

# The social cost of atmospheric release

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**Abstract** I present a multi-impact economic valuation framework called the Social Cost of Atmospheric Release (SCAR) that extends the Social Cost of Carbon (SCC) used previously for carbon dioxide (CO<sub>2</sub>) to a broader range of pollutants and impacts. Values consistently incorporate health impacts of air quality along with climate damages. The latter include damages associated with aerosol-induced hydrologic cycle changes that lead to net climate benefits when reducing cooling aerosols. Evaluating a 1 % reduction in current global emissions, benefits with a high discount rate are greatest for reductions of co-emitted products of incomplete combustion (PIC), followed by sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>x</sub>) and then CO<sub>2</sub>, ammonia and methane. With a low discount rate, benefits are greatest for PIC, with CO<sub>2</sub> and SO<sub>2</sub> next, followed by NO<sub>x</sub> and methane. These results suggest that efforts to mitigate atmosphere-related environmental damages should target a broad set of emissions including CO<sub>2</sub>, methane and aerosol/ozone precursors. Illustrative calculations indicate environmental damages are \$330–970 billion yr<sup>-1</sup> for current US electricity generation (~14–34¢ per kWh for coal, ~4–18¢ for gas) and \$3.80 (–1.80/+2.10) per gallon of gasoline (\$4.80 (–3.10/+3.50) per gallon for diesel). These results suggest that total atmosphere-related environmental damages plus generation costs are much greater for coal-fired power than other types of electricity generation, and that damages associated with gasoline vehicles substantially exceed those for electric vehicles.

## 1 Introduction

Societal assessment of environmental threats depends upon a variety of factors including physical science-based estimates of the risk of impacts and economic valuation of those impacts. Quantitative estimates of costs and benefits associated with particular policy options can inform responses, but such valuations face a myriad of issues, including the choice of which impacts to ‘internalize’ within the economic valuation, the value of future versus present risk, and how to compare different types of impacts on a common scale (e.g. (Arrow et al. 2013; European Commission 1995; Johnson and Hope 2012; Muller et al. 2011; National Research Council 2010, hereafter NRC2010; Nordhaus and Boyer 2000)).

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To examine these issues, I explore here the economic damages associated with a marginal change in the atmospheric release of individual pollutants owing to their effects on climate and air quality. Prior studies have provided compelling demonstrations of the importance of linkages between climate change and air quality valuation (e.g. (Caplan and Silva 2005; Nemet et al. 2010; Tollefsen et al. 2009)) and of the incorporation of economics into emission metrics (e.g. (Johansson 2012; Tanaka et al. 2013)), but typically have not fully represented the climate impact of short-lived emissions, especially aerosols and methane (e.g. (International Monetary Fund 2013; Muller et al. 2011; NRC 2010)). As opposed to previous estimates of damages associated with particular activities (e.g. electricity generation (European Commission 1995)), the general values presented here allow valuation of the impact of any sector or any policy scenario whose emissions are known. While many uncertainties remain in this type of analysis, and hence caution is advised in using these values in policy decisions, this evaluation of a wide variety of pollutants nevertheless allows exploration of how society values human welfare at different timescales and in response to different environmental threats.

This work builds upon the Social Cost of Carbon (SCC), a widely used methodology for valuation of the estimated damages associated with an incremental increase in carbon dioxide (CO<sub>2</sub>) emissions in a given year. The US Government describes it as being “intended to include (but not limited to) changes in net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change.” (US Government 2013; hereafter USG 2013; see also [Electronic Supplementary Material \(ESM\)](#)).

Thus social costs for emissions of other pollutants should at minimum include their impacts on these same quantities (health, agriculture, etc.). This applies even when their effects take place via different processes than for CO<sub>2</sub>. For example, pollutants such as black carbon (BC), organic carbon (OC), sulfur dioxide (SO<sub>2</sub>) or methane (CH<sub>4</sub>), affect human health both by altering climate as CO<sub>2</sub> does (hereafter climate-health impacts) but also by more directly degrading air quality (hereafter composition-health impacts). Hence this work assesses impacts of atmospheric pollutants regardless of the route by which they occur. It thus also builds upon prior valuation of air quality-related health impacts of emissions (e.g. (Muller et al. 2011)). Ideally, the social costs of emissions to the atmosphere should include all affected components of human welfare.

Here I evaluate a broad Social Cost of Atmospheric Release (SCAR) for emissions of the pollutants that are the major drivers of global mean climate change (Myhre et al. 2013) and of the global health burden from poor air quality (particulate matter and ozone; (Lim et al. 2012)) (Table 1). Unlike the SCC, which has nearly always been evaluated for well-mixed greenhouse gases only, the SCAR metric spans a wide range of pollutants, and thus facilitates discussion of the relative importance of those emissions with primarily a near-term influence (years to decades; aerosols, ozone precursors, methane and HFC-134a), including their composition-health impacts, and those with effects that are large over long-terms (centuries; long-lived greenhouse gases such as CO<sub>2</sub> and N<sub>2</sub>O).

## 2 Methods

### 2.1 Basic climate damages

The first component of the SCAR is climate damages that are proportional to global mean surface temperature change (equivalent to the traditional SCC). Global mean temperature changes are driven by the global mean radiative forcing (RF) caused by each emitted

**Table 1** Pollutants examined here and their major impacts

	Global mean surface temperature impact <sup>a</sup>	Enhanced regional hydrologic cycle impact	Pathway to composition-health impacts
Carbon dioxide (CO <sub>2</sub> )	Warming		None
Methane (CH <sub>4</sub> )	Warming		Surface ozone
Nitrous oxide (N <sub>2</sub> O)	Warming		None
HFC-134a	Warming		None
Black carbon (BC)	Warming	X	Surface PM <sub>2.5</sub>
Sulfur dioxide (SO <sub>2</sub> )	Cooling	X	Surface PM <sub>2.5</sub>
Organic carbon (OC)	Cooling	X	Surface PM <sub>2.5</sub>
Carbon monoxide (CO)	Warming		Surface ozone
Nitrogen oxides (NO <sub>x</sub> )	Cooling <sup>b</sup>	X	Surface PM <sub>2.5</sub> & ozone
Ammonia (NH <sub>3</sub> )	Cooling	X	Surface PM <sub>2.5</sub>
Mercury (Hg) <sup>c</sup>	None		Bioaccumulation in fish

See [ESM](#) section 1.1 for discussion of additional pollutants that could be examined

<sup>a</sup> The global mean surface temperature impact is also a proxy for the many additional climate impacts that occur alongside global mean temperature change, including changes in sea-level, rainfall, heatwaves, etc

<sup>b</sup> The uncertainty encompasses this agent causing warming

<sup>c</sup> Valuation of the health impacts of mercury emissions has been performed for the US (see [ESM](#) section 5), and is discussed in the calculations of US sectoral impacts only

compound. RF for most emissions is based on the IPCC AR5 (Myhre et al. 2013). RF attributable to individual aerosol precursors including indirect cloud effects was not provided in AR5, and hence to incorporate this important component for SO<sub>2</sub>, BC and OC I use a combination of modeling and literature analysis (Shindell et al. 2012a; Shindell et al. 2009; United Nations Environment Programme and World Meteorological Organization 2011; hereafter UNEP 2011; see [ESM](#)). The relative uncertainties in RF presented in the AR5 (Myhre et al. 2013) are used for all emissions. These uncertainties, and all others used here, are assumed to be 5–95 % confidence intervals (CI).

Forcing by non-CO<sub>2</sub> emissions includes a component driven by the response of the carbon-cycle to temperature changes induced by those emissions (as in the calculations for CO<sub>2</sub> itself) based on a reduced carbon uptake of 1 GtC per degree warming (Arora et al. 2013; Collins et al. 2013b). The uncertainty in this effect is taken to be equal to the magnitude of the effect itself (Collins et al. 2013b).

Temperature responses to forcings by each individual pollutant are calculated using the time dependence of the impulse-response function from the Hadley Centre climate model (Boucher et al. 2009). The magnitude is set to yield an equilibrium climate sensitivity (ECS) of 3.2 °C for doubled CO<sub>2</sub>, consistent with the AR5 (Collins et al. 2013a). As valuation depends strongly on the transient climate response, uncertainty in sensitivity is based on the range in a recent study of the AR5 models (1.3–3.15 °C; (Shindell 2014)) relative to the mean of those models (1.8 °C, hence –28 %/+75 %; those models also exhibited a mean ECS of 3.2 °C).

Basic climate damages for all pollutants in the SCAR are then calculated from their impact on global mean temperature as in the SCC for CO<sub>2</sub>. The SCAR calculations presented here use the DICE 2007 IAM damage function (Nordhaus 2008), which has damages proportional to the square of the temperature change and equal to 1.8 % of world output at 2.5 °C (see [ESM](#) for context). AR4 suggested that valuation of non-economic and economic impacts at 2.5 °C together contributed ~65 % as much uncertainty to the SCC as did climate sensitivity (Yohe

et al. 2007). Hence I set the uncertainty of the damage function to 65 % of the mean uncertainty associated with climate sensitivity.

GDP increases at  $2 \pm 1 \text{ \%yr}^{-1}$ , as in SRES scenarios, giving a mean 2100 value of \$355 trillion, consistent with USG 2013. Reference temperature change follows a business-as-usual trend with projected increases of  $0.015 \text{ }^\circ\text{C yr}^{-1}$  (as in recent observations). These gradually increase with time, then slow to  $0.008 \text{ }^\circ\text{C yr}^{-1}$  after the total increase exceeds  $4 \text{ }^\circ\text{C}$  and the maximum tolerated warming is  $4.5 \text{ }^\circ\text{C}$  assuming massive societal response to large changes (similar to the ‘backstop’ technology deployed in DICE for large temperature changes). The modeled time horizon is 350 years, but results are minimally sensitive to variations beyond  $\sim 150$  years due to the warming limit. Uncertainty in the trend is  $\pm 0.005 \text{ }^\circ\text{C yr}^{-1}$ . Mean reference temperatures are  $\sim 3.8 \text{ }^\circ\text{C}$  greater than preindustrial in 2100, in accord with projections for the higher end emissions pathways in recent simulations (Forster et al. 2013). Values are presented for 2010 emissions in 2007 \$US (as in USG 2013).

The discount rate is an important choice in valuation of future damages. USG 2013 gives 2010 SCC values using three different constant discount rates, 5, 3 and 2.5 %, based on results from several IAMs examining multiple scenarios for emissions, population, GDP, etc. I use the same discount rates to facilitate comparison and as these reflect the consensus view of the US government about which values reflect plausible choices. I also include analysis using a constant discount rate of 1.4 %, the value used in Stern (2006). Although discount rate selection is subjective, involving growth projections, risk aversion, and ethical choices (e.g. future utility), the large wealth increase with 2–3 % annual GDP growth is less compatible with very low discount rates. Therefore, for the 1.4 % discount rate case only, GDP increases at  $1.3 \text{ yr}^{-1}$ , as in Stern (2006), with an uncertainty of  $+0.3/-0.5 \text{ \% yr}^{-1}$ . Finally, authors have argued for the use of a declining discount rate (DDR) (e.g. (Arrow et al. 2013; Gollier 2008)), and I therefore also use a rate that starts at 4 % and decreases exponentially with a 250 year time constant (i.e. the percentage rate is  $4 * \exp(-t/250)$  where  $t$  is the time in years) which approximates the mean behavior seen in several prior studies discussed in Arrow et al. (2013). Note that the framework employed here does not directly include any economic response to environmental damages other than the backstop assumption.

## 2.2 Additional climate-health valuation

The traditional SCC includes economic impacts of premature mortality and morbidity due to climate change, with these climate-health impacts causing  $\sim 10\text{--}50 \text{ \%}$  of total damages in the IAM studies summarized in Nordhaus and Boyer (2000). The DICE damage function used here includes climate-health impacts attributable to tropical diseases only (see [ESM](#)). Recent estimates of climate-health impacts by the World Health Organization (WHO) (Campbell-Lendrum and Woodruff 2007) find large impacts attributable to other causes, however, especially malnutrition, with 126,000 premature deaths attributed to the current warming ( $\sim 0.8 \text{ }^\circ\text{C}$ ) via causes other than tropical diseases. I therefore perform additional climate-health valuation calculations using this estimate, assuming these effects are also proportional to the temperature change squared. Both the magnitude and long-term trend of climate-health impacts clearly merit further study, however. As WHO provides only qualitative uncertainties, I use an uncertainty of  $\pm 80 \text{ \%}$ , as for the composition-health impacts.

A consistent valuation methodology is used for climate-health and composition-health impact calculations. The WHO found climate-health damages, especially malnutrition, to be heavily weighted towards poorer developing nations (where carbonaceous emissions are currently large). Climate-health calculations therefore use a Value of a Statistical Life (VSL) of \$1.7 million (for 2010), which is the nominal US-based VSL of \$7.5 million adjusted to

account for carbonaceous aerosol exposure- and population-weighted country-specific income differences from prior analyses (UNEP 2011).

Socio-economic projections affect the climate-health damages. The VSL increases along with per capita growth in GDP since it's associated with the willingness-to-pay. As in basic climate damage calculations, GDP increases at  $2 \pm 1 \text{ \% yr}^{-1}$ . Increases in population are  $0.4 \text{ \% yr}^{-1}$ , increasing the number of people exposed to health impacts while reducing per capita GDP increases. Baseline mortality decreases by  $0.45 \pm 0.45 \text{ \% yr}^{-1}$ , with the mean value matching the optimistic scenario of Mathers and Loncar (2006) and the range spanning their baseline scenario ( $\sim 0 \text{ \%}$ ) and the more optimistic trend ( $\sim -0.9 \text{ \%}$ ) in Murray and Lopez (1997).

In the WHO analysis,  $\sim 46 \text{ \%}$  of premature mortalities due to climate change are attributable to malnutrition. Agricultural responses to climate change are expected to be highly sensitive to  $\text{CO}_2$  fertilization effects on plants (Yohe et al. 2007). In particular,  $\sim 3\text{--}10$  times more people are at risk from hunger under future scenarios (across the high SRES A1F1 and low B1) when the beneficial effects of  $\text{CO}_2$  fertilization at their maximum estimated effectiveness are excluded (Parry et al. 2004). I assume a mid-range effectiveness with 3 times more malnutrition cases for warming without  $\text{CO}_2$  fertilization, and an uncertainty of 100 % so that the maximum (6 times more) is consistent with the central portion of the above estimate and the minimum excludes any fertilization effect. Since positive historical non- $\text{CO}_2$  RF has been largely offset by negative aerosol forcing, I assume the current WHO analysis includes  $\text{CO}_2$  fertilization. Therefore, the climate-health effects of non- $\text{CO}_2$  emissions associated with malnutrition (46 %) are multiplied by  $3 \pm 3$  to account for the  $\text{CO}_2$  fertilization effect.

### 2.3 Valuation of regional precipitation changes due to aerosols

Multiple climate modeling studies have shown that both scattering and absorbing aerosols induce strong regional hydrologic cycle changes (e.g. (Levy et al. 2013; Ramanathan and Carmichael 2008; Wang et al. 2009)), and that there is typically a substantially greater precipitation response per unit RF than for well-mixed greenhouse gases (Shindell et al. 2012a, b). As many impacts are closely related to regional changes in precipitation that directly affect water and food, attribution of damages solely to temperature may be a less accurate approximation for regionally highly uneven forcings. Therefore, I include additional impacts stemming from regional disruption of the hydrologic cycle for aerosols.

I assume all precipitation changes lead to net damages as they cause shifts relative to traditional patterns to which human systems are aligned. These shifts can also alter the intensity distribution (e.g. wet areas getting wetter and dry areas drier (Held and Soden 2006)), potentially leading to more extremes either directly (Portmann et al. 2009) or indirectly via teleconnections (Kenyon and Hegerl 2010), which would again lead to damages even in cases where changes in mean precipitation could be beneficial. Hence I assign damages to both scattering aerosols and absorbing BC even though the sign of their impact is sometimes opposite. It is difficult to estimate precisely what portion of the climate-related damages is due to precipitation changes. Even for a particular impact such as human health, temperature and precipitation both play important roles by influencing malnutrition, vector borne diseases, etc. (Campbell-Lendrum and Woodruff 2007). I attribute 50 % of the climate-related damages to precipitation changes, and increase these by a factor of 4.2 for aerosols based on the mean ratio in prior modeling (see ESM). The portion of the global climate response attributable to carbon-cycle feedbacks is excluded. I assume this aerosol enhancement has an uncertainty of  $\pm 50 \text{ \%}$  of its mean value.

## 2.4 Composition-health valuation

Premature deaths attributable to chronic PM<sub>2.5</sub> (particulate matter with a diameter less than 2.5 µm) exposure are calculated using the total current outdoor PM<sub>2.5</sub> impact on human health (3.2 million premature deaths annually (Lim et al. 2012)) and total current emissions, with the fractional contribution of each individual aerosol type given by the fractional contribution of each to population-weighted annual average surface PM<sub>2.5</sub> calculated on a worldwide 0.5° × 0.5° grid (UNEP 2011; Shindell et al. 2012a). Valuation uses the current global mean population- and PM<sub>2.5</sub> exposure-weighted VSL of \$3.05 million, calculated using the same model and methods as for the climate-health VSL (UNEP 2011) (see [ESM](#)).

Impacts of methane on human health (via ozone) are drawn from results of two global composition-climate models (Shindell et al. 2012a), whereas impacts of CO and NO<sub>x</sub> on health via ozone are drawn from one of those models (GISS). Impacts use population- and exposure-weighted country-specific VSL for the ozone-health impact calculated for each pollutant. I account for the time-dependence of the ozone response to methane and CO emissions, and thus these are affected by the discount rate and projected GDP and baseline mortality, which are the same as for climate-health impacts.

The uncertainty is ±80 % for the composition-health impacts based on uncertainty in the epidemiological concentration-response functions and differences in the modeled concentration response to emissions changes (UNEP 2011; Anenberg et al., 2012).

## 2.5 Composition-agriculture valuation

Impacts of methane on agriculture via the induced change in surface ozone are also included. These are incorporated based upon prior work using (1) the surface ozone response to methane emissions changes from two global composition-climate models, (2) the impact of ozone on yields of four staple crops, wheat, maize, soy and rice, based on the methodology of Van Dingenen et al. (2009), and (3) their valuation using world market prices, as described in Shindell et al. (2012a).

## 2.6 Uncertainty analysis

The calculations include the specified uncertainties associated with 11 factors, as discussed throughout this section: RF, climate sensitivity, carbon-cycle response to non-CO<sub>2</sub> forcing, damage function, regionally enhanced precipitation response to aerosols, climate-health, composition-health, baseline mortality projections, effects of CO<sub>2</sub> fertilization on agriculture/malnutrition, GDP projections, and reference temperature projections. I perform Monte Carlo calculations sampling each source of uncertainty randomly within its distribution. I present the median and the 5 and 95 % confidence levels from a 40,000-member sample (the median is lower than the mean owing primarily to the asymmetric distributions of climate sensitivity and GDP growth in real terms). Uncertainty attributable to individual factors is presented in the [ESM](#).

## 3 Results

Valuation of climate damages is, unsurprisingly, highly sensitive to discounting, reflecting the relative value of money over time, and estimated climate-health impacts. The median basic climate damages attributable to CO<sub>2</sub> (equivalent to the traditional SCC) are 10–67 \$/ton in my calculations including conventional climate-health impacts from IAM estimates (Table 2).

These values are consistent with those in many prior studies (e.g. USG 2013; NRC 2010). Median SCAR values for CO<sub>2</sub> increase to 27–150 \$/ton adding the additional climate-health impacts, the valuation of which is larger than the total traditional SCC valuation (Table 2).

SCAR valuation for long-lived N<sub>2</sub>O is much larger than for CO<sub>2</sub> due to its far greater radiative efficiency, but shows broadly similar sensitivity to the choice of discount rate (Table 2). In contrast, valuation for the shorter-lived pollutants is much less sensitive to discounting. This is especially true for aerosol-related species other than BC (SO<sub>2</sub>, OC, NO<sub>x</sub>, and NH<sub>3</sub>) because their composition-health impacts, which are unaffected by discounting, dominate their valuation even though the regional hydrologic cycle response makes the net climate damages of even cooling aerosols positive (see also [ESM](#)). The use of a DDR produces values between the constant 3 and 1.4 % cases with the specified starting rate and decline used here (Table 2). Regardless of the discounting, the SCAR valuation per ton is much larger for methane and the five aerosol-related species than for CO<sub>2</sub>, with a ton of methane causing ~30–100 times more damage than a ton of CO<sub>2</sub> and a ton of the aerosols

**Table 2** Valuation of 2010 emissions (damages per ton in \$2007 US)

Valuation; discount rate	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	HFC-134a	BC	SO <sub>2</sub>	CO	OC	NO <sub>x</sub>	NH <sub>3</sub>
Climate <sup>a</sup> ; 5 %	10	490	2800	19,000	13,000	−900	42	−1800	−56	−240
Climate <sup>a</sup> ; 3 %	32	910	9200	36,000	20,000	−1400	90	−2800	−220	−380
Climate <sup>a</sup> ; 1.4 %	67	1400	19,000	56,000	30,000	−2100	160	−4200	−400	−560
Regional climate, aerosols; 5 %	0	0	0	0	19,000	3000	0	6100	90	820
Regional climate, aerosols; 3 %	0	0	0	0	26,000	4400	0	8700	350	1200
Regional climate, aerosols; 1.4 %	0	0	0	0	34,000	5900	0	12,000	600	1600
Additional climate-health <sup>b</sup> ; 5 %	16	1600	8300	62,000	110,000	4500	140	9000	7	1200
Additional climate-health <sup>b</sup> ; 3 %	45	2800	24,000	110,000	150,000	5700	260	11,000	30	1500
Additional climate-health <sup>b</sup> ; 1.4 %	87	4000	47,000	160,000	190,000	6900	430	14,000	50	1900
Composition-health; 5 %	0	550	0	0	62,000	33,000	200	51,000	67,000	22,000
Composition-health; 3 %	0	670	0	0	62,000	33,000	240	51,000	67,000	22,000
Composition-health; 1.4 %	0	740	0	0	62,000	33,000	250	51,000	67,000	22,000
Median total; 5 %	27	2700	12,000	85,000	210,000	40,000	410	64,000	67,000	24,000
Median total; 3 %	84	4600	37,000	160,000	270,000	42,000	630	68,000	67,000	25,000
Median total; 1.4 %	150	6000	62,000	210,000	310,000	43,000	820	71,000	67,000	25,000
Median total; declining rate	110	4700	47,000	160,000	280,000	42,000	730	69,000	67,000	25,000

Notes: Composition-agriculture impacts via ozone are included in the sum for methane, valued at \$22, \$27 and \$30 per ton for 5, 3 and 1.4 % discounting, respectively. Uncertainties are presented in Table S4

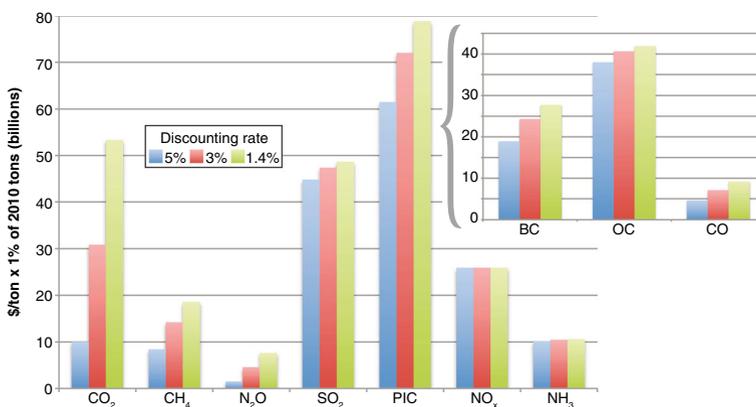
<sup>a</sup> This basic climate valuation includes IAM-based climate-health impacts

<sup>b</sup> This valuation of additional climate-health impacts is based on WHO analyses as described in the section 2.2

causing up to ~7800 times more damage. The larger valuation on a per ton basis stems primarily from the greater radiative efficiency per molecule of non-CO<sub>2</sub> compounds relative to CO<sub>2</sub> and the additional composition-health impacts.

Uncertainties in the valuation are often systematic across pollutants, so do not affect their relative importance. For example, the bulk of the uncertainty in damages associated with emissions of SO<sub>2</sub>, OC, NO<sub>x</sub>, and NH<sub>3</sub> comes from the 80 % range in the effect of particulate matter or ozone on human health (see *ESM*). Similarly, primary contributors to uncertainties in the valuation of the other emissions are climate sensitivity, climate-health impacts, and projected GDP, which are systematic across those pollutants and hence their relative importance is robust. Uncertainty in the regional aerosol impacts is obviously not systematic across all pollutants, but has minimal influence. Uncertainty in GDP, which is the most important factor for CO<sub>2</sub> and N<sub>2</sub>O, largely reflects society's willingness to pay to avoid impacts in the future (wealthier people will pay more) rather than uncertainties in the impacts themselves as for other factors. Note that attribution of uncertainty to individual factors is imperfect in a coupled, non-linear system (see *ESM*).

Another useful perspective can be gained by incorporating the relative magnitude of emissions of each compound as these vary enormously. I present the valuation of 1 % of current global anthropogenic emissions (2010 values from Thomson et al. (2011), including open biomass burning emissions (Lamarque et al. 2010)), a level small enough that it is a marginal change (Fig. 1). With a high (5 %) discounting rate, placing a greater weight on near-term impacts, the valuations of 1 % of current emissions of products of incomplete combustion (PIC; OC, BC and CO) that are usually co-emitted or SO<sub>2</sub> are much larger than the valuation of any other pollutants. Carbon dioxide is valued at about 25 % of the value of SO<sub>2</sub>, and 20 % of the sum of PIC. Towards the other end of the discounting rate spectrum, a rate of 1.4 % leads to larger impacts at long timescales, enhancing the valuation of CO<sub>2</sub> more than five-fold and increasing the valuation of methane, BC and CO by 150 to 230 % while having little impact on reflective aerosols or NO<sub>x</sub>. Valuation of PIC is the largest with 1.4 % discounting, followed by CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub> and methane (Fig. 1). Valuation of HFC-134a is always relatively small despite it having the highest per ton valuation (see *ESM*) due to the small amount currently emitted. Note that open biomass burning emissions, especially those near populated areas



**Fig. 1** SCAR valuation of 1 % of current global anthropogenic (including open biomass burning) emissions to illustrate the relative benefits of a marginal change in emissions, using the indicated discount rates. Products of incomplete combustion (PIC) is the sum of BC, OC and CO (*inset*). Numerical values are in the *ESM*. Uncertainties are given in Table 2. Values with the declining discount rate used in this study are very similar to the 3 % discounting results in this figure (see *ESM*)

which have the largest effects on human health, come from fires largely started or managed by people, but are not exclusively anthropogenic.

Of course the relative ease of reducing emissions is not equivalent across pollutants or sources. The SCAR metric provides a simple way to compare the impacts of aggregate reductions once achievable values have been estimated, however. For example, the valuation of reducing products of incomplete combustion by only  $\sim 2\%$  would be comparable to that of reducing  $\text{CO}_2$  by 10 % with a near-term focus (5 % discounting), while reductions would have to be  $\sim 7\%$  to be as valuable as  $\text{CO}_2$  reductions of 10 % using a long-term perspective (1.4 % discounting). Similarly, reducing  $\text{CH}_4$  emissions by  $\sim 12\%$  provides as much benefit as reducing  $\text{CO}_2$  emissions by 10 % with a near-term perspective, while reductions need to be 30 % with a long-term view.

#### 4 Illustrative applications

The SCAR can be used to explore the societal impacts of emissions attributable to particular activities and locations. For example, valuation of environmental damages due to US emissions from electricity generation, obtained by multiplying the SCAR by emissions attributed to those sectors (US EPA 2012, 2013a, b), are \$330–970 billion at 3 % discounting (Table S3). Much of the uncertainty is systematic, so despite large ranges, differences can be significant (e.g. coal-related damages are \$410 ( $-180/+240$ ; 5–95 % CI) billion greater than gas-related damages at 3 % discounting). Additional damages due to the human health impacts of mercury emissions are relatively small compared to those associated with other emissions (Table S3). As the SCAR is designed to evaluate marginal emissions changes, these values for the entire sector are illustrative only, and presented primarily to facilitate comparison with prior sectoral valuation (see *ESM*). These calculations use the global SCAR metric, and US-specific valuations are  $\sim 10$ –20 % higher (see *ESM*).

Within the transportation sector, the environmental damages per unit of fuel consumption are \$3.80 ( $-1.80/+2.10$ ) per gallon of gasoline using a 3 % discount rate, far larger than the current federal tax of \$0.184 per gallon and more than 7x greater than the typical combined local, state and federal gasoline tax (additional negative externalities associated with gasoline use should be part of an optimal fuel tax). Damages are substantially larger for diesel fuel, \$4.80 ( $-3.10/+3.50$ ) per gallon, owing to the greater BC emissions from diesel engines. US-specific valuations are 20–21 % higher, so again fairly consistent with the global results.

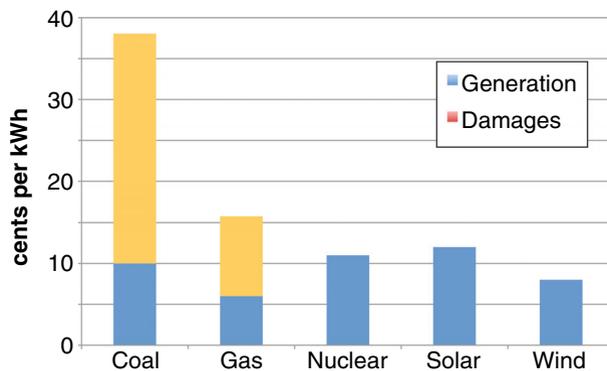
The flexibility of the SCAR, as a general emission metric, readily allows comparison of the environmental damages associated with different fuel types or technology choices as well. I present two examples here, for power generation and vehicles. Mean US damages related to atmospheric releases for power generation are calculated on a per kWh basis by multiplying the SCAR by the emissions associated with a given fuel type (US EPA 2012, 2013a, b), then dividing by the kWh generated using that fuel type. Environmental damages from the US average coal-fired power plant are 24 ( $-10/+15$ ) ¢ per kWh with 3 % discounting (median values are 19 and 30 ¢ per kWh with 5 and 1.4 % discounting, respectively). Comparable values for the average gas-fired plant are 8.4 ( $-4.4/+10.0$ ) ¢ per kWh (4.1 and 12 ¢ per kWh). Total damages from coal are greater than from gas regardless of the discount rate, as the uncertainties are partially systematic and so differences are significant despite the large ranges (e.g. damages from coal are 16 ( $-8/+8$ ) ¢ per kWh greater than from gas for 3 % discounting). There is substantial variation across coal-fired power plants, however, especially in terms of air-quality related emissions, with damages typically greater for older plants and less for newer ones. A coal plant with air-quality related emissions at the 5th lowest percentile (about 5 % of

the average) would have damages close to those for the mean gas plant ( $\sim 8\text{¢}$  per kWh for either; 3 % discounting) while one at the 95th percentile (emissions about 360 % of the average) would have far greater damages ( $\sim 62\text{¢}$  per kWh; 3 % discounting) based on emissions in NRC2010. Variation across gas plants is less, though still substantial, with the best combined-cycle plants having nearly twice the efficiency (and hence roughly half the damages) of typical steam or centralized turbine plants, and lower damages even than the cleanest coal-fired plants. Damages from mercury emissions are less than  $1\text{¢}$  per kWh, so are not included here. Damages using US-specific valuation increase by  $\sim 20\%$  for coal, but by only 4 % for gas as climate damages, which are independent of emission location, play a larger role in the latter.

Similarly, one can easily compute how much methane releases would have to be from the gas sub-sector (e.g. due to leakage) to produce damages as large as those from coal. Using a discount rate of 1.4 %, fugitive (leaked) methane emissions from natural gas systems would have to be 6.6 % for the average gas-fired power plant to produce damages as large as the average coal-fired power plant on a per kWh basis, while with a high discount rate of 5 % emissions would need to be 11 %. The value increases with the near-term focus inherent in the high discount rate due to the very large damages associated with  $\text{SO}_2$  and  $\text{NO}_x$  emissions. In comparison with the aforementioned coal plant at the 5th percentile of current air quality emissions, the leak rate for the natural gas sector has to be only 1.9 %, 1.6 % or 1.1 % for 1.4, 3 and 5 % discounting, respectively, to match the damages from coal. Hence in this latter comparison, which primarily compares the effect of the  $\text{CO}_2$  and  $\text{CH}_4$  emitted by these two sectors (and hence the leak rate threshold decreases with a nearer-term perspective), even very small leak rates would make the mean natural gas plant as environmentally damaging as coal. Current estimates of methane leakage vary widely (see *ESM*), and hence these tradeoffs merit further consideration as better data becomes available. Note that comparison of marginal costs does not include all the factors that would be involved in a more complete transition between fuels within the energy sector.

The total levelized energy generation costs for new capacity in a recent US government estimate (Energy Information Administration 2014) are about equal for conventional coal and nuclear or renewables, with conventional combined cycle gas costing substantially less (Fig. 2). Including atmospheric environmental damages, however, coal-fired power is far more expensive than other sources, while gas becomes more expensive than nuclear or renewables (Fig. 2; contrast is slightly larger using US-specific values; Figure S5). The SCAR can also be used to assess variations between nations. For example, the environmental damages for the mean coal-fired power plant in China are valued at 53 ( $-24/+29$ ) ¢ per kWh with 3 % discounting (46 and 61 ¢ per kWh with 5 and 1.4 % discounting, respectively),  $\sim 200\text{--}250\%$  more than the mean for US coal-fired power plants due to the greater levels of non- $\text{CO}_2$  pollutants.

For vehicles, emissions from a typical midsize US gasoline powered vehicle (26 miles gallon<sup>-1</sup>, 12,000 miles yr<sup>-1</sup>) lead to environmental damages valued at  $\$1700\text{ yr}^{-1}$  using the SCAR with 3 % discounting. In comparison, analogous damages associated with the generation of electricity to power a midsize electric vehicle (EV; 2013 Nissan Leaf, 0.29 kWh mile<sup>-1</sup> (fuelconomy.gov)) are  $\$840\text{ yr}^{-1}$  for electricity from coal,  $\$290\text{ yr}^{-1}$  for electricity from natural gas and miniscule for nuclear or renewables (again the contrast is slightly larger using US-specific valuation; see *ESM*). Hence environmental damages are reduced substantially even if an EV is powered from coal-fired electricity, although they are much lower for other electricity sources (conclusions are similar using 5 or 1.4 % discounting). Clearly, both a switch to less polluting electricity combined with vehicle electrification would be needed to reduce the majority of environmental damages associated with emissions from transportation via electrification.



**Fig. 2** Levelized generation costs for new US electricity generation and SCAR-based environmental damages by fuel type (using the global SCAR with 3 % discounting). Damages are inflated to 2012 \$US to match generation costs

## 5 Discussion and conclusions

Society's will to reduce emissions is influenced by costs as well as benefits. Prior analyses have suggested the potential to achieve large reductions in emissions of all the compounds examined here at relatively low cost (Enkvist et al. 2007; Rypdal et al. 2009; Shindell et al. 2012a; UNEP 2011). Including the larger SCAR valuation would make the economics even more favorable from the perspective of a social planner considering broad societal costs. Market barriers are important, however, and the common 'split incentives' mismatch between those incurring costs and those accruing benefits can be particularly important for planet-wide benefits such as reduced climate damages (see also [ESM](#)).

Furthermore, there are multiple benefits for which valuation methodologies are not as thoroughly developed and hence which are not taken into account in this analysis. For example, neither chronic physical or mental health problems nor effects of indoor household air pollution were included (see [ESM](#)). Beyond health, additional impacts of emissions such as ocean acidification, biodiversity loss, ecosystem impacts of nitrogen deposition, and changes in visibility are omitted, suggesting that these damages are conservative and leaving ample opportunities to further improve the comprehensiveness of social cost metrics. Societal decisions will also be influenced by effects other than atmospheric release, such as impacts on fresh water, waste products (e.g. coal ash ponds, spent nuclear fuel) and national or energy security (e.g. reliance on imported fossil fuels, nuclear proliferation), which are not readily incorporated into an emission metric.

Although much further work is required to fully characterize benefits and compare with costs, this extension of SCC-type analyses to encompass a broader range of both pollutants and impacts facilitates examination of how society values various impacts occurring over different timescales. When near-term impacts are deemed most important, the results indicate that society can reap the greatest benefits by targeting emissions reductions at PIC and sulfur dioxide. This reflects the large impact of  $PM_{2.5}$  on near-term human health via air quality and the substantial impact of BC on climate. If instead longer-term impacts are given more weight, as reflected in use of a low discounting rate that arguably better captures multi-generational impacts, reductions of carbon dioxide provide comparable valuation to those of PIC and  $SO_2$ .

The large impacts of aerosols and methane, especially at high discount rates, reflect the high immediate values placed upon reduced mortality risk by society. They appear to capture the reality that near-term health impacts seem to typically be considered more important to citizens

than longer-term impacts of any sort, consistent with the vastly greater sums spent on medical care and research than on long-term environmental protection, and within the realm of air quality consistent with an emphasis on SO<sub>2</sub> and NO<sub>x</sub> reductions. Such a strategy has been fairly well aligned with the optimal path suggested by this analysis given a preference for avoiding near-term impacts. However, even with such a preference, greater efforts to reduce PIC and methane emissions appear warranted due to their large impacts. To avoid longer-term damages, society clearly will have to greatly reduce CO<sub>2</sub> emissions given their importance in total emission valuation at low discount rates. Hence these results suggest that irrespective of time preference, society should pursue a multi-pollutant emissions reduction strategy that includes multiple greenhouse gases and aerosols in order to obtain maximum socioeconomic benefits. Many potential actions, such as the examples of using renewable energy for electricity or transport, can simultaneously reduce both. Use of the SCAR metric, as in the illustrative applications presented here, can help society determine the optimal pathways to achieve such reductions.

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