

What is meant by ‘balancing sources and sinks of greenhouse gases’ to limit global temperature rise?

REBECCA THOMAS, DR HEATHER GRAVEN, PROFESSOR SIR BRIAN HOSKINS, PROFESSOR IAIN COLIN PRENTICE

The headlines

- In an effort to limit global temperature rise to well below 2°C, the COP21 Paris Agreement stipulates that a ‘balance’ between anthropogenic (man-made) sources and sinks of greenhouse gases must be reached by 2050-2100. An overall greenhouse gas ‘balance’ must consider individual gases in terms of how strongly they absorb solar infrared radiation, their concentration in the atmosphere, and their lifetime in the atmosphere.
- Long-lived greenhouse gases, including carbon dioxide (CO₂), accumulate in the atmosphere and continue to affect the climate for many centuries. To stabilise the concentrations of these long-lived gases, and thereby their effect on the climate, their sources must be progressively reduced towards zero.
- For short-lived greenhouse gases that remain in the atmosphere for less than 100 years, including methane, stable or decreasing concentrations could be achieved within decades if emissions were stabilised or decreased. However, these gases currently only contribute about 20% of the total warming from greenhouse gases, so their reduction alone cannot successfully stabilise global temperature.
- An overall ‘balance’ of sources and sinks of greenhouse gases could be facilitated by deliberate removal of CO₂ from the atmosphere, for example, by combining biomass energy production with carbon capture and storage. Most current greenhouse gas emission scenarios that keep global temperature rise below 2°C include some deliberate removal of CO₂ to compensate for continued emissions of CO₂ and other greenhouse gases.

Introduction

The Paris Agreement from the 21st Conference of Parties (COP21) to the UN Framework Convention on Climate Change (UNFCCC) in December 2015 states that by 2050-2100, there should be a “balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases” (GHGs) to limit the global mean temperature rise to less than 2°C relative to the pre-industrial climate¹. The purpose of this briefing note is to clarify what a ‘balance’ of greenhouse gases means in the context of the Paris Agreement and to discuss how this could be achieved. We highlight the need to reduce net emissions of carbon dioxide

(CO₂) and other long-lived GHGs towards zero, and the importance of considering short- and long-lived GHGs separately.

The change in concentration of a gas in the atmosphere is the difference between the sources (emissions to the atmosphere) and sinks (removals from the atmosphere). A number of sinks remove GHGs naturally from the atmosphere. Carbon dioxide (CO₂) dissolves in the ocean, and is taken up by plants during photosynthesis. Methane (CH₄) and nitrous oxide (N₂O) are destroyed primarily by photochemical reactions in the atmosphere. These gases are produced by human activity but also naturally by respiration and other biological processes. Stable GHG concentrations are possible only if sources are equal to sinks.

Box 1: Definitions

Stabilisation: A stable global mean temperature means that on average, it remains constant with time. Similarly, a stable gas concentration means that on average, there is no change in the concentration of the gas in the atmosphere. Stabilisation refers to the change from increasing temperatures or concentrations to stable temperatures or concentrations.

Greenhouse effect: The global mean surface temperature is determined by the energy balance of the Earth, primarily the amount of incoming solar radiation and the outgoing radiation from Earth back into space. The energy balance is also affected by gases, particles and clouds in the atmosphere that can absorb or reflect radiation from the sun or from the Earth’s surface. Greenhouse gases (GHGs) in the atmosphere absorb some radiation emitted by the Earth’s surface and re-emit it back to Earth, raising the surface temperature. Some GHGs are naturally present in the atmosphere, causing a natural greenhouse effect. However, anthropogenic emissions of GHGs such as CO₂ during the Industrial Era (post-1750) are increasing the greenhouse effect, resulting in a continuing increase in global mean temperature.

Radiative Forcing: The change in the energy balance of the Earth, relative to pre-industrial time, caused by changes in global GHG concentrations. Global mean surface temperature change is approximately proportional to radiative forcing. A positive radiative forcing means that the total energy in the climate system increases and global mean temperature increases.

Atmospheric lifetime: The average amount of time a gas remains in the atmosphere before being removed. For most gases this is approximately the current atmospheric concentration of a gas divided by the rate of its removal by sinks.

Global Warming Potential (GWP): A metric often used to compare the emissions of different GHGs. It is calculated as the average radiative forcing over a specified period (commonly 100 years) caused by a pulse emission of a specified greenhouse gas, divided by the average radiative forcing over the same period due to a pulse emission of the same mass of CO₂.

What are the sources and sinks of CO₂?

CO₂ is the most important GHG driving climate change today^{2(Section C)}. Most of the CO₂ resulting from human activities (90%) is emitted by burning fossil fuels; about 10% is emitted as a consequence of land use changes including deforestation³. Currently, on average, 55% of anthropogenic CO₂ emissions are rapidly removed from the atmosphere by natural sinks in the ocean and land biosphere, while 45% accumulate in the atmosphere (Table 1). The capacity of natural CO₂ sinks is determined by ocean chemistry and ocean mixing, and by multiple factors in terrestrial ecosystems influencing photosynthesis and respiration of plants and soils. These include CO₂ ‘fertilisation’ – the increase in photosynthesis and plant growth resulting from increased CO₂ levels in the atmosphere⁴.

What is meant by balancing the sources and sinks of CO₂?

There are a variety of possible methods to balance sources and sinks of CO₂ to produce ‘net zero emissions’. The two most common approaches are to either progressively reduce global anthropogenic CO₂ emissions towards zero, or to combine continued emissions with (currently undeveloped) methods for deliberate large-scale removal of CO₂ from the atmosphere.

Slowing the rate of CO₂ rise will reduce the rate of CO₂ uptake by natural sinks. Net uptake of anthropogenic CO₂ emissions by these sinks is taking place principally because atmospheric CO₂ concentration is rising. On land, CO₂ fertilisation and other processes are increasing plant growth (resulting in increased CO₂ uptake) more than the decomposition of organic matter in soils (which releases CO₂).

Table 1: Sources and sinks of CO₂ in 2014³, and towards the end of the century (2080-2100) for two of the scenarios considered by the IPCC (2013)^{2 (Box SPM1),5}. Units are Gt CO₂ yr⁻¹ (1 Gt = 10⁹ kg). For comparison, a 1 part per million (ppm) increase in global CO₂ concentration is equal to 7.7 Gt CO₂. The increase in atmospheric CO₂ concentration in 2014 was 1.8 ppm.

	Atmospheric CO ₂ increase	Sources		Sinks	
		Fossil fuel emissions	Land use change	Natural removal	Deliberate removal
Current (2014)	+14	+35	+4	-25	0
High emissions scenario (RCP 8.5, 2080-2100)	+68	+102	+1	-34	0
Low emissions scenario (RCP 2.6, 2080-2100)	-4	+8	+2	-4	-11

In the oceans, a concentration gradient between the surface ocean and the rising CO₂ concentration in the atmosphere drives net CO₂ uptake. As CO₂ emissions decrease, these sinks will inevitably weaken. For example, in the low emission scenario in Table 1, natural removal of CO₂ at the end of the century is projected to be only 4 Gt CO₂ yr⁻¹, less than a quarter of the current rate of CO₂ removal, even though atmospheric CO₂ concentration at the end of the century in this scenario is higher than the current level of 400 ppm. CO₂ emissions will have to be continually reduced to compensate for weakening sinks.

It may be possible to create artificial CO₂ sinks that remove CO₂ from the atmosphere using so-called ‘negative emissions’ technologies. The main negative emission technology currently discussed combines bioenergy with carbon capture and storage (BECCS)⁶. In BECCS, where CO₂ produced from the combustion of plant material such as wood, corn or algae is permanently stored underground in depleted fossil fuel reservoirs or saline aquifers (see Figure 1). These technologies are still in their early development stages. The feasibility of implementing BECCS on the required scale has been questioned, as this would require large land areas be dedicated to production of biofuels, among other challenges⁷. Despite these concerns, BECCS plays a key role in low emissions scenarios considered by the Intergovernmental Panel on Climate Change (IPCC). For example, the low emission scenario in Table 1 requires CO₂ removal by BECCS to be equivalent to more than 100% of fossil fuel emissions in 2080-2100, which is equal to nearly 30% of current fossil fuel emissions.

What about non-CO₂ greenhouse gases?

The largest contributor to radiative forcing from greenhouse gases is CO₂, responsible for 65% of radiative forcing in 2015⁸. But several other GHGs emitted by human activities contribute to radiative forcing. GHGs can be classified by atmospheric lifetime (see Box 1), i.e. the average amount of time a gas remains in the atmosphere before being removed by sinks. Short-lived GHGs have lifetimes up to decades; long-lived GHGs have lifetimes of a century or more. Here, we consider only GHGs with a lifetime longer than a few years, which become mixed throughout the atmosphere. Ozone present at low altitudes in the atmosphere is also an important greenhouse gas, but it has a short lifetime of a few weeks so it is not well-mixed in the atmosphere.

How BECCS works

1 BECCS involves planting forests and bioenergy crops (which absorb CO₂ as they grow), and using forestry and agriculture residues (waste),



2 burning them to produce electricity and capturing and storing the subsequent carbon emissions,



3 resulting in a net removal of carbon dioxide from the atmosphere, also described as ‘negative emissions’.



Figure 1: How bioenergy with carbon capture and storage (BECCS) works. Reproduced from AVOID 2¹³

CO₂ is a long-lived GHG but it does not have a single lifetime because the land and ocean sinks are due to several distinct processes that operate on multiple time scales (from seconds to millions of years). As a result, about 55% of the CO₂ added to the atmosphere is removed within a year but about 25% will remain in the atmosphere for more than a thousand years² (Section E.8). Individual molecules of CO₂ will be exchanged between the atmosphere, ocean and land plants over this time, but the atmospheric concentration will remain elevated. CH₄, the next most important GHG, is a short-lived GHG with a lifetime of about 12 years and N₂O is a long-lived GHG with a lifetime of about 120 years.

Many man-made GHGs have lifetimes far longer than 100 years (see Table 2). Some of these (chlorofluorocarbons, CFCs and hydrochlorofluorocarbons, HCFCs) are being phased out under the Montreal Protocol as these gases have contributed to the depletion of stratospheric ozone, including the ‘ozone hole’. These gases were partly replaced with hydrofluorocarbons (HFCs) that do not react with ozone but are strong GHGs with lifetimes of up to several hundred years. Other fluorine-containing compounds, sulphur hexafluoride (SF₆), nitrogen trifluoride (NF₃) and perfluorocarbons (PFCs), have lifetimes of several hundreds or thousands of years. Currently these compounds are only present in the atmosphere in tiny concentrations, but their long lifetime means that a balance cannot be achieved for these gases for millennia. The only way to stabilise atmospheric concentrations of these gases is to reduce their emissions towards zero.

Why is GHG lifetime important?

Distinguishing GHGs by lifetime is important because current emissions of long-lived GHGs, including CO₂, will accumulate in the atmosphere and affect the concentrations of these gases – and therefore the climate – for many generations. In contrast, current emissions of short-lived GHGs, including CH₄, will have only a small and declining influence on the climate in the latter half of the century. For example, if anthropogenic emissions of CH₄ stopped today, anthropogenic radiative forcing from CH₄ would decline to zero within decades^{9,10}. Policies to reduce greenhouse gas emissions and limit global temperature rise need to consider the different behaviours of long-lived and short-lived GHGs and treat both types of GHGs effectively.

Table 2: Greenhouse gases and their main sources and sinks. Anthropogenic sources are in **bold**.

Gas	Lifetime	Sources	Sinks
CO ₂	About 25% of emitted CO ₂ remains for over 1,000 years	Plant and soil respiration, ocean exchange, wildfires, volcanoes, fossil fuel use, land use change	Photosynthesis, ocean exchange, weathering of silicate rocks
CH ₄	12 years	Microbial processes in wetlands, reservoirs, termites, ruminant animals, geological seeps, wildfires, landfills, rice paddies, livestock, fossil fuel extraction and use	Chemical reactions in the atmosphere, microbial processes in soils
N ₂ O	120 years	Microbial processes in soils, fresh waters and oceans, wildfires, fertiliser manufacture and use	Chemical reactions in the atmosphere
CFCs	45 – 1,020 years	Refrigeration, propellants, solvents	Chemical reactions in the atmosphere
HCFCs	<1 – 17 years		
HFCs	<1 – 242 years		
PFCs	<1 – 50,000 years	Aluminium production, semiconductor manufacturing	Chemical reactions in the atmosphere
SF ₆	3,200 years	High voltage electrical insulation, industrial applications	Chemical reactions in the atmosphere
NF ₃	~500 years	Semiconductor manufacturing	Chemical reactions in the atmosphere

Comparisons of emissions of different GHGs have generally been based on the metric of global warming potential (GWP)² (Section D.2) (see Box 1). The use of GWPs allows emissions of any GHG to be expressed as CO₂ equivalent (CO₂-eq) emissions.

GWP has been a widely used metric because it is one method by which emissions can be expressed in a common currency, and has therefore been found to be convenient for policy making, e.g. in the development of the Kyoto Protocol. However, the calculation of GWP is sensitive to the time period chosen, and whether or not the effects of the reactions with other atmospheric chemicals are included². With respect to long-term temperature stabilisation, GWP does not distinguish between the different behaviours of short- and long-lived GHGs (see Pierrehumbert 2014¹⁰ for a more detailed discussion). An alternative metric, or several metrics, are required that effectively capture the differences between short- and long-lived GHGs. Several metrics are currently under discussion in the scientific literature, including a two-basket approach with one basket for long-lived GHGs and one basket for short-lived GHGs. There is general agreement that an effective metric would be based on the cumulative emissions of long-lived GHGs (the sum of all long-lived GHG emissions since the Industrial Revolution) and on the ongoing emissions of short-lived GHGs (the emission rate of short-lived GHGs in a target period such as the year 2030 or 2050)^{11,12}.

What GHG emissions reductions are needed to limit global temperature rise?

The level of climate change over one or more centuries depends on (a) the cumulative anthropogenic emissions of long-lived GHGs, since these GHGs will contribute additional radiative forcing for many hundreds or thousands of years, and (b) the continuing anthropogenic emission rate of short-lived GHGs⁹. Thus, future radiative forcing and climate change could be stabilised by (a) capping the cumulative emissions of CO₂ and other long-lived GHGs, and (b) capping the rate of emission of short-lived GHGs.

Current research suggests that having a greater than 66% chance of staying below 2°C warming requires that cumulative anthropogenic emissions of CO₂ post-2011 are kept below about 1,000 Gt CO₂² (Section E.8). At current emission rates (35 Gt CO₂ yr⁻¹) this implies a need for CO₂ emissions to peak soon, followed by rapid reductions during the next few decades⁹. Short-lived GHGs represent a much smaller contribution to climate change (only around 20% of the total anthropogenic GHG radiative forcing currently, with little expected change without intervention), but reducing and capping the emissions of short-lived GHGs soon will strongly increase the likelihood of meeting the 2°C target.

Acknowledgements

We would like to thank Professor Nicholas Stern for his contribution in identifying this question. We would also like to thank Professor Pierre Friedlingstein, Professor Keith Shine and Professor Nicholas Stern for their feedback on this paper during the review process. The authors are also grateful for the contribution that Alyssa Gilbert, Simon Levey and Alex Cheung from the Grantham Institute made during the production and editing of this paper.

About the authors

Rebecca Thomas is a PhD student in the Department of Life Sciences and part of the Science and Solutions for a Changing Planet Doctoral Training Partnership at the Grantham Institute at Imperial College London. Her research focuses on the seasonal fluxes of carbon dioxide in terrestrial biosphere models.

Dr Heather Graven is a Lecturer in the Department of Physics and the Grantham Institute at Imperial College London. She studied for her PhD at Scripps Institution of Oceanography, USA and worked previously at ETH Zurich, Switzerland. Her research focuses on the use of atmospheric measurements to understand the global carbon cycle and its response to human activities and climate change.

Professor Sir Brian Hoskins, CBE, FRS is the Chair of the Grantham Institute at Imperial College London and Professor of Meteorology at the University of Reading. His research expertise is in weather and climate processes. He is a member of the UK Committee on Climate Change and a member of the scientific academies of the UK, USA, and China.

Professor Iain Colin Prentice holds the AXA Chair of Biosphere and Climate Impacts at Imperial College London. His research aims to discover fundamental principles governing the responses of plant and ecosystem processes to environment, and to develop next-generation models for the impacts of climate change on the biosphere.

References

1. FCCC/CP/2015/L.9/Rev.1, Adoption of the Paris Agreement, 2015, UNFCCC.
2. IPCC, Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker, et al., Editors., Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA.
3. Le Quere, C., et al., Global carbon budget 2014. *Earth System Science Data*, 2015. 7(1): p. 47-85.
4. Prentice, I.C., S. Williams, and P. Friedlingstein, Biosphere feedbacks and climate change. Grantham Institute Briefing Paper, 2015. 12.
5. (RCPs), I.R.C.P. Scenario Process for AR5. 2014 [cited 2016 July 2016]; Available from: http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html.
6. Fuss, S., et al., Betting on negative emissions. *Nature Clim. Change*, 2014. 4(10): p. 850-853.
7. Smith, P., et al., Biophysical and economic limits to negative CO₂ emissions. *Nature Climate Change*, 2016. 6: p. 42-50.
8. Index, NOAA Annual Greenhouse Gas Index 2016 [cited 2016 July 2016]; Available from: <http://www.esrl.noaa.gov/gmd/aggi/aggi.html>
9. Allen, M.R., et al., Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, 2009. **458**(7242): p. 1163-1166.
10. Pierrehumbert, R.T., Short-Lived Climate Pollution. *Annual Review of Earth and Planetary Sciences*, Vol 42, 2014. **42**: p. 341-+.
11. Smith, S.M., et al., Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Climate Change*, 2012. **2**(7): p. 535-538.
12. Allen, M.R., et al., New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Clim. Change*, 2016. **advance online publication**.
13. AVOID 2, Can we deploy enough Bioenergy with Carbon Capture and Storage to achieve climate targets? infographic, Available from: <http://www.avoid.uk.net/BECCS/>



About the Grantham Institute

The Grantham Institute is committed to driving research on climate change and the environment, and translating it into real world impact. Established in February 2007 with a £12.8 million donation over ten years from the Grantham Foundation for the Protection of the Environment, the Institute’s researchers are developing both the fundamental scientific understanding of climate and environmental change, and the mitigation and adaptation responses to it. The research, policy and outreach work that the Institute carries out is based on, and backed up by, the world-leading research by academic staff at Imperial.

www.imperial.ac.uk/grantham

About Imperial College London

Consistently rated amongst the world’s best universities, Imperial College London is a science-based institution with a reputation for excellence in teaching and research that attracts 13,000 students and 6,000 staff of the highest international quality.

Innovative research at the College explores the interface between science, medicine, engineering and business, delivering practical solutions that improve quality of life and the environment—underpinned by a dynamic enterprise culture. Since its foundation in 1907, Imperial’s contributions to society have included the discovery of penicillin, the development of holography and the foundations of fibre optics.

This commitment to the application of research for the benefit of all continues today, with current focuses including interdisciplinary collaborations to improve health in the UK and globally, tackle climate change and develop clean and sustainable sources of energy.

www.imperial.ac.uk

This is **naturally responsible** Printing *virtually Zero*

100% carbon neutral 100% EMAS 100% renewable energy 100% ISO14001 100% eco-friendly simitri® toner 100% recycled FSC stock

virtually **0%** waste

printed by **seacourt** proud to be counted amongst the top environmental printers in the world www.seacourt.net

What is meant by ‘balancing sources and sinks of greenhouse gases’ to limit global temperature rise?