Institution: University of Reading		
Unit of Assessment: 7 – Earth Systems and Environmental Sciences		
Title of case study: Research supporting the use of climate emission metrics in policymaking		
Period when the underpinning research was undertaken: Between 1 January 2003 and 31 December 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Keith P Shine William Collins	Professor Professor	October 1994 to Present November 2012 to Present
Period when the claimed impact occurred: Between 1 August 2013 and 31 December 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

International climate treaties use metrics to place emissions of greenhouse gases (GHGs) other than carbon dioxide (CO_2) on a common CO_2-equivalent (CO_2e) scale. Research at Reading has made a major contribution to the computation of a necessary input to such metrics: the 'Radiative Efficiency' (RE) of individual gases. This work expanded the number of gases for which RE values are available, helped resolve discrepancies reported in the literature, and developed consistent methodologies for their computation. Reading's research is used extensively by the Intergovernmental Panel on Climate Change (IPCC) to compute metrics required in treaties including the Kyoto Protocol and the Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC). Reading's research also contributed to the debate on the design of metrics; it created a new metric called the Global Temperature-Change Potential (GTP) and helped develop a variant (GWP*) of the widely-used Global Warming Potential (GWP) metric. These have gained traction in how individual countries and sectors approach climate change mitigation.

2. Underpinning research

Human activity causes emissions of many GHGs that differ from CO_2 in their effect on climate. International and national climate policy employs 'exchange rates' to place emissions of such gases on a common 'CO_2e' scale. These exchange rates are calculated using 'climate emission metrics' (hereafter 'metrics') which enable the climate effect of the emission of a given gas to be compared with the effect of emissions of CO_2.

Reading has contributed significantly to calculations of RE values for many GHGs; these are a necessary input for calculating metrics such as the GWP. This work included the first published calculations of RE for many gases. One example is nitrogen trifluoride (NF_3), which is widely used in the electronics industry, and for which, prior to 2006, an RE value had never been published. Shine asked Ford Motor Company colleagues to perform new spectroscopic measurements; Reading's calculation of its RE was 60% higher than what could be (indirectly) inferred from earlier work [R1]. Research at Reading also helped resolve significant differences in RE values in earlier literature. For example, RE values for some of the most abundant hydrofluorocarbons (HFCs) differed by more than 20%. Reading [R2] led a detailed intercomparison with the University of Oslo, which increased confidence in these RE values. Results from [R1] and [R2] were used by the IPCC to produce its GWP tabulations in their Working Group 1 Fourth Assessment Report (AR4, approved in June 2007). IPCC tabulations are the definitive source of GWP values used in policy applications.

Shine then played a major role, as part of an international collaboration, in a detailed critical assessment of available REs and the underlying spectroscopic data [R3]. Prior to this, AR4 had used REs for 60 halocarbons, and related gases, which had been drawn from different sources, employing diverse methodologies. Reference [R3] developed a common methodology to estimate RE, enabling improved internal consistency, and then applied it to over 200 gases. IPCC's fifth Assessment Report (AR5, approved in September 2013 and formally published in January 2014) adopted this greatly expanded dataset in its metric tabulations [R4]. Collins was AR5's author with prime responsibility for generating these tabulations, having moved to Reading during the writing of this assessment.

Since the early 1990s, there has been an ongoing debate within academic and policymaking circles about whether alternatives to the GWP might serve climate policy better. However, no new metrics had gained significant traction. In 2005, Shine led the development of the GTP metric [R5]. The GWP is the time-integrated radiative forcing following a pulse emission of a gas, relative to the same quantity due to an equal emission of CO_2; it is currently the most widely-used metric, normally employing a 100-year integration period (GWP(100)). By contrast, the GTP provides the temperature change at a given time after an emission of a GHG, again, compared to an equal emission of CO_2. Hence, unlike the GWP, the GTP specifically addresses the temperature impact of emissions [R5] and so may be more appropriate to temperature targets specified in the UNFCCC Paris Agreement. As a demonstration of the effect of using GTP on the perceived importance of emissions, the GWP(100) of methane is 24, whereas the GTP(100) is four [R4]. Tabulated values of GTP were included, for the first time, in AR5. Collins calculated these values for AR5 [R4] using an updated methodology compared to [R5] for over 200 gases; this made GTP values readily available to the policy community.

Shine collaborated with colleagues at the University of Oxford and other institutions in developing an alternative metric, known as GWP* [R6], which built heavily on his GTP work [R5]. The GWP* is based on a distinct application of existing GWP values; it exploits the fact that the impact of emissions on temperature is better captured by comparing pulse emissions of long-lived species (e.g. CO_2) to sustained emissions of short-lived species (e.g. methane). Notably, the work identified possible flaws in the standard application of the GWP in future scenarios with decreasing emissions of short-lived species. The GWP* employed existing GWP values, for example from [R4], to provide continuity with the conventional use of GWP, but adopted several approximations to do so. Collins, with Shine, then developed a new pulse-sustained metric which avoided these approximations, and so placed the concept on a physically more robust footing [R7].

3. References to the research

Research Quality Statement: All references were published in the peer-reviewed literature and meet or exceed the two-star quality criteria ("provides useful knowledge and influences the field"; "involves incremental advances"). Evidence of influence is indicated by Web of Science Citations in square brackets, as of December 2020. Authors in **bold** were at Reading when the output was produced.

[R1] **Robson** JI, **Gohar** LK, Hurley MD, **Shine** KP and Wallington TJ. (2006). 'Revised IR spectrum, radiative efficiency and global warming potential of nitrogen trifluoride' *Geophys. Res. Lett.* **33**, L10817. DOI: 10.1029/2006GL026210 [31].

[R2] **Gohar** LK, Myhre G, **Shine** KP (2004). 'Updated radiative forcing estimates of four halocarbons'. *J. Geophys. Res.* **109**, D01107. DOI: 10.1029/2003JD004320 [24].

[R3] Hodnebrog Ø, **Etminan** M, Fuglestvedt JS, **Marston** G, Myhre G, Nielsen CJ, **Shine** KP, Wallington TJ (2013). 'Global Warming Potentials and Radiative Efficiencies of Halocarbons and Related Compounds: A Comprehensive Review'. *Reviews of Geophysics.* **51**, 300-378. DOI: 10.1002/rog.20013 [217].

[R4] Myhre G, Shindell D, Bréon F-M, **Collins** W, Fuglestvedt J, Huang J, Koch D, Lamarque J-F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T, Zhang H. (2013) 'Anthropogenic and natural radiative forcing'. In TF Stocker et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth IPCC*

Assessment Report,659–740. Cambridge University Press. Link (see the chapter's supplementary material) [1793].

[R5] **Shine** KP, Fuglestvedt JS, **Hailemariam** K, **Stuber** N. (2005) 'Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases' *Climatic Change*. **68**, 281-302. DOI:10.1007/s10584-005-1146-9 [337].

[R6] Allen MR, **Shine** KP, Fuglestvedt JS, Millar RJ, Cain, M, Frame DJ, Macey AH, (2018). 'A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation'. *NPJ Climate and Atmospheric Science*. **1,** (16). DOI:10.1038/s41612-018-0026-8 [53].

[R7] **Collins** WJ, Frame DJ, Fuglestvedt J, **Shine** KP. (2020). 'Stable climate metrics for emissions of short and long-lived species - combining steps and pulses'. *Environmental Research Letters,* **15**:024018 . DOI: 10.1088/1748-9326/ab6039 [2].

4. Details of the impact

Policy Implementation: Reading's RE calculations made significant contributions to tabulations of metrics presented by IPCC in AR4 [S1] and AR5 [S2]. These have subsequently been used to implement climate policy worldwide. Several examples follow, first considering UNFCCC and then other policy applications.

First, the 2012 Doha Amendment to the UNFCCC Kyoto Protocol, which covers emissions in the period between 2013 and 2020, added NF_3 [R1] to its list of GHG emissions to be included in national commitments, using its AR4 GWP(100) value. This Amendment was accepted by 146 of the current 147 signatory countries during the REF2021 Impact Period. In November 2013, the UNFCCC adopted AR4 GWP(100) values in its requirement for countries to report their annual CO_2e emissions. Then in November 2018, under the UNFCCC Paris Agreement, which supersedes the Kyoto Protocol, it formally adopted AR5 GWP(100) values [R4] for this reporting. Similarly, in May 2020, the European Union (EU) adopted AR5 GWP values in its regulations for member states to report their greenhouse gas emissions from 1 January 2021 onwards [S3].

A specific policy focus has been HFC emissions, because of their growing usage in air-conditioning units in buildings and vehicles, and other sectors, including refrigeration. UNFCCC data shows that CO_2e emissions from developed nations (Annex 1) rose by a factor of three between 1990 and 2017, whereas total CO_2e emissions remained almost constant. Thus, HFC emissions constituted a growing percentage of the total (for example now 3% in UK, 3.5% in Japan). To curb future growth, there have been widespread efforts to move to low-GWP HFC alternatives. The legislation, some of which is detailed in the next paragraph, is reliant on reliable GWP (and hence RE) values for its implementation.

In 2014, the EU Fluorocarbon Gas Regulation adopted AR4 GWP values. This regulation mandated that HFC usage in different sectors should be phased out between 2015 and 2025. As an important example, the EU identified one gas, HFC-32, as being a technologically feasible low-GWP alternative. Its RE, in AR4, originates from Reading-led research that resolved earlier disagreements [R2, S1]. This regulation led to a major shift in HFC usage, for example, in air conditioning units manufactured by Mitsubishi UK. In 2018, the European Environment Agency reported a subsequent 54% (CO_2e) reduction in HFC usage in the EU, relative to 2011-2013, which is an indicator of the regulation's success. Japan (in 2016) and Canada (in 2019) implemented similar legislation that required HFC GWP values. The 2016 Kigali Amendment to the UN's Montreal Protocol on Substances that Deplete the Ozone Layer [S4] set binding targets for reducing HFC emissions in developed and developing nations based on AR4 GWP(100) values. This Amendment entered into force (i.e. became legally binding) in January 2019 and is currently ratified by 112 countries [S4].

Contribution to Policy Debate: Reading's work on alternative metrics (GTP and GWP*) to the GWP has impacted public policy by enabling a debate on the most appropriate metrics for use in meeting specific climate policy objectives. Prior to AR5, no proposed alternatives had gained traction with policymakers, and the GWP had been the only metric recommended by IPCC. Thus, GWP, and specifically GWP(100), became UNFCCC's established standard metric. In 2013, tabulated values of GTP were included, for the first time, in IPCC's AR5 [R5, S5]; unlike earlier IPCC assessments, AR5 refrained from specifically recommending any particular metric, GWP(100) or otherwise.

The GTP is used in numerous national and international contexts. As examples, the Norwegian Environment Agency adopted it in its 2016 action plan to reduce emissions of short-lived climate pollutants; and in 2016, the UN Environment Program-hosted Life Cycle Initiative (which includes many governmental and industrial funding partners) recommended the GTP(100) as one of three climate indicators in Life Cycle Impact Assessment [S6].

The GTP is also discussed in some Nationally Determined Contributions (NDCs) which embody efforts by each country to reduce national emissions under the UNFCCC Paris Agreement. Brazil's 2016 NDC states that the GTP is "most consistent with contributions to hold the increase in global average temperature below 2°C above pre-industrial levels" (i.e. the specific aim of the Paris Agreement). Uruguay's 2016 NDC highlights the AR5 comment that "the GWP metric is not directly related to a temperature limit, as the 2°C target ..., whereas other metrics like the GTP may be more suitable …" [S7].

In 2018, a UN climate agreement included specific mention of the GTP for the first time. The UNFCCC's 2018 decision to adopt the AR5 GWP(100) values (see above and [S3]) was accompanied by the statement that "each Party may … also use other metrics (e.g. global temperature potential) to report supplemental information on aggregate emissions …". This reflects an ongoing, unresolved debate within the UNFCCC's Subsidiary Body for Scientific and Technological Advice (SBSTA), which noted: "limitations in the use of GWPs based on the 100-year time horizon in evaluating … emissions of [gases] with short lifetimes" [S8].

In the short time since the GWP* was proposed, it has already impacted on the policy debate, particularly for countries and sectors that are major methane emitters because of the scale of their agricultural activity. Shine played a significant role in disseminating the concept to stakeholders, including a side-event at the UNFCCC COP23 (Bonn, 2017), and invited talks at the Climate and Clean Air Coalition's Scientific Advisory Panel Expert Workshop (Ottawa, 2017) and IPCC's Expert Meeting on Short-lived Climate Forcers (Geneva, 2018).

The most notable policy impact of GWP* was its role in motivating a new treatment of agricultural methane emissions by New Zealand in their national climate legislation. New Zealand's 2019 Climate Change Response (Zero Carbon) Amendment Act sets separate targets for emissions of (1) long-lived greenhouse gases, aiming for net zero by 2050, and (2) biogenic methane emissions, aiming for a reduction of 24 to 47% below 2017 levels by 2050. Targets were set on the advice of New Zealand's Productivity Commission which had concluded that the GWP* can "help people make better decisions about mitigation." This decision is now reflected in New Zealand's 2020 NDC [S9].

The GWP* was considered in detail by the UK Committee on Climate Change in their 2020 report 'Land use: Policies for a Net Zero UK.' A joint statement by agricultural organisations in the UK and New Zealand, including the National Farmers' Union, supported the adoption of the GWP*. Furthermore, the International Dairy Sustainability Framework (IDSF) launched a project to examine "the potential benefits and disadvantages for the global ruminant sector of applying GWP*," with the IDSF acting on behalf of organisations including Arla Foods, International Dairy Federation, McDonalds, and Meat and Livestock Australia [S10].

In summary, Reading's research has contributed directly to climate policy, by providing results that are required to implement methods for placing emissions of non-CO_2 greenhouse gases on a CO_2e scale. These methods are needed to enact both international climate policy and policies developed by individual nations and groups of nations. Reading's work has regularly updated those results, in the light of improved understanding, and it has helped enable the calculation of values for an increasing number of such gases. Its contribution to definitive tabulations in international climate assessments has enabled their wide uptake by stakeholder communities throughout the world and hence influenced mitigation actions, most notably in the area of fluorocarbon emissions. Its work on methodologies for placing emissions on CO_2e scales has contributed to an ongoing debate within the UNFCCC, and beyond, on the most appropriate methodologies. This has influenced the framing of mitigation actions by individual nations and stakeholder communities. Thus, Reading's research has had both a global reach and a significant influence on an important component of international and national environmental policymaking.

5. Sources to corroborate the impact

[S1] The metric calculations in AR4 Table 2.14 are largely taken from Table 2.6 of an earlier (2005) IPCC "TEAP" special report. Footnotes (e) and (j) in TEAP refer to Reading's work (including [R2]); footnotes (d), (e) and (f) in AR4 refer to Reading's work (including [R1]). The AR4 table lists 60 halocarbons or related gases covered by the Kyoto Protocol; RE values for a quarter of these can be traced directly to Reading's research.

[S2] The metric calculations for halocarbons in AR5 [R4] almost all originate from [R3] – this can be traced via the (a) supplementary material (Section 8.SM.13) to Chapter 8 of AR5's Working Group 1's report which points to (b) http://cicero.uio.no/halocarbonmetrics/.

[S3] The UNFCCC Doha Amendment entered into force in December 2020 having achieved the required acceptances in October 2020; prior to this, many countries (the EU included) had already agreed to fulfil their Doha commitments. The UNFCCC 2013 decision to adopt AR4 GWPs decision is in Annex III of (a) this document. The 2018 decision to use AR5 GWPs and GTPs is on page 25, para 37 of (b) this document. The May 2020 European Union regulation on using AR5 GWPs is (c) here.

[S4] The EU F-gas legislation is (a) here, with the EU's identification of HFC-32 as "climate friendly" (b) here. The impact on Mitsubishi is (c) here. The European Environment Agency's report (published February 2020) is (d) here (e.g. Figure ES2). An English language description of Japan's legislation is (e) here. Canada's legislation is (f) here. The 2016 (g) Kigali Amendment to the UN Montreal Protocol on Substances that Deplete the Ozone Layer includes HFC GWPs from AR4.

[S5] AR5 WG1 Section 8.7.1.3 [R4] attributes the GTP concept to paper [R5].

[S6] The Norwegian Environment Agency Action Plan is (a) here; Life Cycle Initiative recommendations of the use of the GTP in the Life Cycle Initiative recommendations is (b) here.

[S7] UNFCCC NDCs are documented (a) here, including (b) Brazil's and (c) Uruguay's NDCs.

[S8] The UNFCCC SBSTA recognition of the GWP's limitations date back to before the REF2020 period as evidenced (a) here (Paragraphs 100-102); the fact that this debate remains unresolved at UNFCCC COP25 meeting (in 2019) is indicated (b) here. The subsequent SBSTA meeting scheduled for June 2020, where further discussion on metrics was an agenda item, was postponed to 2021 because of COVID.

[S9] The New Zealand's Productivity Commission's Report is (a) here; their Government's response is (b) here. New Zealand's Climate Change Response (Zero Carbon) Amendment Act (2019) is (c) here, and its 2020 NDC update is (d) here.

[S10] The Committee on Climate Change's 'Land use: Policies for a Net Zero UK' report is (a) here. The statement by farming organisations supporting the use of GWP* (b) is here. The Dairy Sustainability Framework GWP* project is (c) here.