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# The implications of carbon dioxide and methane exchange for the heavy mitigation RCP2.6 scenario under two metrics

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## ABSTRACT

Greenhouse gas emissions associated with Representative Concentration Pathway RCP2.6 could limit global warming to around or below a 2 °C increase since pre-industrial times. However this scenario implies very large and rapid reductions in both carbon dioxide (CO<sub>2</sub>) and non-CO<sub>2</sub> emissions, and suggests a need to understand available flexibility between how different greenhouse gases might be abated. There is a growing interest in developing a greater understanding of the particular role of shorter lived non-CO<sub>2</sub> gases as abatement options. We address this here through a sensitivity study of different methane (CH<sub>4</sub>) emissions pathways to year 2100 and beyond, by including exchanges with CO<sub>2</sub> emissions, and with a focus on related climate and economic advantages and disadvantages.

Metrics exist that characterise gas equivalence in terms of climate change effect per tonne emitted. We analyse the implications of CO<sub>2</sub> and CH<sub>4</sub> emission exchanges under two commonly considered metrics: the 100-yr Global Warming Potential (GWP-100) and Global Temperature Potential (GTP-100). This is whilst keeping CO<sub>2</sub>-equivalent emissions pathways fixed, based on the standard set of emissions usually associated with RCP2.6. An idealised situation of anthropogenic CH<sub>4</sub> emissions being reduced to zero across a period of two decades and with the implementation of such cuts starting almost immediately gives lower warming than for standard RCP2.6 emissions during the 21st and 22nd Century. This is despite exchanging for higher CO<sub>2</sub> emissions. Introducing Marginal Abatement Cost (MAC)

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curves provides an economic assessment of alternative gas reduction strategies. Whilst simpler than utilising full Integrated Assessment Models (IAMs), MAC curves are more transparent for illustrative modelling. The GWP-100 metric places a relatively high value on climate change prevented for methane emission reduction, as compared to an equivalent mass of CO<sub>2</sub> reduction. This in combination with the strong non-linearity in MAC curves (moving quickly from relatively cheap removal to emissions difficult to cut at any cost) causes little change under cost minimisation from standard RCP2.6 emissions. This reflects the original development of RCP2.6 standard emissions from similar minimisation. With gas exchange under GTP-100, however, we find much less methane is abated, resulting in higher temperatures, whilst costs are slightly lower.

Our results also highlight the point at which greater methane mitigation would become beneficial from both a climate and economic aspect. If by 2030 removal of all methane were to become possible at an average cost less than \$1000 per tonne of CH<sub>4</sub>, then this would be the cheapest option, for GWP-100 metric and our CO<sub>2</sub> MAC curve. Critically this would increase the possibility of constraining warming to two degrees.

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## 1. Introduction

Technological advances, lifestyle changes and welfare considerations may mean that it becomes cheaper or preferable to mitigate (i.e. abate) one greenhouse gas more so than another. At present there is significant debate surrounding how to balance mitigation action between CO<sub>2</sub> and CH<sub>4</sub>, the two dominant perturbed greenhouse gases in terms of contemporary radiative forcing (e.g. Shindell et al., 2012). Finding a cost optimum for the balance between CO<sub>2</sub> and CH<sub>4</sub> mitigation becomes especially important as society debates the massive emission reductions needed to stabilise global warming at two-degrees above pre-industrial levels. However these gases have very different atmospheric lifetimes. A large fraction of CO<sub>2</sub> has a lifetime of magnitude hundreds of years and so emissions of this gas have a generally cumulative impact on peak warming levels (Allen et al., 2009), whereas methane atmospheric lifetime is approximately 12 years in the current state of the atmosphere. Early action on multiple short-lived gases including CH<sub>4</sub> has been argued for (e.g. by Shindell et al., 2012), and possibly by implication at the expense of CO<sub>2</sub> reductions. Others, such as Shoemaker and Schrag (2013), Myhre et al. (2011), Boucher and Reddy, (2008), Bernsten et al. (2010) have noted potential dangers of an over-emphasis on reductions of short-lived greenhouse gases, given this may delay mitigation of CO<sub>2</sub> emissions. Reductions in short-lived greenhouse gases are only useful to stabilise warming if CO<sub>2</sub> emissions are also heavily mitigated (Bowerman et al., 2013).

Representative Concentration Pathways (RCPs) (Meinshausen et al., 2011a; Moss et al., 2010) are scenarios for the possible future evolution of concentrations of the various gases that affect climate. RCP2.6 (van Vuuren et al., 2007, 2011) represents strong abatement relative to a no-climate policy reference scenario, with CO<sub>2</sub> concentrations reaching no higher than around 450 ppm and CH<sub>4</sub> concentrations reaching approximately 1800 ppb. This particular RCP is the focus of our study. Each RCP also has a set of standard emissions associated with it (Meinshausen et al., 2011a), calculated with the MAGICC6 model (Meinshausen et al., 2011b) and normalised to have

emissions in year 2005 consistent with observations. Further, in conjunction with an IAM, this scenario represents the multi-gas emissions with minimum cost that achieves a total eventual radiative forcing of 2.6 Wm<sup>-2</sup> (van Vuuren et al., 2010, 2011).

Metrics provide a mechanism to calculate the emissions of a non-CO<sub>2</sub> gas that are equivalent to an amount of CO<sub>2</sub> emissions in terms of their influence on climate. Such climate influence is either an instantaneous value or a value integrated over a specified time interval, and for a key climatological variable such as radiative forcing change or temperature change. Equivalent emissions are usually presented in tonnes of CO<sub>2</sub>-equivalent per year (tCO<sub>2</sub>e yr<sup>-1</sup>), found by multiplying the emissions for each non-CO<sub>2</sub> gas in native units by metric value. However there is no single universal value to the metric, as each reflects comparison of alternative features of climate change, the metric application, and may be derived for different time intervals (O'Neill, 2003; Tanaka et al., 2013). Hence emissions from gases may have a different ranking in terms of the climate impact depending on metric choice (e.g. Moura et al., 2013). In terms of any attempt to mitigate climate change, Aamaas et al. (2013) show that in most cases CO<sub>2</sub> emissions are important regardless of the metric and time interval. However the relative importance of the short-lived climate forcers depends strongly on metric chosen. Despite this, Ekholm et al. (2013) suggest that there may be a metric that is universally only slightly sub-optimal. What constitutes a robust metric and the value judgements involved is discussed by Fuglestad et al. (2003, 2010) and Deuber et al. (2013). Additionally new metrics have been recently introduced and these include: integrated temperature change potential (Peters et al., 2011), the Cost-Effective Temperature Potential (CETP) which is a metric that attempts to simultaneously account for physical climate response and capture IAM-based economic costs (Johansson, 2012), the multi-basket approach metrics such as the peak commitment temperature and sustained emissions temperature (Smith et al., 2012) and the similar methane specific approach of Lauder et al. (2013). Deuber et al. (2014) include the short-lived climate forcers (SLCF) in CO<sub>2</sub>-equivalence metrics with a

generic approach based on radiative forcing and the efficacy of the SLCF.

Two metrics do, though, receive particular attention. The GWP (Lashof and Ahuja, 1990; Shine et al., 1990) is the ratio of additional radiative forcing integrated over a prescribed time horizon due to a pulse emitted of one tonne of non-CO<sub>2</sub> greenhouse gas, compared to that due to a pulse of one tonne of CO<sub>2</sub>. The GWP metric has been central to gas comparison discussion by the Intergovernmental Panel on Climate Change (IPCC), including back to its first report (Houghton et al., 1990; page xi, Executive summary). The GTP (Shine et al., 2005, 2007) similarly compares such emissions pulses, but is the resultant ratio of warming amounts at end of the time horizon. A time horizon of 100 years is frequently considered for GWP, and to allow comparison, we consider this timescale also for GTP, giving metrics named GWP-100 and GTP-100, respectively. For methane, GWP-100 is an order of magnitude larger than GTP-100. Although GTP-100 is advocated less, this size difference allows a sensitivity study of metric size to be undertaken.

The issues of metric choice and scenario development are closely linked, with exchanges between different gases being a necessary aspect of all scenario design. In RCP2.6, the mix of emissions is not completely free to be determined by cost optimisation, with gas exchange controlled by the GWP-100 metric. Aaheim et al. (2006) suggest that if this constraint on cost-optimisation is removed, abatement costs can be reduced by approximately 2%, while Johansson et al. (2006) suggest the reduction to be approximately 4% of total abatement cost. Recently aspects of the problem of there being no unique metric for comparable gas exchange has also been investigated by Smith et al. (2013) and Reisinger et al. (2013), using respectively the GCAM and MESSAGE IAMs. Tanaka et al. (2013) go one step further, arguing that the large range of different possible metrics implies the only sensible approach is full engagement between climate researchers and economists to prevent arbitrary choice of metric.

In this study we examine the potential choices of methane pathway under RCP2.6 through sensitivity studies with alternative methane emissions. Our aim is to focus on both the climate science and mitigation cost aspects as both will likely have a bearing on the real world. Thus we use a differing experimental design to earlier work. One possibility is to derive new emissions profiles following exactly the methodology of van Vuuren et al. (2010, 2011), employing again their full IAM. However, for clarity, we instead assume a potential starting point to policy discussion is to fix combined CO<sub>2</sub>e emission trajectories and for the emissions (Meinshausen et al., 2011a) associated with heavy mitigation scenario RCP2.6. This CO<sub>2</sub>e pathway is therefore metric-dependent. We then consider gas exchange options but whilst keeping the CO<sub>2</sub>e pathways invariant, using an available multi-gas climate model to estimate warming implications. Within a choice of a single metric (GWP-100), Daniel et al. (2012) consider the temperature and radiative forcing implications for pathways that are CO<sub>2</sub>e invariant but exchange CO<sub>2</sub> and CH<sub>4</sub> emissions. This work conducts a similar analysis under GWP-100 and GTP-100 metrics, whilst also considering the economic consequences of the gas exchanges. Related financial calculations are performed independently of an IAM, enabling the

subtlety of findings to be more clearly related to the shape of the MAC curves used.

Specifically, in this sensitivity study, we envisage a world that decides to follow the standard emissions for RCP2.6 (van Vuuren et al., 2011), although it allows flexibility through carbon dioxide and methane exchange. This may prove to be a more readily adopted starting point, even though it will give deviations away from the radiative forcing targets implicit in the RCPs. What is the influence of choice of metric that governs these exchanges on peak warming under exchange of shorter-lived CH<sub>4</sub> with CO<sub>2</sub>, and how is the desirability and timing of such exchange modulated by economic considerations? The algorithm used is that, for a CH<sub>4</sub> metric of value  $M$ , then changes away from standard emissions in carbon dioxide,  $\Delta\text{CO}_{2,\text{Emiss}}$  (tCO<sub>2</sub> yr<sup>-1</sup>), and changes from standard emissions in methane,  $\Delta\text{CH}_{4,\text{Emiss}}$  (tCH<sub>4</sub> yr<sup>-1</sup>), satisfy the balance of  $\Delta\text{CH}_{4,\text{Emiss}} = -(\Delta\text{CO}_{2,\text{Emiss}}/M)$ . Higher CO<sub>2</sub> emissions are exchanged for lower CH<sub>4</sub> emissions (or vice versa), whilst keeping invariant a metric-dependent CO<sub>2</sub>e emission pathway calculated for the sum of CO<sub>2</sub> and CH<sub>4</sub>. This exchange is calculated on a yearly basis, for the time-evolving CO<sub>2</sub>e pathway.

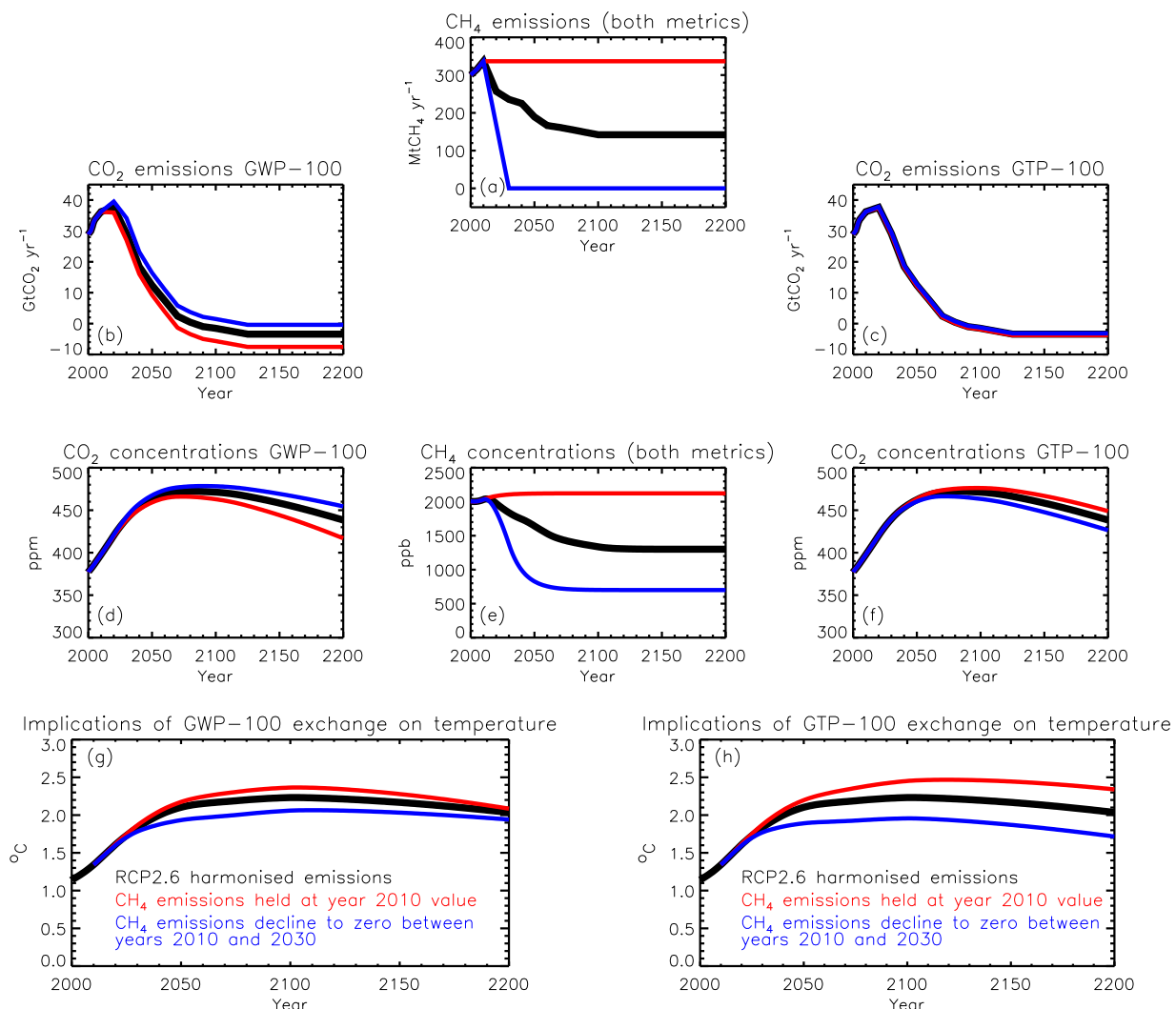
## 2. Methods

The climate component of our modelling structure uses a zero-dimensional energy balance formulation and with a diffusive thermal ocean (Bowerman et al., 2011; Allen et al., 2009). There is a three-box description of the carbon cycle, one of which represents the Revelle buffer factor (describing saturation of ocean CO<sub>2</sub> uptake under high CO<sub>2</sub> concentration), one representing advective processes and one representing diffusive processes in the carbon cycle, all capturing CO<sub>2</sub> “draw-down” from the atmosphere in to the oceans and terrestrial ecosystems. Climate and carbon cycle parameters in the model have been tuned to best reproduce historical observations (Bowerman et al., 2011; Allen et al., 2009). Non-CO<sub>2</sub> greenhouse gas concentrations, including methane, are modelled as non-interacting gases and that decay exponentially with gas-dependent constant lifetimes. These lifetimes are taken from standard 4th assessment IPCC values (Forster et al., 2007, Table 2.14), apart from methane which was also tuned to reproduce historical trends. As such, the CH<sub>4</sub> timescale will include, implicitly, feedbacks related to tropospheric ozone and stratospheric water interactions. The other non-CO<sub>2</sub> and non-CH<sub>4</sub> greenhouse gases modelled are nitrous oxide, ozone and multiple CFCs, as driven by their RCP2.6 standard emissions. In addition, F-gases, SF<sub>6</sub> and PFCs associated with RCP2.6 are presented as an additional radiative forcing, and a negative component for aerosol cooling is included.

GTP-100 and GWP-100 metric values are calculated by modelling the impact of a pulse of emissions of different gases on radiative forcing and on future temperature. The effect of a pulse of CO<sub>2</sub> includes a component of climate–carbon cycle feedbacks, where warming triggers further natural release of CO<sub>2</sub> in to the atmosphere. In common with others calculating metric values, this response to warming is switched off when calculating the implications of a pulse of CH<sub>4</sub>. The IPCC 5th

Assessment report observes that this is actually inconsistent and that including carbon cycle feedbacks in the warming from non- $\text{CO}_2$  gases would significantly increase their GWP and GTP, although this error will tend to be greater for higher emissions scenarios. Our calculations are for conditions generally representative of pre-industrial climate i.e. we adopted as our background state, pre-industrial atmospheric gas composition levels and global temperature. We recognise that recent convention is to instead use contemporary concentration levels. IPCC (1995) and Fuglestad et al. (2003) do assess the impact of alternative background states, and based on their work, changes between current and pre-industrial background atmospheres are estimated to have an order 10% impact on GWP-100 for  $\text{CH}_4$ . These calculations combine to return values of 21.23 and 1.76, respectively for the GWP-100 and GTP-100 of methane. Full climate model details are given in Bowerman (2013), which explains how constraints

placed on the model are derived from the fit of an historical simulation to the known global effective heat capacity, the 20th century warming trend,  $\text{CO}_2$  concentration rise since pre-industrial times, contribution of the temperature feedback to  $\text{CO}_2$  concentration rise and rate of advection of  $\text{CO}_2$  in to the deep ocean (Bowerman, 2013, Section 2.6). This yields a median equilibrium climate sensitivity for the model of around  $2.9^\circ\text{C}$ . Using this model, the black curves in the panels in Fig. 1 are for RCP2.6 standard emissions (other curves of Fig. 1 are described later). Shown are these prescribed emissions for  $\text{CH}_4$  (panel (a)), and for  $\text{CO}_2$  (black curves, same in panels (b) and (c)), associated calculated  $\text{CH}_4$  concentrations (panel (e)) and  $\text{CO}_2$  concentrations (black curves, same in panels (d) and (f)) and finally calculated warming implications (black curves, same in panels (g) and (h)). These standard emissions give a maximum global warming of approximately  $2.2^\circ\text{C}$  above pre-industrial levels. This is within the range



**Fig. 1** – Implications of outer bounds on exchange between  $\text{CO}_2$  and  $\text{CH}_4$  emissions, using both the GWP-100 metric (left-hand panels) and GTP-100 (right-hand panels). Three emission scenarios are shown, each maintaining the same path of total  $\text{CO}_2\text{e}$  emissions over time for each metric. Scenarios are RCP2.6 standard emissions (black curves),  $\text{CH}_4$  emissions reduced to zero by 2030 (blue curves), and  $\text{CH}_4$  emissions maintained at 2010 levels (red curves). Panel (a) shows the prescribed  $\text{CH}_4$  emissions, panels (b) and (c) show resulting  $\text{CO}_2$  emissions to maintain the  $\text{CO}_2\text{e}$  emissions pathways. Panels (d) and (f) are associated  $\text{CO}_2$  concentrations, and common to both metrics are  $\text{CH}_4$  concentrations in panel (e). Implications in terms of global temperature rise are presented for GWP-100 in panel (g) and GTP-100 in panel (h).



of warming simulated for RCP2.6 within the IPCC 5th assessment, although situated in the warmer half of the sample of full complexity climate models, which overall find a likely chance of keeping warming below the 2 °C level.

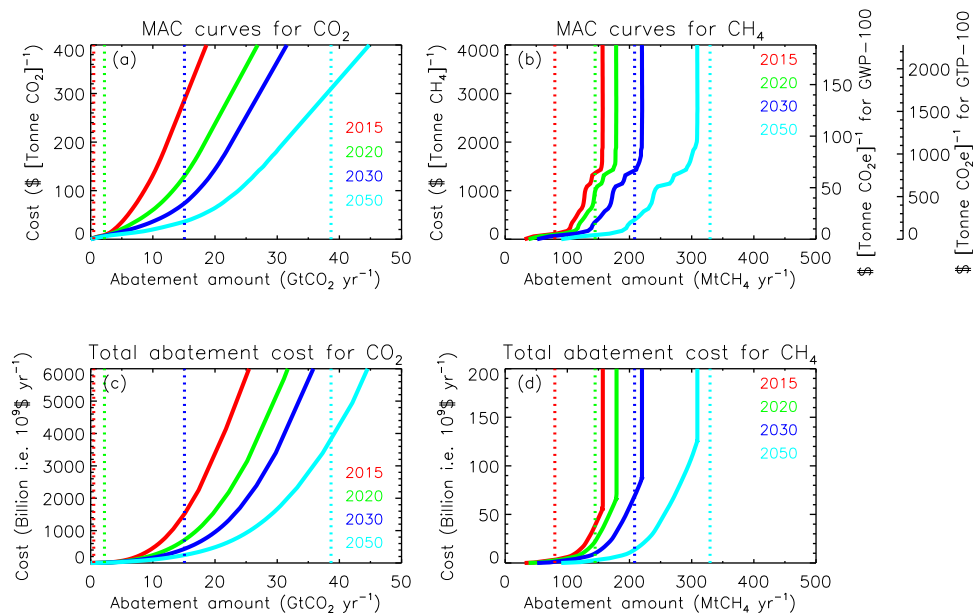
MAC curves provide the costs associated with any reductions in emissions, from a no-climate-action policy baseline (i.e. “business-as-usual”) down to emissions associated with policy-driven mitigation scenarios. MAC curves are widely used in government analyses, although they have some limitations (e.g. Kesicki and Ekins, 2012). For instance, while they show costs of options at a single point in time, the costs are usually path-dependent. Also, different options in the same curve may not be independent (i.e. one choice may negate, or reinforce, another). Despite these caveats, we use such an approach, and where our curves are derived from the UK Department of Energy and Climate Change (DECC)’s Global Carbon Finance (GLOCAF) model. These capture modelling from multiple sources, aggregating sectorial and regional MAC curves to produce the global curves of Fig. 2 (top panels). The energy and industry CO<sub>2</sub> curves, including international aviation and marine emissions, are based on World Energy Outlook 2011 and determined by Enerdata’s POLES model (<http://www.enerdata.net/enerdatauk/knowledge/subscriptions/forecast/marginal-abatement-cost-curves-MACCs.php>), imposing a carbon tax and recording an induced reduction of CO<sub>2</sub> emissions. The forestry and land-use MAC curves are from the G4M (Kindermann et al., 2008) and GLOBIOM (Nayer, 2009) models run by the International Institute of Applied Systems Analysis (IIASA). For forestry, they include deforestation and afforestation for all countries and forestry management for Annex I countries only (data are not available for non-Annex I forestry management).

Abatement potential from peat is not included. In the power and industry sectors the MAC curves for later years include a small amount of abatement potential from biomass Carbon Capture and Storage (CCS), and by 2050 there is enough abatement potential from biomass CCS to lead to negative emissions at high carbon prices in these sectors in some regions (a component of what is sometimes referred to as BECCs). The CH<sub>4</sub> MAC curves are from PBL’s IMAGE and FAIR model (Lucas et al., 2007). Up to the year 2020, these are also based on the EMF21 project (Weyant et al., 2006), along with additional assumptions on reduction potential beyond 2020.

The energy CO<sub>2</sub> MAC curves are modelled as abatement amounts away from a baseline no-climate-policy “business-as-usual” emissions scenario, which is also calibrated to the World Energy Outlook 2011 Current Policy scenario. For methane, the baseline emissions are PBL’s IMAGE model runs (Bouwman et al., 2006) for the OECD Environmental Outlook to 2050 (OECD, 2012).

MAC curves are provided for years 2015, 2020, 2030 and 2050, and up to a trading price of \$190 [tCO<sub>2</sub>e]<sup>−1</sup>, calculated in steps of \$2.7 [tCO<sub>2</sub>e]<sup>−1</sup>, and we linearly interpolate in time to intermediate years. In later years, RCP2.6 standard emissions require CO<sub>2</sub> abatement amounts higher than the derived upper MAC values of \$190 [tCO<sub>2</sub>e]<sup>−1</sup>. Hence we extrapolate linearly our MAC curves for CO<sub>2</sub> beyond this cost threshold. Ultimately a level might be achieved where CCS is feasible for a fixed cost and can be globally implemented. Then the MAC curves would have an upper horizontal limit. However at present, there remains large uncertainty as to the cost level of this.

Although uncertainty exists in the precise shape and the timing of MAC curves, generic features should be valid over



**Fig. 2 – MAC curves for CO<sub>2</sub> and CH<sub>4</sub>.** Panels (a) and (b) are MAC curves for CO<sub>2</sub> and CH<sub>4</sub> plotted for years 2015, 2020, 2030 and 2050; colours as marked. The vertical dotted lines (same colours) are abatement amounts required to fulfil the RCP2.6 standard CO<sub>2</sub> and CH<sub>4</sub> emissions. For the same years, the bottom panels (c) and (d) are the integration of the MAC curves, linking abatement amount to total cost. For the CH<sub>4</sub> MAC curve, units of \$ [Tonne CO<sub>2</sub>e]<sup>−1</sup> are also shown to right of panel (b), and for both GWP-100 and GTP-100.

the next decades. CO<sub>2</sub> emissions across a broad range of different elements can be reduced significantly, following a convex abatement cost curve. CH<sub>4</sub> emissions can be reduced particularly cheaply for some sources until further sources are reached that are very hard or impossible to abate. The position of the strong “cusp” of non-linearity for methane switching between the two cases could depend on activity changes (e.g. dietary changes involving eating less meat). Diverse elements also contribute to the CH<sub>4</sub> curves, including the transport of gas, enteric fermentation, coal production and rice fields. In Fig. 2b, for methane, we also show the MAC curves in units of CO<sub>2</sub>e for both metrics (right-hand axes).

### 3. Results and discussion

Our analysis maintains the (metric-dependent) total CO<sub>2</sub>e emission pathways consistent with RCP2.6. Hence for metrics GWP-100 and GTP-100 respectively, carbon dioxide and methane exchanges away from these emissions satisfy either  $\Delta\text{CH}_4_{\text{Emiss}} = -(\Delta\text{CO}_2_{\text{Emiss}}/21.23)$  or  $\Delta\text{CH}_4_{\text{Emiss}} = -(\Delta\text{CO}_2_{\text{Emiss}}/1.76)$ . Starting with idealised simulations, these provide bounds on warming changes through gas exchange. For this, we consider where CH<sub>4</sub> is either reduced to zero over 20 years, starting in the year 2010 and with corresponding more CO<sub>2</sub> emissions, or alternatively CH<sub>4</sub> emissions are held at year 2010 values and with fewer CO<sub>2</sub> emissions. These are the blue and red curves respectively throughout Fig. 1, demonstrating that such exchange, if based on either GWP-100 or GTP-100, can affect peak warming by around  $\pm 0.2^\circ\text{C}$ . Additionally, as expected, there are differences depending on metric. The lowest peak warming for both metrics corresponds to CH<sub>4</sub> emissions reducing to zero. This is  $2.06^\circ\text{C}$  for GWP-100. However due to a smaller exchanged CO<sub>2</sub> emissions increase for GTP-100, this is only  $1.95^\circ\text{C}$  of warming. The warming implications shown in Fig. 1g,h have similarities to Figure 2 of Daniel et al. (2012). It is noteworthy that under GTP-100 and higher methane emissions i.e. red curve, then the associated CO<sub>2</sub> concentrations are higher than those associated with standard emissions i.e. black curve (Fig. 1f). This is due to the additional warming triggering a positive feedback on the carbon cycle, and that is larger than the direct influence of lower exchanged CO<sub>2</sub> emissions. Related to this, Gillett and Matthews (2010) make a strong case that metrics for comparing non-CO<sub>2</sub> gas metrics should themselves account for climate–carbon cycle feedbacks. Thus in summary, when we focus purely on the climate response, we find that for our idealised fixed CO<sub>2</sub>e emissions pathway it is possible to reduce the warming compared to the standard RCP2.6 set-up through a greater share of emission reduction focusing on methane. The benefit is present with both gas exchange metrics but appears larger for the GTP-100 case.

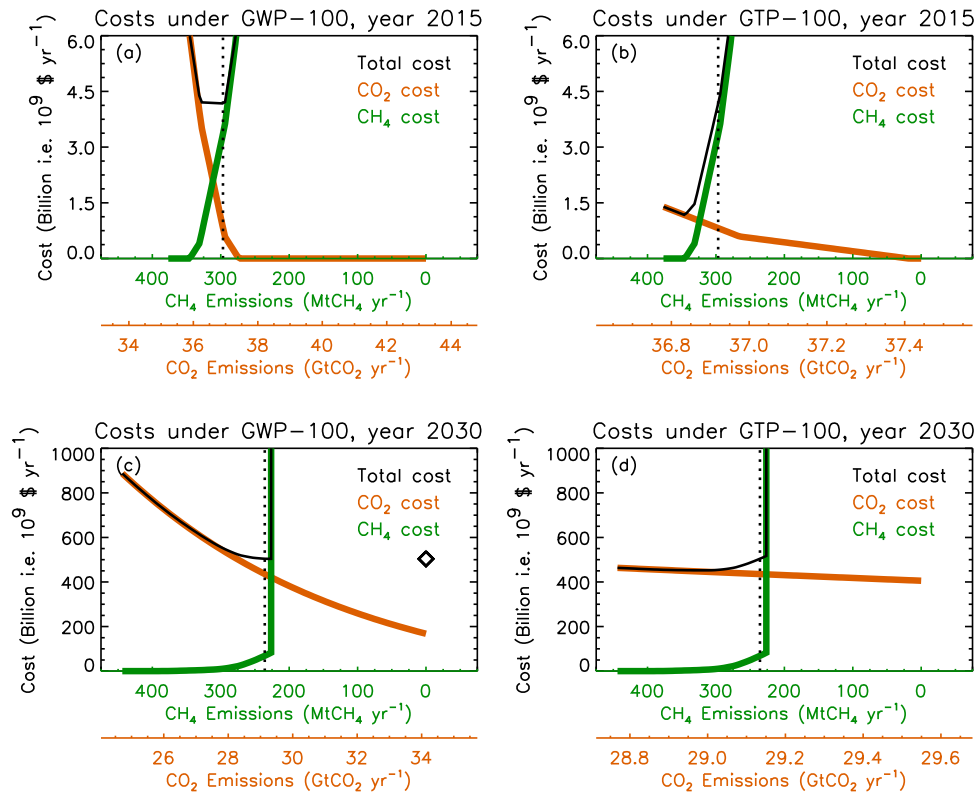
We now focus more on the related abatement cost aspects. Our global MAC curves (Fig. 2; top panels) are used to evaluate the costs of global emission reductions from “business-as-usual” to a range of lower CO<sub>2</sub> and CH<sub>4</sub> emissions. Abatement required to the standard RCP2.6 emissions levels are shown as vertical dotted lines in Fig. 2, and for years 2030 and 2050 are near to the maximum possible removable methane. This can to some extent be expected as the developers (Moss et al., 2010)

of this heavy mitigation RCP used an Integrated Assessment Model (IAM) with similar MAC curves, adopted a least-cost approach, and used the GWP-100 metric for gas exchange. The maximum amount of methane is abated before costs asymptote to infinity, and CO<sub>2</sub> emissions compensate in order to follow the RCP2.6 radiative forcing profile. CO<sub>2</sub> reduction is partly through Bioenergy and Carbon Capture and Storage (BECCS) in the mitigation portfolio allowing ultimately net negative emissions to fulfil RCP2.6 (later years; Fig. 1b,c). Integration of the MAC curves gives the total cost for different abatement amounts of CO<sub>2</sub> and CH<sub>4</sub> emissions (Fig. 2, bottom panels).

We can now cost our gas exchanges about RCP2.6-based CO<sub>2</sub>e profiles. For higher CO<sub>2</sub> emissions (lower abatement), costs for that gas decrease whilst simultaneously our exchanged CH<sub>4</sub> costs increase. This balance creates a minimum cost solution, generating new CO<sub>2</sub> and CH<sub>4</sub> emission pathways, whilst fulfilling the prescribed metric-specific CO<sub>2</sub>e pathways. We illustrate this balance in Fig. 3, for the 2 years 2015 and 2030, and for both metrics. Presented are monetary costs of different levels of exchange, with CH<sub>4</sub> – green curves and green horizontal axis – varying between no abatement (left in each panel) through to zero methane emissions (right in each panel). As CH<sub>4</sub> emissions decrease (moving left to right), then exchanged CO<sub>2</sub> emissions – brown curves and brown horizontal axis – increase along with their decreasing CO<sub>2</sub> abatement costs. Black curves are the sum of CO<sub>2</sub> and CH<sub>4</sub> curves describing the overall costs of abatement of both gases, and each curve has a minimum value. Our exchanges assume financial independence between CO<sub>2</sub> and CH<sub>4</sub>, although in the energy sector some of these emissions occur in tandem. Also we assume no feedback where major abatement expenditure influences other economic activity and thus emissions.

In Fig. 3 for 2030 – and later years not shown – the costs of CO<sub>2</sub> reductions to fulfil RCP2.6 are much larger than those for methane (when considering CH<sub>4</sub> emissions that are removable, so below the emissions cut threshold beyond which costs asymptote to infinity). For GWP-100, the minimum cost solution, i.e. lowest value of black curves, occurs at the “cusp” in the CH<sub>4</sub> curve, which means abating all removable methane, and is very near the standard emissions (dashed lines). Again, we expect this as the RCP2.6 profile has been developed with cost minimisation and the GWP-100 metric. For GTP-100, however, the situation is different. Now the minimum cost solution (minimum of continuous black curve, Fig. 3d) retains some potentially removable CH<sub>4</sub> emissions, as under this metric, methane is less “valuable” in terms of its reduction impact on climate. (This is consistent with calculating equal trading costs for gases across MAC curves when they are expressed in units of \$ [tonne CO<sub>2</sub>e]<sup>−1</sup>; these units are shown for methane in Fig. 2b, right-hand axes. In Fig. 2b for GTP-100 there remains change in the methane MAC curve (with respect to cost) at the equivalent high trading values of CO<sub>2</sub> abatement needed to fulfil RCP2.6, whereas for GWP-100 all removable methane has been abated above approximately \$90 [tonne CO<sub>2</sub>e]<sup>−1</sup>).

Fig. 4 is time-evolving minimum cost solutions, shown as thick light green lines. For GWP-100, as calculated for each year to 2050 and across all potential CO<sub>2</sub> and CH<sub>4</sub> exchanges under that metric, this solution is extremely close to the



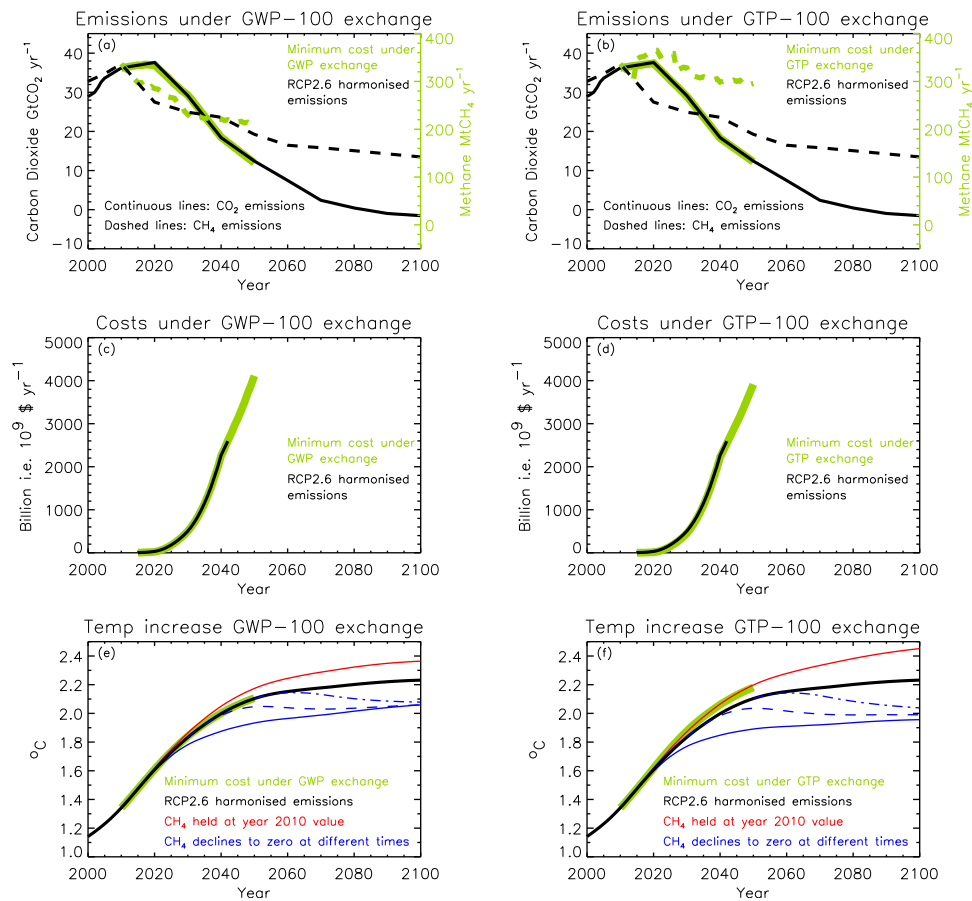
**Fig. 3 – Abatement costs for reduction to different emission levels.** Costs of reducing both CO<sub>2</sub> and CH<sub>4</sub> from no-climate-policy reference emissions, in years 2015 and 2030. This is for different levels of exchange by GWP-100 (left hand panels (a) and (c)) and GTP-100 (right hand panels (b) and (d)). The horizontal axis is emissions and as CH<sub>4</sub> emissions decrease then CO<sub>2</sub> emissions will increase to maintain yearly prescribed CO<sub>2</sub>e appropriate to RCP2.6. Methane emissions have a common scale for both metrics, and hence the CO<sub>2</sub> scales are smaller (for less exchange) under GTP-100. Vertical dotted black lines are RCP2.6 CO<sub>2</sub> and CH<sub>4</sub> standard emissions and so correspond to no gas exchange. CO<sub>2</sub> costs are brown, CH<sub>4</sub> costs are green and combined costs are black. The diamond, in panel (c) and so for year 2030 and GWP-100 exchange is minimum cost i.e. lowest value of the black curve, but plotted instead at the point of zero methane emissions (see text).

original standard emissions. This is seen comparing the thick light green and the black lines of Fig. 4a; continuous lines for CO<sub>2</sub> emissions (associated with left axis) and dashed lines for CH<sub>4</sub> emissions (right axis). These small changes to CO<sub>2</sub> and CH<sub>4</sub> emissions then translate to cost and warming implications that are also nearly identical to those of the standard emissions (Fig. 4c,e). For the GTP-100 metric, methane emissions are higher than the standard emissions (Fig. 4b) and this results in higher levels of warming (Fig. 4f). However this is despite the costs remaining almost identical to those for the standard emissions.

Fig. 4 presents minimum cost findings in terms of earlier discussions. In panels (e, f), the thin continuous red and blue curves repeat those of Fig. 1 (a, b), i.e. these are the idealised situation of anthropogenic methane emissions as either held at year 2010 emission rates (red curves) or linearly falling to zero by year 2030 (blue curves). We then add to these two additional and similar examples of linearly reducing anthropogenic methane emissions to zero, again away from standard RCP2.6 emissions and whilst keeping the metric-dependent CO<sub>2</sub>e pathway invariant. These correspond to later CH<sub>4</sub> reductions, occurring between years 2030 and 2050 (blue

dashed lines) and between years 2050 and 2070 (blue dash-dot lines). Many gains by this course of action in restricting peak warming are lost if initiation is delayed until 2050. That early action on CH<sub>4</sub> is necessary for reductions of that gas to be effective at decreasing peak warming is a consequence of the heavy mitigation RCP2.6 profile, which includes large on-going CO<sub>2</sub> emissions cuts and starting soon. Bowerman et al. (2013) demonstrate this point, showing that for other much lower mitigation profiles that wait until later before implementing major CO<sub>2</sub> reductions, then CH<sub>4</sub> reductions can be postponed until that time. Waiting still allows CH<sub>4</sub> to subsequently remain effective as an extra control towards reducing peak temperatures.

With anthropogenic CH<sub>4</sub> reductions to zero in the next two decades having most impact on peak warming (Fig. 4e,f), then this encourages a return to Fig. 3 to ask: what cost per tonne of CH<sub>4</sub> abatement in year 2030 would make a total cessation of anthropogenic methane emissions a minimum cost solution? Based on panel (c) of Fig. 3, the cost of reducing CO<sub>2</sub> emissions down only to approximately 34 GtCO<sub>2</sub> yr<sup>-1</sup> (the level at which exchanged CH<sub>4</sub> emissions are zero on a GWP-100 basis i.e. marked zero on green horizontal axis, 34



**Fig. 4 – Minimum cost solutions.** Comparison of RCP2.6 standard  $\text{CO}_2$  and  $\text{CH}_4$  emissions, costs and warmings with those of the minimum cost solutions based on MAC curves. Left panels are gas exchange under GWP-100 metric and right panels under GTP-100 metric. Panels (a) and (b) show standard emissions for RCP2.6 (black) and minimum cost (thick light green);  $\text{CO}_2$  continuous lines and left-hand scale;  $\text{CH}_4$  dashed lines and right-hand scale. Panels (c) and (d) show total costs (i.e. sum of  $\text{CO}_2$  and  $\text{CH}_4$  abatement), same colours as panels above. Standard emissions based costs plotted to year 2042 only, beyond which the emissions for methane move just across in to where costs are infinite (e.g. see Fig. 2b vertical black dash line for year 2050). Panels (e) and (f) show global temperature changes, same colours, and with the addition of the thin red and blue curves from Fig. 1 for  $\text{CH}_4$  emissions held at 2010 rates (red) and dropping linearly to zero between years 2010 and 2030 (blue). Also in panels (e, f), are warming implications of dropping methane emissions linearly away from the standard values starting year 2030 and reaching zero by 2050 (blue dashed lines), and similarly decreasing from year 2050 down to zero in year 2070 (blue dash-dot lines).

on the brown horizontal axis) is around  $\$300 \text{ bn yr}^{-1}$  less than the minimum total cost. To illustrate this, the minimum total cost level (lowest value on black continuous curve, where  $\text{CH}_4$  emissions are slightly larger than  $200 \text{ Mt CH}_4 \text{ yr}^{-1}$ ) is re-marked as a “diamond” symbol, but now plotted for zero methane emissions: the last right-hand point of the brown curve is roughly  $\$300 \text{ bn yr}^{-1}$  below this. Hence a cessation of  $\text{CH}_4$  emissions would be a cost-minimal strategy if this could be achieved for this cost i.e.  $\$300 \text{ bn yr}^{-1}$ . This would imply an additional  $200 \text{ Mt CH}_4 \text{ yr}^{-1}$  1 being removed (i.e. moving further along the green “x”-axis) for less than around  $\$200 \text{ bn yr}^{-1}$ , given the approximate  $\$100 \text{ bn yr}^{-1}$  already committed in mitigating  $\text{CH}_4$  to reach the minimum (of black curve) solution. Changing units, this corresponds to an average cost of less than  $\$1000$

per tonne of  $\text{CH}_4$  abatement. Pictorially, in Fig. 3c, achieving such a  $\text{CH}_4$  abatement cost, as opposed to having  $\text{CH}_4$  emissions difficult to remove at any cost, would make the black curve (brown curve plus new non-infinite green curve) instead move approximately horizontally from its current minimum solution, over to the black diamond mark. Such complete removal of all anthropogenic methane emissions by year 2030 would give a lower peak warming, similar to that of the thin blue dashed line (Fig. 4e). Under the GTP-100 metric these costs for abating all methane would have to be significantly lower and potentially much less achievable. This is because in Fig. 3d, for GTP-100, the  $\text{CO}_2$  cost gradient decreases at a much smaller rate, and so less savings from higher  $\text{CO}_2$  emissions are available to instead spend on  $\text{CH}_4$  reductions.



#### 4. Conclusions

To stabilise climate at two degrees centigrade of global warming since pre-industrial times will be especially challenging for society, requiring deep cuts to current emission levels. Further, there is relatively little room for manoeuvre in the timing and magnitude of when such cuts are required in order to remain below this warming threshold (e.g. [Huntingford et al., 2012](#)). Given the expected difficulties to achieve such large emissions reductions, there is enormous interest in what flexibility is available for exchanges in abatement levels between the different greenhouse gases. This is particularly so for how smaller carbon dioxide emission cuts could be exchanged for larger methane cuts, or vice versa. Such comparison of gases is generally achieved, including in IAMs, through the use of metrics that convert emissions of non-CO<sub>2</sub> greenhouse gases in to CO<sub>2</sub>-equivalent emissions. However depending on climate influence of choice, then even for the same gas, these metric values can have order-of-magnitude differences. Here we analyse the influence of metric choice for methane emissions. Modelling is kept as simple as possible, to illustrate in general global terms how warming estimates, metrics and abatement costs might interact.

Radiative forcing of the RCP2.6 scenario would likely constrain global warming to below two degrees centigrade for a mid-range estimate of climate sensitivity. To follow this, associated standard emissions and concentrations ([Meinshausen et al., 2011a; van Vuuren et al., 2011](#)) for a mix of different greenhouse gases have been previously created from cost-minimisation principles based on exchange under the GWP-100 metric, and by coupling an IAM with a climate model ([Moss et al., 2010; van Vuuren et al., 2011](#)). Unfortunately few modelling groups have simultaneous access to climate models and IAMs, making it difficult to test implications of alternative metrics on emissions, whilst still following the RCP2.6 radiative forcing profile. Additionally, as the RCP2.6 standard emissions are now strongly entrained in to policy discussion, we ask in this sensitivity study: “What are the implications of CO<sub>2</sub> and CH<sub>4</sub> exchange away from these standard emissions, whilst maintaining the same – i.e. metric-dependent – CO<sub>2</sub>e pathways for the two different metrics of GWP-100 and GTP-100?” That is, for each metric the CO<sub>2</sub>e pathway is calculated based on the standard emissions ([Meinshausen et al., 2011a](#)) associated with the RCP2.6 scenario. We then consider exchanging CO<sub>2</sub> emissions with CH<sub>4</sub> emissions, but whilst keeping our metric-specific CO<sub>2</sub>e emission pathways fixed. This pragmatic offline approach, which has similarities to [Daniel et al. \(2012\)](#), might become one more regularly asked. Here it is addressed with the simplest of economic descriptions of abatement costs through global MAC curves for CO<sub>2</sub> and CH<sub>4</sub>. Such a basic approach helps make transparent metric–economics–climate interactions.

Our results are similar to those of [Smith et al. \(2013\)](#) and [Reisinger et al. \(2013\)](#), in that the choice of GTP versus GWP has a relatively small but significant impact on global mitigation outcomes under heavy mitigation. In general terms, it can affect global warming in year 2100 by order 0.1 °C. We find that idealised anthropogenic methane emissions falling to zero (with exchanged higher carbon dioxide emissions) and within the next two decades decreases peak

warming by approximately 0.2 °C compared to standard RCP2.6 emissions; the lowest peak warming occurring under GTP-100. With economic considerations incorporated via MAC curves, then the GWP-100 metric prevents very little change from standard emissions. This is expected given the original calculation of RCP2.6 standard emissions also uses a cost minimisation approach, and the GWP-100 metric. However for the GTP-100 metric, this gives less methane abatement and more warming, although for almost zero gain in abatement costs, suggesting GWP-100 is the better metric in the circumstances when cost-minimisation is included. Restating, the minimum-cost solution for each year is that of all possible CO<sub>2</sub> and CH<sub>4</sub> exchanges, whilst keeping CO<sub>2</sub>e emissions pathway invariant. Time-evolving MAC curves give abatement costs for both CO<sub>2</sub> and CH<sub>4</sub> emission cuts away from “business-as-usual” profiles, and our solution is the exchange, in each year, which yields the lowest sum of abatement costs for both gases.

If technology emerges by year 2030 where currently perceived difficult-to-remove CH<sub>4</sub> emissions could be eliminated, a price of around \$1000 (Tonne CH<sub>4</sub>)<sup>−1</sup> and exchanging under GWP-100 could lower peak warming by around 0.2 °C. This would be approximately \$47 (Tonne CO<sub>2</sub>e)<sup>−1</sup> in CO<sub>2</sub>e units and for our GWP-100 metric.

We present one method to understand the cost implications of greenhouse gas exchange under two different metrics, here restricted to the heavy mitigation RCP2.6 scenario, for methane versus carbon dioxide emissions only, and a single 100-year time horizon in metric derivation. Other proposed metrics comparing units of CO<sub>2</sub> and CH<sub>4</sub> gas emissions, or for different timescales, may fall outside the range of 1.76 (GTP-100) to 21.23 (GWP-100), but general features of our analysis should be amenable to extrapolation. Although our study is in the absence of coupling between climate and IAMs, for this illustrative analysis it allows better understanding of climate–economic trade-offs. Our headline result is that from a climate perspective a lower temperature outcome can be achieved with a larger fraction of emissions reductions in an RCP2.6-like scenario coming from methane. However, this is found to not be a cost-optimal approach with current estimates of methane abatement potential and costs. The conclusions apply with the two alternative gas exchange metrics we use here, although some of the precise numbers are metric-dependent.

One outcome of this study could be to request, for eventual more precise metric assessment, that full climate model–IAM coupling becomes routine. In general terms, another possibility is to consider not using metrics at all, and just find cost minimisation (either instantaneous, or averaged over a prescribed period) across gas emissions such that they cause the RCP2.6 pathway of radiative forcing to be followed. [Aaheim et al. \(2006\)](#) and [Johansson et al. \(2006\)](#) suggest, respectively, this could save 2% or 4% of total abatement cost. However any overall rejection of metrics would remove a simple and very useful mechanism to compare and discuss emissions of different greenhouse gases.

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