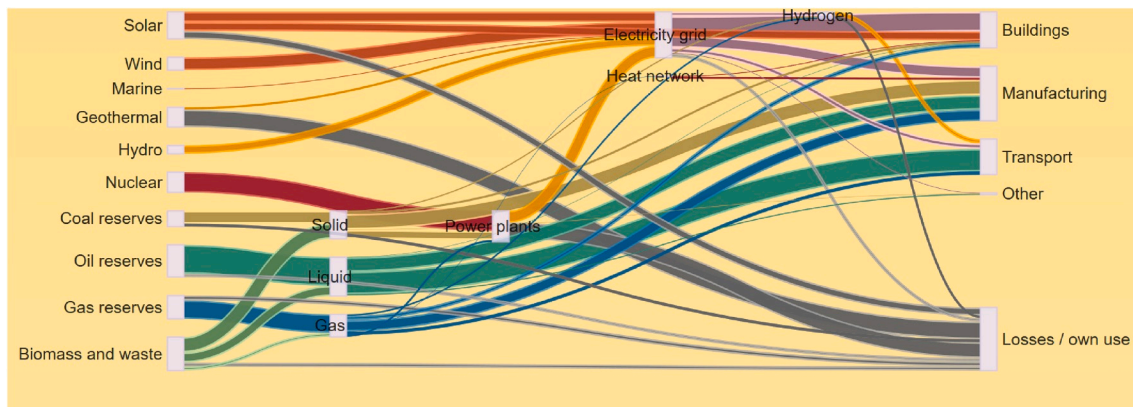


Fig. 6. Energy flows under the GC's 2D pathway. Source: Simulated by the authors, using the Global Calculator.

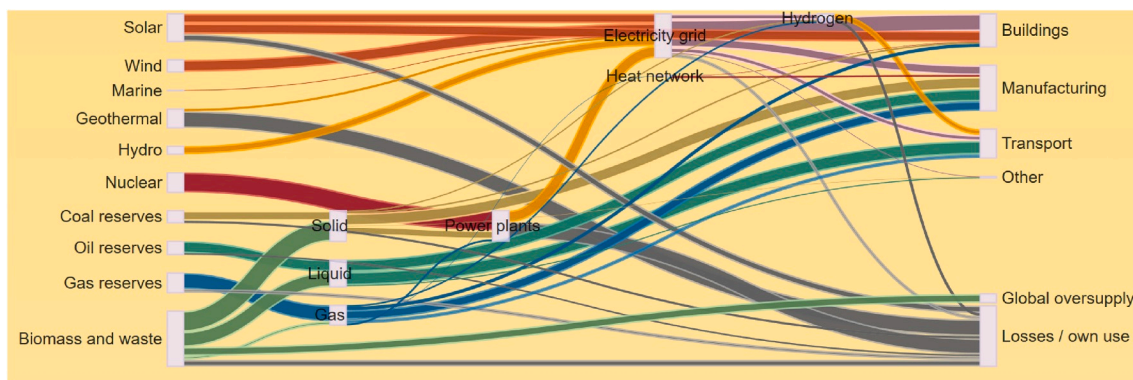


Fig. 7. Energy flows under the GC's 1.5D pathway. Source: Simulated by the authors, using the Global Calculator.

the need for higher reductions afterwards, otherwise to face potential severe climate change impacts. Future versions of the GC could update the historical data used in the model and the accuracy of these trajectories, but apart from the modelling limitations and the several uncertainties involved in this type of simulation, the results highlight the urgent need for reducing GHG emissions.

As a comparison of the magnitudes of the emissions trajectories simulated, the IPCC's RCP 2.6 W/m² scenario also assumes that global GHG emissions peak between 2010 and 2020, declining thereafter, and the simulation of this RCP trajectory in the GC results in 16.2 GtCO₂eq.

y⁻¹ in 2050, as shown on the example pathways of the GC web tool. Another comparative example is the FT climate change calculator [1], which shows that the 2 °C pathway would require global emissions not to exceed 20 GtCO₂eq.y⁻¹ in 2050. The FT calculator also demonstrates that, if all INDCs were implemented as proposed in the context of the Paris Agreement, GHG emissions would reach around 50GtCO₂eq.y⁻¹ in 2050, i.e. well above the UNFCCC targets, with combined emissions from China, United States, European Union, India, Russia, Japan, Australia, Brazil and Canada responsible for more than half of these total emissions. In a similar context, Rogelj et al. [11] assessed the

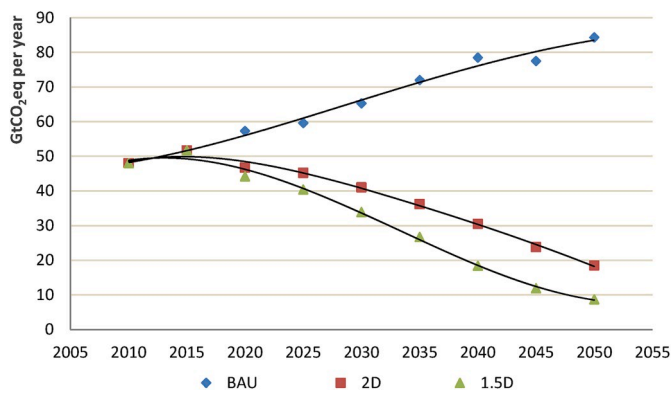


Fig. 8. Global emissions trajectory by different GHG mitigation scenarios (GtCO₂eq.y⁻¹). Source: Prepared by the authors, using the Global Calculator.

assumptions behind the NDCs of the UNFCCC’s Member States and estimated that their emissions would range from 47 to 63 GtCO₂eq.y⁻¹ in 2030, and that this uncertainty has critical implications for meeting temperature change targets.

In terms of emissions by activity/sector (Fig. 9), in 2030, under the 6 °C BAU scenario, most of the emissions would come from fuel combustion (65%), followed distantly by agriculture (11%). This split does not change much for neither the 2 °C scenario nor the 1.5 °C scenario whereas the sharpest increase in emissions between 2010 (actual data) and 2030 seen in industrial processing activities for the 6 °C scenario whereas the sharpest decrease in emissions for the 2 °C scenario between 2010 and 2030 happens in the land use and forestry sector, which becomes a net sink already by 2030. This is also the case for the 1.5 °C scenario. In both distributed-effort scenarios, emissions coming from industrial processing increase by 42% and 37%, respectively, between 2010 and 2030.

By 2050, in the 6 °C scenario, the largest share of emissions comes from fuel combustion (61% of total), followed by land use and forestry (18%), which has the highest proportional increase in emissions, with a 149% increase between 2011 and 2050, mainly because of deforestation and soil carbon changes. In the 2 °C scenario, by 2050, the highest share of emissions comes from fuel combustion (48% of total); however, emissions from fuel combustion are only slightly greater than those from

agriculture, with the largest reductions in emissions occurring in the land use and forestry activities. This is because rather than deforestation, an increase in global forest cover by 2050 occurs, acting as a source of negative emissions by sequestering carbon not only in the above ground vegetation but also as soil carbon. Finally, in the 1.5 °C scenario, by 2050, global net GHG emissions undergo a very significant reduction, and most emissions arise from agriculture (42%) followed distantly by fuel combustion (21%) with the sharpest decline in emissions observed in the fuel combustion sector. These simulations show the importance of the land use sector for the climate agenda which is often neglected. This sector can move from a source of positive GHG emissions to a net carbon removal option, as also recently demonstrated by Strapasson et al. [2].

3.2. Results from the sensitivity analysis

The results from the sensitivity analysis of the GC are shown in Fig. 10. The impact of exclusive changes to the levels of each lever compared to BAU in 2050, in terms of avoided emissions, are provided, as previously described in Methods (Section 2). Variations between levels 3 and 4 represent an extreme level of action, although still technically possible. The levers related to diet and food production have the largest effects on GHG emissions. However, changes in diet are related to lifestyle and cultural aspects and hence is considered likely to generate high levels of inertia compared to BAU. A reduction in per capita meat consumption, especially beef, is calculated to reduce the demand from pastureland and croplands for producing animal feed, freeing up land resources for other purposes, such as afforestation/reforestation and the expansion of energy crops, both with substantial GHG savings. On the other hand, if dietary patterns are kept at BAU levels, then increases in livestock and associated resource use efficiency, particularly by increasing the global average number of ruminant animals per hectare (animal density on pasturelands), could also free up land resources for other purposes. However, increasing fossil fuel use efficiency is also a key strategy for reducing GHG emissions, as well as changes in global population, and other high impact levers. Some levers may not show significant impacts depending on the level of ambition for carbon mitigation. For example, geothermal energy is not deployed significantly in levels 1 and 2, but it is required when adopting levels 3 and 4.

The calibration of levels 1 to 4 within each lever is not homogenous and changes over time are often non-linear. For instance, the diet lever is related to a behavioural change rather than a technological innovation.

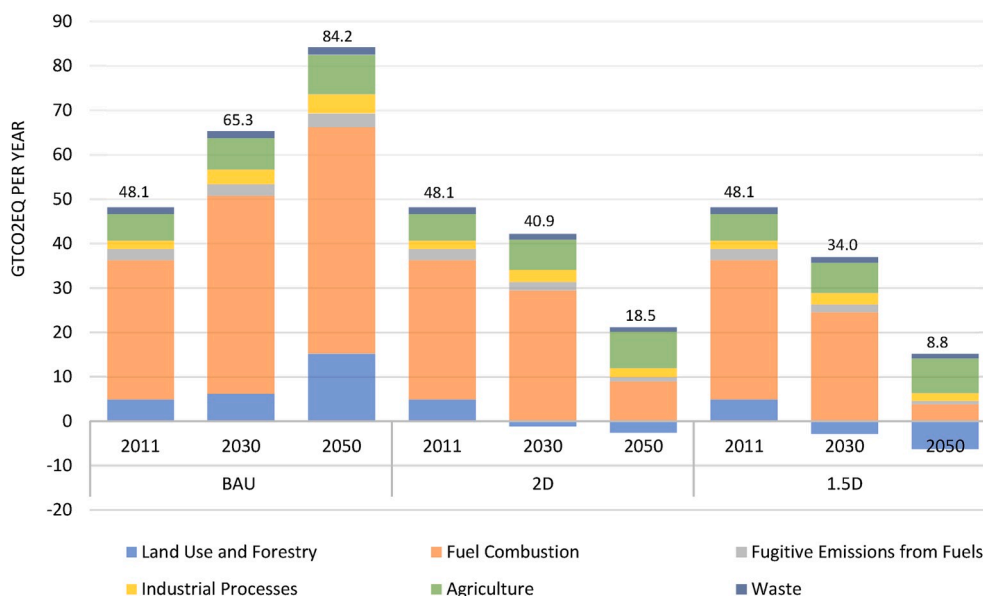


Fig. 9. Global emissions per scenario by source in 2011 (actual), 2030 and 2050, incl. total values, in GtCO₂eq.y⁻¹. Source: Prepared by the authors, using the Global Calculator.

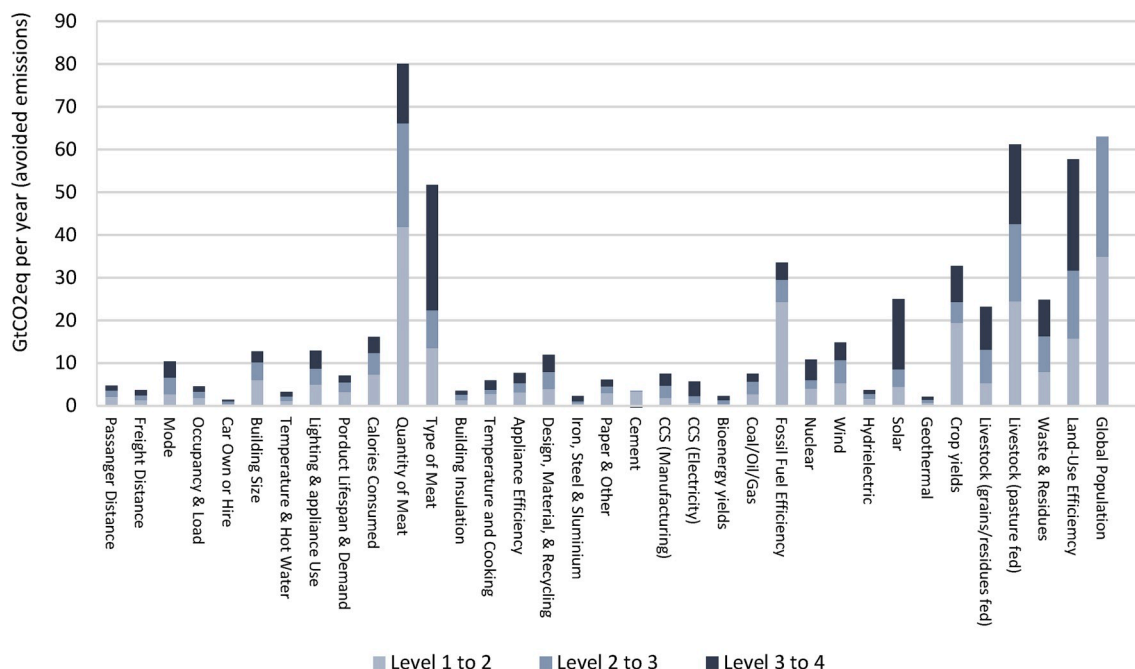


Fig. 10. Sensitivity analysis of lever settings, regarding emissions reductions in the Global Calculator, with varying levels of mitigation effort against the BAU scenario (6 °C) by 2050, in GtCO₂eq per year. Source: Prepared by the authors, using the Global Calculator.

Meat consumption, particularly, has a very broad range of mitigation efforts: level 1 represents a pessimistic scenario with a substantial increase in global meat consumption with levels of consumption that are similar to those currently observed in the European Union, i.e. much above global trends, which are more aligned with level 2, calibrated based on trends suggested by the UN Food and Agriculture Organization (FAO) [12]. Setting level 3 results in a gradual reduction in per capita meat consumption towards the 90 g of meat per day suggested as a healthy level of consumption by the World Health Organization (WHO) [13], and level 4, an extreme reduction is assumed, analogous to current per capita meat consumption rates in India, where the majority of the population adopt a vegetarian diet. These changes have major

implications for GHG emissions, not only by reducing emissions from enteric fermentation of ruminant animals, but also by allowing the expansion of forests and energy crops on freed-up land, with implications also in terms of soil carbon balances, and even public health [14]. Such abrupt changes in global dietary patterns have no precedent in recent history, yet they are assessed to be technically possible enabling their inclusion in the GC. Thus, the interpretation of the sensitivity analysis requires an understanding of the assumptions behind each lever’s level, which are all described in the GC web tool and its supplementary documents.

Fig. 11 shows the impact of each sector on global GHG emissions. It provides a sensitivity analysis assembling levers according to reference

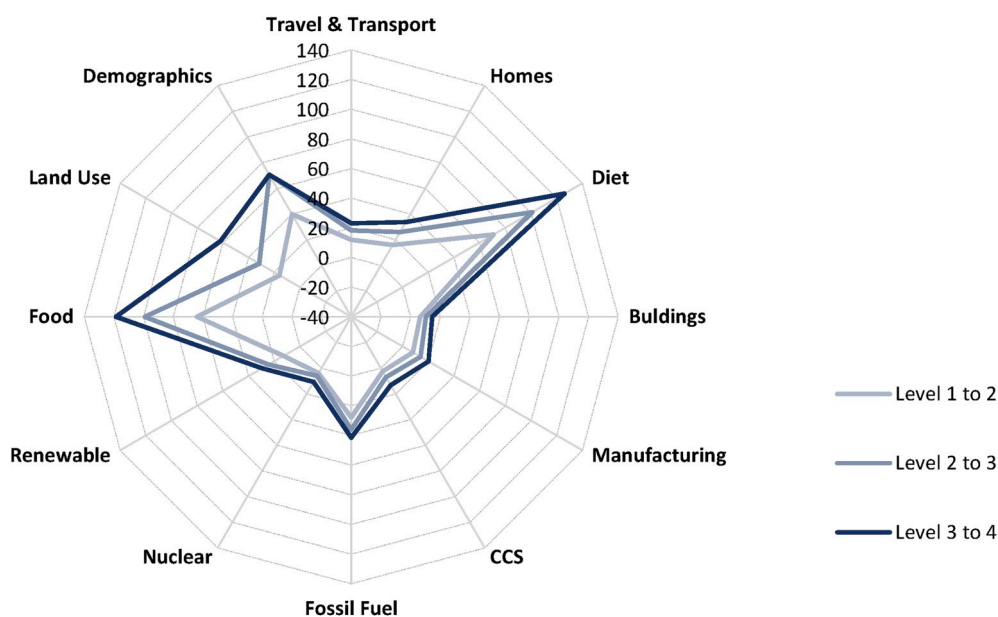


Fig. 11. Sensitivity analysis of sectors, regarding emissions reductions in the Global Calculator, with varying levels of mitigation effort against BAU scenario (6 °C) by 2050, in GtCO₂eq per year. Source: Prepared by the authors, using the Global Calculator.

sectors: travel (passenger distance, freight distance, mode, occupancy load, car own or hire) & transport (transport efficiency, electric & hydrogen); homes (building size, temperature & hot water use, lighting & appliance use, product lifespan & demand); diet i.e. changes in dietary patterns (calories consumed, quantity of meat, type of meat); buildings (building insulation, temperature and cooking technology, appliance efficiency); manufacturing (design materials & recycling, iron, steel & aluminium, chemicals, paper & other, and cement); carbon capture and storage (CCS manufacturing, CCS electricity); fossil fuel (coal/oil/gas, fossil fuel efficiency); nuclear (nuclear energy); renewables (wind, hydroelectricity, marine, solar, geothermal, storage & demand shifting), food (crop yields, livestock - grains/residues fed, livestock - pasture fed, wastes & residues); land use (surplus land – forest & bioenergy, land use efficiency); demographics (global population, urbanisation). In this sensitivity analysis, all the levers comprising each sector were set simultaneously to each level, rather than setting the levels for each individual lever. Therefore, Fig. 11 (radar graph) shows sectorial impacts instead of the impacts of isolated actions, which were already shown in Fig. 10. From a sectorial perspective, for example, the impacts of diet, land use and food sectors combined are very high, which is perhaps surprising when compared to more traditionally acclaimed areas for climate policy, such as, transport, building and renewables. The centre of this radar graph was not set as zero, in order to better visualise the variations of the three projected polygons.

The results of the sector-level sensitivity analysis show that the calculator is much more sensitive to the settings in some of the individual sectors, such as food production, dietary patterns and land use, when compared to the others, in terms of avoided emissions. Changes in global demographics, which can only be varied between three levels (1–3), also shows a high sensitivity to its level setting, as well as efficiency gains in the use of fossil fuels, and the expansion of renewable energies. On the other hand, some sectors are dependent on other sectors to become effective, such as transport technologies. For example, the expansion of electric vehicles based on high-carbon electricity would not result in major emissions reductions; however, if this technology expands alongside a higher availability of low carbon electricity, the avoided emissions could be relevant. Bioenergy is not directly represented in this figure, because it depends on the availability of surplus

land before it can make a significant contribution to emissions reductions, with surplus land only becoming available dependent on potential productivity improvements in cropping and in energy crops, moderation in diets (as discussed above) and the use of agricultural residues, as discussed by Strapasson et al. [2] also using the GC.

The sensitivity analysis may also vary according to the baseline considered for the assessment. Fig. 12 shows, for example, the sensitivity analysis assuming as baseline a GC intermediate emissions scenario that would lead to a global temperature increase of approximately 4 °C (its 'IEA4DS' example pathway) instead of 6 °C, as shown in the previous figure. Emissions trajectory after 2050 for IEA4DS (level 1.5) also differs to those in IEA6DS (level 2.3) example pathway. Whilst comparing Fig. 11 with Fig. 12, they present minor variations for some sectors. However, these alternative simulations are able to exemplify the point that some technology developments in one sector are needed to enable the developments in other sectors in order to meet the 1.5 °C target. In addition, it is worth noting that the GC adopts 2011 as a base-year across all sectors, homogenously, for consistency reasons and due to limitation on data availability at global scale until the calculator was launched in Jan 2015. However, the carbon budget for meeting either 2 °C or 1.5 °C target has been recently updated in the literature [15], requiring a future update of the GC model, too, including recent changes in global emissions due to the effects of the coronavirus pandemic in the global economy.

3.3. Additional comments

All the results are presented in terms of global averages; however, they are certain to have substantial spatial (region to region) and temporal variations. Each mitigation pathway simulates changes only up to 2050 and some technologies may take longer to become feasible or to become costly competitive against conventional technologies. Take, for example, the case of fusion energy, which is not included in the calculator, but may potentially become a major source of energy after 2050, as well as disruptive innovations such as artificial meat, and the emergence of many unexpected technologies, including carbon dioxide removal. Hence, the GC provides estimates for a broad range of carbon mitigation pathways, but it is still constrained by current knowledge of

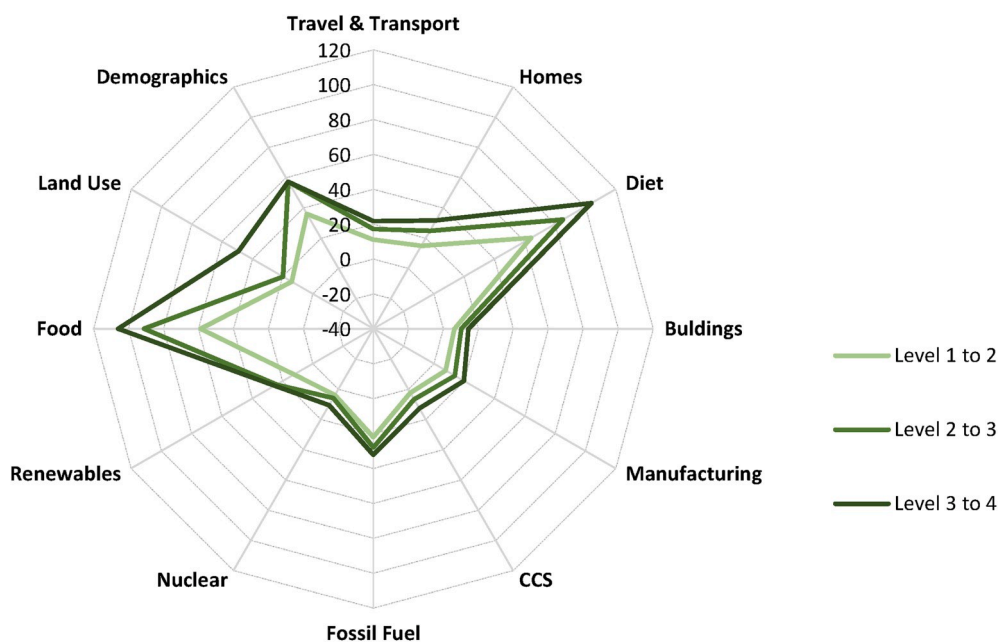


Fig. 12. Sensitivity analysis of the emissions reductions in the Global Calculator by major sectors with varying levels of mitigation effort against an intermediate emissions scenario (4 °C) by 2050, in GtCO₂eq.y⁻¹.

Source: Prepared by the authors, using the Global Calculator.

future technological potentials and climate dynamics.

It is important to clarify that the GC model does not provide disaggregated results, for example, per continent or at country level. This is because the model's dataset either uses consolidated information at global scale or estimated global weighted averages using regional data e. g. in the case of assessing changes in transport modes (travel sector) and variations of carbon stocks according to different forest biomes worldwide. Moreover, the GC does not provide options for simulating the effects of carbon taxes or price elasticities regarding the adoption of different technologies and fuels, given that it is not an econometric model. On the other hand, this was not the aim of the GC, and it can be potentially complemented by other types of existing and future models, such as agent-based models, networks, and game theory models. The Financial Times' Calculator, as already cited in the Introduction (Section 1), does provide some simulations at country level, although only for major emitters. Several countries have their own national 2050 calculators (as also mentioned in the Introduction) and a similar assessment to this article was already performed for some them, such as for the Mexico 2050 Calculator [16] and the European Calculator [17], which does offer simulations at country level for its 28-Member States (EU-28).

Another important observation is that the current version of the GC (version 23) does not include feedback-looping effects for assessing the impacts of climate change according to different carbon emissions trajectories, such as an increase in climate vulnerabilities (e.g. impacts on crop yields due to changes in temperature and rainfall) and adaptation costs (e.g. due to sea level rise in the coastal areas and to an increase in the frequency of extreme weather events) by 2050. Moreover, biodiversity and water balance issues were not directly covered in the GC, but some related variables were included in the recently published European Calculator.

4. Conclusion

The GC is able to simulate a very large number of climate change mitigation pathways, as well as changes in the global energy mix and land use. The suggested distributed efforts for meeting the 2 °C and 1.5 °C targets show that these targets are still possible to be achieved, but that success in achieving them will require urgent and very substantial levels of effort across all sectors of the global economy. These simulations are illustrative pathways among many other possibilities that the world could take towards reducing GHG emissions. For example, the GC also allows simulations to be made that are focused on a higher use of solar photovoltaic systems and electric vehicles, with these highly cost effective technologies taking up a large share of the global energy supply, in a similar context to the analysis recently made by Sussams et al. [18] for disruptive changes in technology. Some other examples are pathways that are focused on dietary patterns and land use [2], and on sustainable transport systems in cities [3]. In addition, the calculator can compare carbon mitigation pathways to approximate representations of the IPCC's Representative Concentration Pathways (RCP), providing useful insights for climate change analysts.

The sensitivity analysis of the GC shows that there is no 'silver bullet' for carbon mitigation by 2050, demonstrating the contribution of each sector for reducing GHG emissions. It shows that all sectors are important to mitigate carbon emissions. However, it clearly highlights the importance of moving towards more sustainable diets, whilst also increasing livestock efficiency sustainably, and the need for very rapid improvements in the efficiency of fossil fuel use, whilst also reducing global dependence on fossil fuels by speeding up the expansion of renewable energies.

For future versions of the GC, the model could improve the accuracy of the assumptions and equations used for the scenario simulations, as well as provide confidence intervals for the projected data. There are several uncertainties in the GC, which arise from a model aimed at making broad simulations for all sectors of the economy combined with a relatively simple interface designed to enable its use by policy makers,

business leaders, NGOs and researchers. The cost analysis, in particular, would be better represented if cost estimates for individual pathways could be compared to potential adaptation costs of not acting to curb carbon emissions. Despite these limitations, the Global Calculator enables its users to design and reflect on new strategies for climate change mitigation, whilst also raising awareness of the urgent need for moving towards a low carbon economy through systems thinking and inspiring the development of new system dynamics models worldwide.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Alexandre Strapasson: Conceptualization, Investigation, Methodology, Formal analysis, Writing - original draft. **Jeremy Woods:** Investigation, Methodology, Writing - review & editing. **Vanessa Pérez-Cirera:** Investigation, Formal analysis, Writing - original draft. **Alejandra Elizondo:** Investigation, Formal analysis, Writing - original draft. **Diego Cruz-Cano:** Investigation. **Julien Pestiaux:** Investigation, Writing - review & editing. **Michel Cornet:** Investigation, Writing - review & editing. **Rajiv Chaturvedi:** Writing - review & editing.

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APPENDIX

All calculations presented in this article can be repeated using the GC web tool (version 23) at: <http://tool.globalcalculator.org>. For greater detail, they can also be repeated by using the MS Excel spreadsheet that originated this web tool. The MS Excel version and source code provide all the equations and assumptions behind the GC and can be both accessed in public domain and downloaded at: <https://bit.ly/2050Calculators>. This web site is hosted at Imperial College's Centre for Environmental Policy (CEP) and includes some detailed explanation on how each sector was modelled and its main references, the limitations of the calculator, and how to use the spreadsheet model. Some additional information can be found on the UK Government's website at: <https://www.gov.uk/guidance/international-outreach-work-of-the->

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