Chapter 6

Bridging the gap – The role of short-lived climate pollutants

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6.1 The contribution of SLCPs to climate change – Introduction and framing

This chapter outlines the opportunities to reduce the emissions gap afforded by limiting emissions of short-lived climate pollutants (SLCPs). This is a topic that has not been included in previous Emissions Gap Reports.

Greenhouse gas (GHG) emission reduction policies contribute to varying degrees to reducing emissions of SLCPs: while methane sources are covered, black carbon sources are only partially covered (for example, through policies to regulate emissions from diesel engines). In light of this, and given that SLCPs have a relatively short residence time in the atmosphere, implementing targeted SLCP reduction measures can provide rapid reductions in global warming. For this reason, this chapter focuses on measures that are specific to SLCPs.

Anthropogenic climate change is largely driven by human-induced changes in the composition of the atmosphere, including long-lived GHGs (that have lifetimes of approximately eight years or more) and short-lived climate pollutants (that have lifetimes of approximately 20 years or less) (Myhre *et al.*, 2013)[1]. The most recent assessment report by the Intergovernmental Panel on Climate Change (IPCC) found that increases in carbon dioxide (CO_2) were the largest single contributor to climate change. However, other compounds also play large roles and, for this reason, it is standard practice to include all climate drivers in analyses of historical and projected trends[2]. In sum, although some SLCPs — particularly black carbon — are not explicitly part of the Paris Agreement, which targets long-lived GHGs only, SLCPs are routinely included in analyses aimed to identify emission trajectories that are consistent with temperature targets.

This report defines the 'emissions gap' as the difference between the emission trajectories resulting from implementation of Nationally Determined Contributions (NDCs), and the trajectories associated with emission scenarios that are consistent with temperature targets, such as the 2°C target. For some SLCPs, however, such a definition is problematic. For example, emissions of black carbon can increase relative to current policies under a 2°C pathway, due to a greater reliance on biofuels, or growing numbers of diesel vehicles without particulate filters and/or stringent fuel quality standards. In light of this, the definition of 'emissions gap' that applies to this chapter is "the difference between emission levels that are consistent with emission trajectories resulting from NDC implementation, and the lowest emission levels achievable using current mitigation technologies and policies". For methane and hydrofluorocarbons, results are presented in CO_2 equivalents (CO_2e). Additionally, the temperature response associated with mitigation measures covering all SLCPs is presented[3].

Strategies to reduce SLCPs will typically target methane, tropospheric ozone, black carbon and hydrofluorocarbons. Other short-lived climate forcers, such as sulphur dioxide and organic carbon, lead to cooling and are therefore not targeted. These SLCP reduction strategies will sometimes affect only a single pollutant, for example intermittent rice irrigation affects methane alone. Nonetheless, most strategies to reduce SLCPs will affect multiple pollutants. It follows that an evaluation of mitigation measures must

1 These groupings of pollutants by lifetime are consistent with the IPCCs Fifth Assessment Report (AR5), and methane is included within both groups.

2 This extends to allowable carbon budgets, for which the IPPC's Fifth Assessment Report presented analyses for both CO_2 alone and all climate drivers.

3 The analysis presented in this chapter cannot assess the emissions gap in terms of national pledges, as most countries pledged reductions in CO_2e.

examine emissions of both long-lived GHGs and all SLCPs, to assess the net impact on warming.

Sustained SLCP reduction strategies can help limit long-term warming, especially when combined with CO_2 reduction, and therefore contribute to closing the emissions gap. A complete separation between SLCP and CO_2 reductions is not possible for two reasons. Firstly, decarbonization strategies will lead to a reduction of some SLCPs, including black carbon, about one third of which originates from fossil fuel sources (Bond *et al.*, 2013; Klimont *et al.*, 2017). Secondly, efficiency increases can reduce all types of emissions, but many SLCP mitigation strategies are distinct from strategies to reduce CO_2, especially in the near term, as many decarbonization measures require lengthy structural changes.

Reductions in SLCPs have the potential to decrease the rate and degree of warming in the next few decades, with SLCP mitigation having a rapid effect on temperature. In contrast, reducing CO_2 (and associated emissions, which often include cooling agents such as sulphur dioxide or nitrogen oxides) tends to reduce warming more slowly. Hence, the climate impact of mitigating SLCPs is not equivalent to reducing CO_2, which is a much longer-lived GHG, owing to the differing temporal evolution of the radiative forcing response to these emissions (Myhre *et al.*, 2013). It has been estimated that SLCP mitigation has the potential to avoid up to 0.6°C of warming by mid-century (for example Hu *et al.*, 2013; Rogelj *et al.*, 2014; Shindell *et al.*, 2012), while aggressive CO_2 mitigation in a comparable scenario leads to less than half as much near-term reduction in warming (Hu *et al.*, 2013). SLCPs will also affect long-term global mean temperatures. In that context, the impact of sustained emissions changes of SLCPs can be usefully compared with pulse emission changes of long-lived GHGs (Allen *et al.*, 2016). Furthermore, existing air quality and CO_2 mitigation policies will reduce emissions of sulphate and nitrogen oxides, which will drive up warming in the near term (despite improving air quality). Enhancing SLCP mitigation measures can help counteract this unmasked warming.

When considering opportunities to reduce the emissions gap, it is also important to consider how the measures and strategies adopted to cover the temperature gap will affect societies, human well-being and health, as well as ecosystems. The text of the Paris Agreement commits the world to an ambitious long-term temperature target (Article 2a and 4.1), but places this ambition within the context of "sustainable development and efforts to eradicate poverty." Through the lens of sustainable development, the path that the world choses to reach the long-term climate target is as important as achieving the target itself, particularly for those that are already suffering from the impacts of climate change (Shindell *et al.*, 2017a).

In this context, near-term mitigation of SLCPs is perhaps even more important. In addition to the fast temperature response, reductions of SLCPs would contribute to reducing climate change impacts that are based on cumulative heat uptake (for example, sea-level rise, and glacier and ice sheet melting). They would also help reduce the likelihood of passing irreversible thresholds and triggering large positive feedbacks. In doing so, they would strengthen other climate change mitigation efforts (Shindell *et al.*, 2017a; Xu and Ramanathan, 2017). SLCP reductions also improve air quality, with benefits for human health, agricultural yields, rainfall stability and other environmental and social policy goals (section 6.5).

Finally, cutting levels of black carbon and other SLCPs delivers short-term benefits, which may help governments to increasingly view collective action on climate change as feasible (Victor *et al.*, 2015). Capitalizing on efforts such as the Climate and Clean Air Coalition or the Montreal Protocol on Substances that Deplete the Ozone Layer can increase the momentum for climate change mitigation (Sabel and Victor, 2015).

6.2 Recent SLCP emissions trends and outlook towards 2030

Efforts to estimate emissions of SLCPs and their future trends have intensified, following a global assessment of emission trends for black carbon and tropospheric ozone precursors (UNEP/WMO, 2011). Many recent studies have focused on improving the understanding about emissions from poorly quantified sources[4], with a secondary focus on large emitting regions[5].

6.2.1. Historical estimates

Recent work has led to revised global estimates of SLCP emissions (Crippa *et al.*, 2016; Höglund-Isaksson, 2017; Höglund-Isaksson *et al.*, 2017; Klimont *et al.*, 2017; Purohit and Höglund-Isaksson, 2017; Wang *et al.*, 2014), and to the re-estimation of historical emissions of SLCPs that were used to develop the Representative Concentration Pathways (Lamarque *et al.*, 2010) and Shared Socio-Economic Pathways (Rao *et al.*, 2017)[6]. While estimates of SLCP emissions remain uncertain, the revised historical estimates are higher than previously assumed (Hoesly *et al.*, 2017; Klimont *et al.*, 2017). This is especially important with regard to black carbon, where the inclusion of emissions from kerosene lamps, open burning of waste, gas flaring, and regional data on coal use in China results in emission levels that are over a million tonnes (over 15 percent) higher in 2010 than in the integrated assessment models used in the

4 These include black carbon from kerosene lamps (Jacobson *et al.*, 2013; Lam *et al.*, 2012), gas flaring (Conrad and Johnson, 2017; Stohl *et al.*, 2013; Weyant *et al.*, 2016), brick manufacturing (Cardenas *et al.*, 2012; Maithel *et al.*, 2012; Weyant *et al.*, 2014), open burning of residential waste (Christian *et al.*, 2010; Wiedinmyer *et al.*, 2014), open burning of agricultural residues (Stockwell *et al.* (2016), and methane from the oil and gas industry (Höglund-Isaksson, 2017).

5 Notably China, India, Russia and the Arctic (Evans *et al.*, 2017, 2015; Huang *et al.*, 2015; Kholod *et al.*, 2016; Kondo *et al.*, 2011; Kurokawa *et al.*, 2013; Lu *et al.*, 2011; Shen *et al.*, 2012; Winiger *et al.*, 2017).

6 See Hoesly *et al.* (2017) for additional details concerning past trends on anthropogenic emissions of reactive gases and aerosols.

Representative Concentration Pathways and Shared Socio-Economic Pathways scenarios[7].

Asia's role in emissions of black carbon and methane is ever-increasing, while North America and Europe (including Russia) combined represented nearly one third of global methane emissions in 2010, primarily via emissions from the oil and gas sector. Although sectoral structures of emissions vary greatly across pollutants, a few sectors tend to dominate. For black carbon, residential combustion (cooking and heating in solid fuel stoves) has been a key source of emissions, with transport and industry gaining importance in recent years (Hoesly *et al.*, 2017).

6.2.2. Projected emissions (including NDCs)

Within Nationally Determined Contributions (NDCs), identifying particular compounds is usually difficult or impossible. This is because emissions reduction targets are expressed in CO_2e, often without specific targets for methane, hydrofluorocarbons or black carbon, but rather providing a list of target sectors. Only Mexico, Chile, Nigeria and Canada name SLCPs (black carbon) in their NDCs (and only Mexico specifies a target)[8]. It follows that NDCs are unsuited to analyses of SLCP projections. For this reason, the assessment below relies upon air pollutant and GHG emissions modelling that provides pollutant-specific estimates.

Recent projections of black carbon emissions indicate a change in trends (figure 6.1), driven by legislation developed to address primarily the health impacts of particulate matter[9]. Following the introduction of diesel particulate filters, black carbon emissions from diesel engines in OECD countries have continued to decline since about 2005. A similar impact is expected in developing countries, where comparable legislation has been recently introduced (DieselNet, 2015; GOI, 2014; MoRTH, 2016) in addition to measures to reduce smoke exposure among rural populations cooking with biomass and using kerosene for lighting (Venkataraman *et al.*, 2010). Finally, China's policy to reduce coal use in households and small industries is likely to play an important role in near-future emissions of black carbon.

Recent scenarios reflect these policies to curb emissions of black carbon. figure 6.1 shows how projected emissions of black carbon (and methane and hydrofluorocarbons) compare with Shared Socio Economic Pathways scenarios[10]. In addition to the three Shared Socio-Economic Pathways scenario ranges, an 'updated policy' pathway is shown, reflecting the latest policy assessments[11]. In the period prior to 2030, this pathway is consistent with all the Shared Socio-Economic Pathways trajectories associated with a radiative forcing of 2.6 Watts/m^2 (which corresponds to a 2°C increase in global mean temperature at the end of this century). After 2030, the 'updated policy' pathway is consistent with Shared Socio-Economic Pathway – narrative 3 trajectories associated with a radiative forcing of 3.4 Watts/m^2. Unlike recent estimates, the Shared Socio-Economic Pathway – narrative 3 (reference - no mitigation) scenario does not include the most recent policies in the transport sector. Considering the latest developments with respect to diesel engines (notably stricter standards, bans in cities, and the development of alternative propulsion systems), the projected decline in emissions from diesel engines over the next decades appears plausible. Finally, it is worth noting that the estimated near-term baseline developments do not consider some of the ongoing discussion that could bring further commitments to reduce SLCP emissions[12].

7 A recent study by Höglund-Isaksson (2017) reports a considerably higher release of methane and ethane from global oil and gas systems for the period 1980 to 2012, with oil production emerging as a much larger contributor than natural gas production. The results of this study show much closer consistency between bottom-up and top-down estimates of global ethane emissions from fossil sources than existing bottom-up inventories (EC-JRC/PBL, 2013; US EPA, 2012).

8 By 2030, Mexico aims to achieve a 51 percent reduction in emissions of black carbon, compared to the country's emissions levels in 2013. This is an ambitious goal, requiring significant reductions in transport (over 70 percent), residential combustion (nearly 60 percent), and industry (50 percent), and the enforcement of a ban on open burning of residues (INDC-Mexico, 2015). Beyond developing the strategy, the government issued new legislation regarding the transport sector requiring improved efficiency and emission standards.

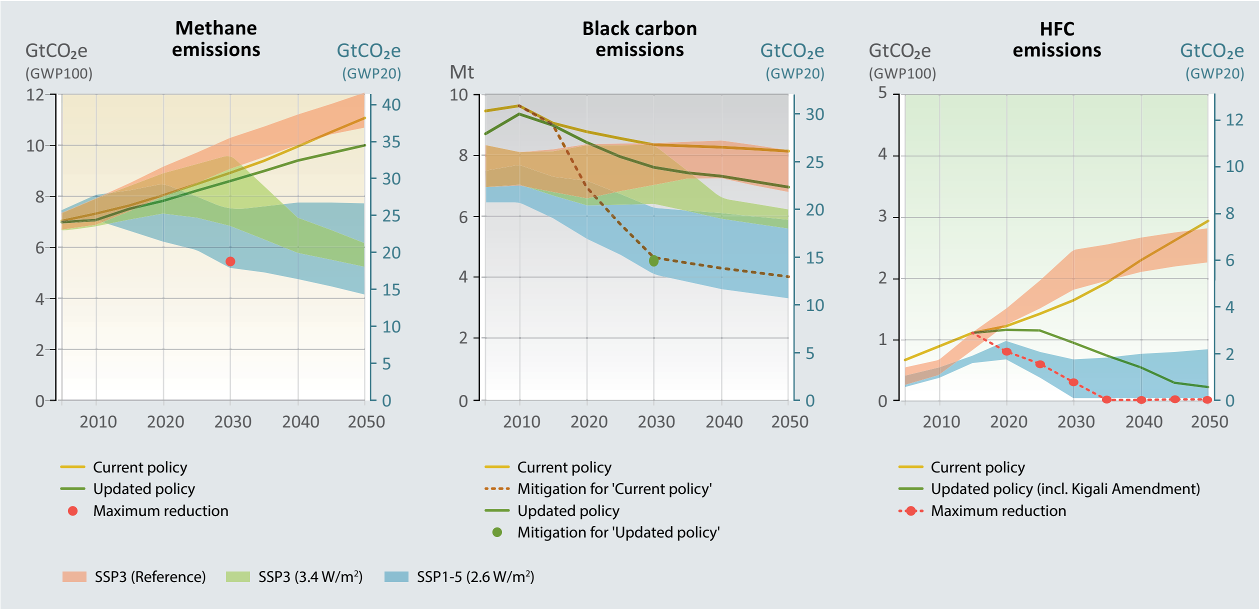
9 Reductions in emissions of black carbon is an ancillary benefit of policies aimed to curb particulate matter emissions.

10 The figure shows projected emission ranges for three Shared Socio-Economic Pathways scenario groups. Shared Socio-Economic Pathway – narrative 3 (reference - no mitigation) assumes a focus on national and regional policies, slow economic growth, lack of collaboration, large population remaining in poverty, and low priority for environmental policies, leading to strong environmental degradation in some regions. Shared Socio-Economic Pathway – narrative 3 (3.4 Watts/m^2) assumes the same socio-economic pathways, except that they include aggressive policies to curb climate change. Shared Socio-Economic Pathways 1-5 (2.6 Watts/m^2) trajectories are consistent with the 2°C target that is achieved for all Shared Socio-Economic Pathways except Shared Socio-Economic Pathway – narrative 3 (reference – no mitigation) (Rao *et al.* 2017; Riahi *et al.* 2017).

11 Updates include recent emission legislation (as of 2015) and updated energy projections, as described in IEA (2016).

12 Four commitments are especially significant:
- The member states of the Arctic Council have pledged to reduce black carbon emissions by between 25 percent and 33 percent of 2013 levels by 2025.
- Black carbon is covered by the Gothenburg Protocol to the United Nations Economic Commission for Europe's Convention on Long-Range Transboundary Air Pollution. While no specific target is set, the Convention requires parties to prioritize important sources of black carbon emissions in their strategies to reduce emissions of particulate matter.
- The International Maritime Organization is considering options to reduce emissions of black carbon from the maritime industry.
- Thirty-eight partner countries to the Climate and Clean Air Coalition have pledged to develop or refine inventories of black carbon (55 countries are now partners in the coalition, which targets SLCPs, including black carbon). Other non-state actors have also made commitments, with the state of California in the United States adopting specific legal targets for reductions of each of the major SLCPs.

Figure 6.1: Global annual emissions of methane, black carbon (including forest and savannah fires) and hydrofluorocarbons.



Note: For black carbon, values are shown in million tonnes and also based upon conversion to CO_2e using 20-year global warming potentials (Bond *et al.*, 2013). For methane and hydrofluorocarbons, the values shown are based upon conversion to CO_2e using both 100-year (left axis) and 20-year (right axis) global warming potentials, to highlight the dependence of comparisons between SLCPs and CO_2 on the choice of metric. Note that a 100-year global warming potential of 21 is used for methane, for consistency with prior issues of the 'emissions gap report', even though current studies and IPCC assessments use values more than 60 percent higher (Gasser *et al.*, 2017; Myhre *et al.*, 2013).
Source: The figures were developed using data from Shared Socio Economic Pathways database (https://tntcat.iiasa.ac.at/SspDb/dsd), Riahi *et al.* (2017) and data for policy and mitigation scenarios from the GAINS model (http://gains.iiasa.ac.at) documented in Klimont *et al.* (2017); Stohl *et al.* (2015), and Purohit and Höglund-Isaksson (2017).

For methane and hydrofluorocarbons, the baseline trajectories (labelled 'current policy' in figure 6.1) relying on near-term energy projections (IEA, 2016; Purohit and Höglund-Isaksson, 2017) appear similar to the Shared Socio-Economic Pathway – narrative 3 trajectories. Numerous parties to the United Nations Framework Convention on Climate Change (including the top three global consumers of hydrofluorocarbons, China, the United States and European Union) are already taking action to reduce emissions through national policies and legislation. In their Intended Nationally Determined Contributions INDCs/NDCs, 99 countries pledged to reduce emissions of hydrofluorocarbons[13].

6.2.3. Impact of the Kigali Amendment

A 2015 study found that phasing down hydrofluorocarbons could avoid between 4.0 $GtCO_2e$ and 5.3 $GtCO_2e$ per year by 2050, compared to a reference scenario (Velders *et al.*, 2015). A related study from 2017, which uses more up-to-date assumptions about emission reduction policies and a revised reference scenario, found that full compliance with the Kigali Amendment to the Montreal Protocol could reduce global hydrofluorocarbon emissions by 0.7 Gt CO_2e per year by 2030, and up to 2.7 Gt CO_2e per year by 2050 (Höglund-Isaksson *et al.*, 2017). This would avoid cumulative emissions of 39 $GtCO_2e$ between 2018 and 2050 (figure 6.1)[14]. Strengthening phase-down efforts (that is, pursuing a reduction in emissions that goes beyond that afforded by the implementation of the Kigali Amendment and that seeks to reach the maximum potential) could provide about 30 percent greater cumulative benefits (figure 6.1), while avoiding additional future emissions by precluding a build-up of storage hydrofluorocarbon banks (Velders *et al.*, 2014).

In addition to efforts to avoid direct emissions of hydrofluorocarbons, additional indirect CO_2e mitigation is likely through parallel improvements in the energy efficiency of refrigeration and air-conditioning appliances and equipment. Past phase-outs under the Montreal Protocol have catalysed significant improvements in the energy efficiency of appliances — up to 30 percent in some subsectors (US EPA, 2002). Höglund-Isaksson *et al.* (2017) found that full compliance with the Kigali Amendment could reduce global electricity consumption by between

13 Three sets of initiatives are worth noting:
- In May 2014, as part of an action plan to implement the energy conservation and emission reduction targets of its 12th five-year plan, the State Council of China announced that it would strengthen emission reduction requirements for hydrofluorocarbons, and accelerate their phase-out and replacement. In its INDC/NDC, China has stated that it will completely phase out hydrofluorocarbon-123.
- The European Union's regulation 842/2006 on fluorinated greenhouse gases, which entered into effect on 1 January 2015, envisages that, by 2030, hydrofluorocarbon levels will have reduced by 79 percent of the levels registered in the period between 2009 and 2012.
- The United States considered federal-level measures to reduce the manufacture and use of hydrofluorocarbons. In August 2017, a court struck down part of a 2016 decision by the country's Environmental Protection Agency, which sought to revoke approval for several of the most potent hydrofluorocarbons. However, it is unclear how much impact this ruling will have, as it returned the decision to the Agency, for further justification. In parallel, several state administrations in the United States are regulating hydrofluorocarbons. For example, California has set a new emissions reductions target for hydrofluorocarbons (a 40 percent reduction to 2013 levels by 2030).

14 These estimates are based on a 100-year global warming potential.

0.2 percent and 0.7 percent over the period 2018 to 2050, due to the adoption of more energy-efficient technologies[15,16].

6.3 SLCP mitigation potential

Some of the reduction potential for black carbon identified in early studies (Shindell *et al.*, 2012; UNEP/WMO, 2011) is expected to be realized in the updated baselines (Section 6.2). Nonetheless, significant additional opportunities exist, which could reduce black carbon emissions by about 70 percent by 2030 (and more, in the longer term) (figure 6.1). Provided that strong targeted SLPC policies are introduced, these reductions in emissions could be achieved quickly[17]. While the illustrated potential was estimated for an energy scenario with CO_2 emission levels similar to the Shared Socio-Economic Pathway – narrative 3 trajectory, the shown potential appears comparable with, or even larger than, the strict climate mitigation strategies that assume significant structural changes in the energy system. However, these strict climate policy scenarios are not compatible with the socio-economic developments associated with Shared Socio-Economic Pathway – narrative 3. Therefore, the intermediate climate target scenario results (reaching a 3.4 Watts/m^2 forcing level, or approximately a concentration of 550 ppm of CO_2) were added. These results illustrate the co-benefits of climate policies on black carbon emissions. Indeed, under this scenario emissions are reduced by about 30 percent by 2050, compared to the Shared Socio-Economic Pathway – narrative 3 trajectory.

Any further mitigation of black carbon emissions would require either tightened air quality standards, and/or strengthened development policy. These are included in the SLCP mitigation case, and in the strict climate policies case (as shown in the 2.6 Watts/m^2 scenarios). By 2030, very limited reduction is demonstrated in this scenario, contrary to the SLCP mitigation case, where effective technological solutions and tested policy approaches afford much larger emission reduction potentials. In general, the new global set of scenarios (Shared Socio Economic Pathways) shows a fairly large span of emissions, even within the same Shared Socio Economic Pathways (Rao *et al.*, 2017). This differs from the Representative Concentration Pathways data set, where assumptions that economic growth automatically leads to decreases in pollution were uniformly used across all the models for projecting changes in emissions of air pollutants, including SLCPs (Amann *et al.*, 2013).

In the Shared Socio-Economic Pathway – narrative 3 scenarios, the global technical mitigation potential for methane is estimated at about 45 percent by 2030, provided that an appropriate policy environment is introduced[18]. Most of the emission reduction opportunities are in the exploration and distribution of coal, oil and gas, and in the waste sector[19]. The reductions available are comparable with those in the deep climate mitigation scenarios (figure 6.1). In general, policies to reduce emissions of CO_2 will effectively cover a large portion of methane emissions.

Technical measures could bring about fast and significant reductions in emissions of black carbon and methane (for example Amann *et al.*, 2013; Höglund-Isaksson, 2012; Klimont *et al.*, 2017)[20]. However, introducing such measures has proven problematic in some instances. For example, programmes that focus on substituting cooking stoves with clean alternatives have often had disappointing results, with declining penetration rates over time (Aggarwal and Chandel, 2004; Pine *et al.*, 2011; Ruiz-Mercado *et al.*, 2011; Venkataraman *et al.*, 2010; Wickramasinghe, 2011)[21]. Nevertheless, some other types of programmes have been successful, including emissions reduction strategies for motor vehicles, such as those focused on diesel particulate filters or emissions standards (CAI-Asia, 2011; Chambliss *et al.*, 2013; Coan, 2012; Kodjak, 2015; Saikawa, 2013; US EPA, 2017).

This chapter presents estimates of technical mitigation potentials, since they are more widely used, and therefore more abundant, than estimates of economic mitigation potentials. Notwithstanding, it is acknowledged that economic potentials may be more relevant with regard to understanding the political feasibility of mitigation actions[22].

15 This would result in a cumulative reduction of about 5.5 $GtCO_2e$ due to electricity savings when using country-specific emission factors that take into account country-specific transformation and distribution losses (Brander *et al.*, 2011).

16 A 2015 study suggested that, in the air conditioning sector alone, improving the energy efficiency of equipment by 30 percent, while simultaneously transitioning to alternatives with low global warming potential, could provide cumulative mitigation of nearly 100 $GtCO_2e$ by 2050 (Shah *et al.*, 2015).

17 Past experience on a regional and local scale exists, demonstrating fast and effective implementation, provided that appropriate enforcement mechanisms are set in place along the regulation; several examples are provided in, for example, Coaen (2012); Klimont *et al.* (2017); Kodjak (2015); Saikawa (2013); Shindell *et al.* (2012).

18 In figure 6.1 this is coded 'maximum reduction', and represented by the following symbol: ●.

19 The emissions reduction potential associated with rice and anaerobic digestion is only significant in certain regions.

20 Emission reduction rates would be faster than those brought about by transformational changes associated with low CO_2 strategies.

21 Nonetheless, locally tailored projects, often embedded in a larger scale policy process, and coupled with awareness-raising efforts, have proven successful (GACC, 2015; Sinton *et al.*, 2004; Thomas *et al.*, 2015). Political feasibility depends strongly on the design of the programme, its local sustainability, the strong involvement of local stakeholders, and on the incentives for national governments to act.

22 The economic potential of SLCP mitigation differs substantially from the technical potential of CO_2 mitigation for two main reasons: (i) the total benefits of SLCP mitigation are typically larger, because they include non-climate benefits; and (ii) with SLCP mitigation, a large share of the benefits is nationally appropriable, in particular for black carbon. Shindell *et al.* (2017b) estimate that the social cost of methane (that is, the monetized societal damages resulting from a tonne of emissions incorporating climate and air quality related impacts) is 50 to 100 times greater than the corresponding social cost of CO_2. Estimates of the net benefits that are nationally appropriable are not yet available in the literature. Research programmes are ongoing to bridge this research gap.

6.3.1 Methane

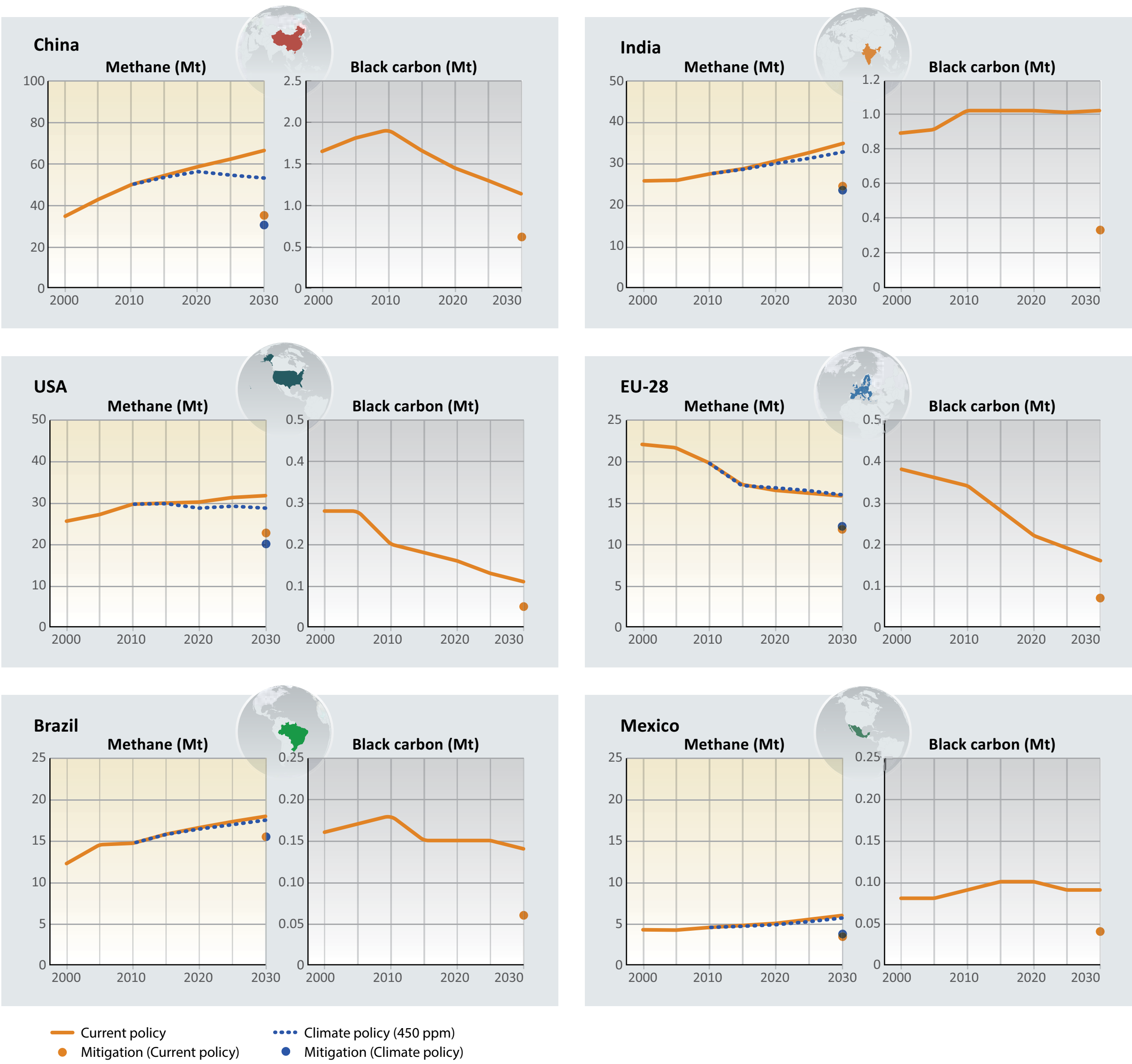
The technical mitigation potential identified through the integrated assessment models used to develop Shared Socio-Economic Pathways scenarios draws primarily on the work of United States Environmental Protection Agency (US EPA, 2013). The estimates for methane have been further updated (Höglund-Isaksson, 2012; UNEP/WMO, 2011) to include explicit consideration of unconventional gas production, new regional characteristics for oil and gas production (Höglund-Isaksson, 2017), and waste management. For coal production, a structural update was made, to allow for the separate estimation of emissions and mitigation potentials from pre-mining operations (de-gasification), mining operations (ventilation air methane oxidation), and post-mining activities. Finally, current model implementation includes impacts of animal feed and manure management options as described in FAO (2013), but does not include changes in consumer preferences or behaviour, which could add mitigation potentials in the agricultural sector through reduced consumption of meat (especially beef) and reduced food waste generation (Stehfest *et al.* (2009) (Chapter 4). Figure 6.2 shows regional estimates of 'Current policy' emission trajectories and reduction potentials in the coming decades. These estimates are consistent with International Energy Agency projections of energy use (IEA, 2012), and integrate the refinements highlighted above[23].

Mitigation potentials vary across regions, and are often characterized by a dominating source sector[24]. Nonetheless, solid waste separation and treatment offers opportunities across all regions. In Europe and Brazil, reduction potentials are smaller, as agriculture is the dominating methane source, and there are relatively limited technical mitigation opportunities. The comparison with the 'Climate policy' scenario (based on the IEA (2012) 450 ppm CO_2 mitigation strategy) shows that most of the near-term emissions reduction potential appears to require dedicated SLCP measures.

23 In terms of CO_2 emission levels, the International Energy Agency's scenario is comparable to Shared Socio-Economic Pathway – narrative 3 (reference - no mitigation) and 'Current policy', shown in figure 6.1.

24 For example, capturing ventilation air methane from coal mines represents the key mitigation opportunity in China.

Figure 6.2: Regional baseline methane and black carbon [shaded background] emissions and mitigation potential by 2030 [Mt per year].



Source: The figures were developed using data from the GAINS model (http://gains.iiasa.ac.at) and scenarios documented in Höglund-Isaksson (2012, 2017); Klimont *et al.* (2017); Stohl *et al.* (2015), with underlying energy scenarios from IEA (2012).

6.3.2 Black carbon

Figure 6.2 gives estimates of mitigation potentials for black carbon in a number of world regions. The estimates reflect updates referred to above (Klimont *et al.*, 2017; Stohl *et al.*, 2015). With regard to black carbon, key updates include improved characterisations of the gas flaring sector, kerosene lighting, diesel generators, and the brick-manufacturing sector.

The 'Current policy' trajectory varies greatly between regions, depending on the structure of emissions and current policies. Consequently, the mitigation potential varies too. For the European Union and the United States, a strong decline is observed (owing to strict transport legislation), which explains the limited mitigation potential that remains. In China, the transformation in the coke sector, ever-more stringent policies in transport, and reductions of coal use in the residential sector lead to significant reductions relative to the reference scenario emission levels. Therefore, mitigation potential is larger in China than in the European Union and the United States. In some of the other regions with a large share of emissions from biomass cooking (notably India), significant opportunities exist.

While the overall global potential by 2030 was estimated at over 70 percent (figure 6.1), the regional potentials vary from about 40 percent to over 80 percent. In regions where solid fuel cooking and heating dominates emissions of black carbon, the emissions reduction potential increases significantly beyond 2030 (not shown)[25].

6.3.3 Hydrofluorocarbons (HFCs)

Full compliance with the Kigali Amendment would achieve a 61 percent decrease in hydrofluorocarbon emissions in the period between 2018 and 2050, compared to the emission levels in a reference scenario (Höglund-Isaksson *et al.*, 2017). Transitioning to available low global warming potential alternatives faster and more thoroughly than contemplated by the Kigali Amendment represents a major opportunity to reduce emissions of hydrofluorocarbons. Such accelerated transition is feasible. In countries with high ambient air temperatures, almost 70 percent of sectors currently using hydrochlorofluorocarbons can leapfrog past high global warming potential hydrofluorocarbon refrigerants, directly to low global warming potential alternatives with equal or better energy efficiency (Zeiger *et al.*, 2014). The same study notes that other low global warming potential alternatives are in development, and expected to be ready to replace the remaining uses by 2025. Höglund-Isaksson and colleagues (2017) report that the maximum technical abatement potential, relying on existing technologies, is 85 percent below the reference scenario emission levels (in the period between 2018 and 2050) (figure 6.1). They further note that, towards the end of the period, the mitigation potential could represent as much as 98 percent of the annual reference scenario emission levels. Interestingly, most of the model realizations of the Shared Socio-Economic Pathways scenarios consistent with the 2.6 W/m^2 trajectories assume even faster and steeper reductions than the Kigali Amendment (figure 6.1).

6.4 Implications for the emissions gap

Compared to the Shared Socio-Economic Pathway – narrative 3 trajectories, assessments of the impact of updated policies show weaker growth or, depending on the pollutant, greater decreases in emissions of methane, black carbon, organic carbon, and sulphur dioxide (and CO_2). These trends can be translated into likely changes in temperature[26]. Recent policies lead to roughly 0.09 ± 0.04°C less warming due to methane, 0.04 ± 0.02°C less warming due to CO_2, and 0.17 ± 0.11°C less cooling due to sulphate in 2030[27]. These results evidence that, in the near term, the net warming due to reductions in CO_2 and co-emissions (primarily sulphur dioxide) is roughly offset by reductions in SLCP, primarily methane. Modelling results highlight that SLCP holds a substantial additional emission reductions potential, as described in section 6.3.

Table 6.1: Warming mitigation resulting from SLCP emission reductions

Additional SLCP mitigation	**Change in temperature (°C)**	
	2030	**2050**
All SLCPs (HFCs following the Kigali Amendment)	0.22 ± 0.11	0.59 ± 0.27
Methane	0.09 ± 0.03	0.30 ± 0.12
HFCs following Kigali Amendment	0.005 ± 0.002	0.07 ± 0.02
HFCs Maximum Feasible Reduction	0.02 ± 0.01	0.10 ± 0.03
Black carbon-rich sources	0.1 ± 0.1	0.2 ± 0.2

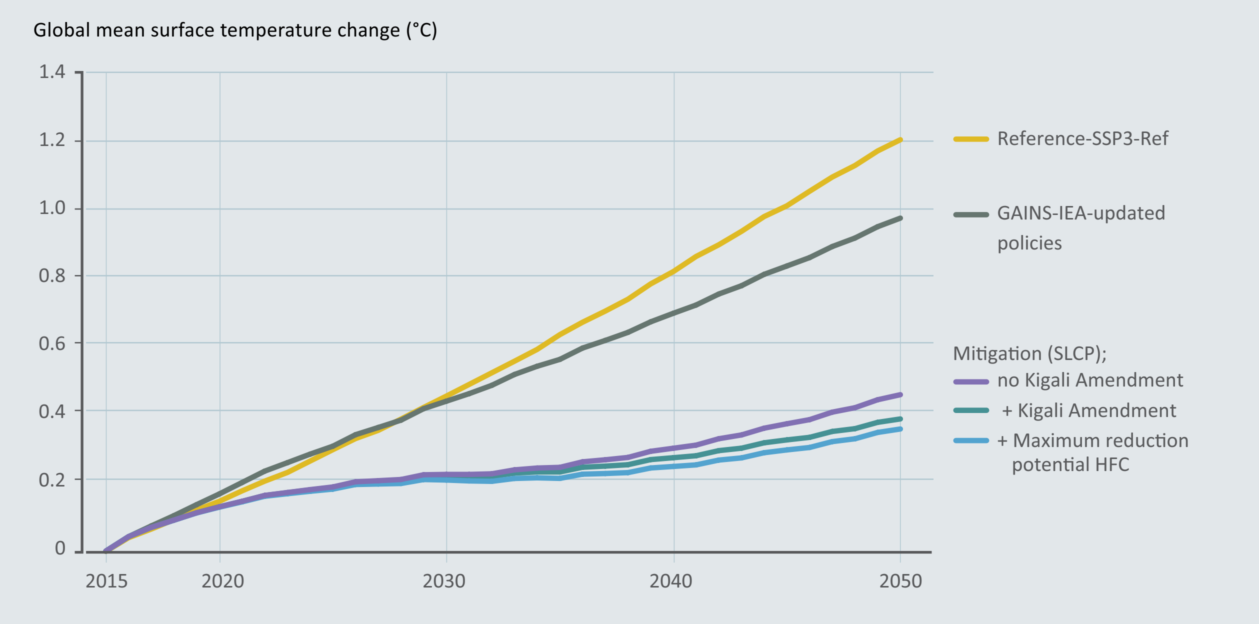
Note: The estimates in the table represent departures from the estimates associated with the International Energy Agency's 'current policies' scenario (see the main text for details). HFCs stands for hydrofluorocarbons. HFCs Maximum Feasible Reduction includes Kigali Amendment.
Source: Own elaboration.

25 This is due to the assumptions made about the effectiveness of cooking stove programmes, and the large increases in diesel vehicle emissions in some regions.

26 To do so, we used the complementary analyses described in Shindell *et al.* (2017b) that included:
- a simple energy-balance calculation, incorporating climate response functions based on the CMIP5 models (Geoffroy *et al.*, 2013);
- estimate of the impact of emissions on the carbon cycle (Gasser *et al.*, 2017);
- updated radiative forcing for methane, including shortwave absorption (Etminan *et al.*, 2016).

27 Smaller changes due to other pollutants are not reported here.

Figure 6.3: Temperature trajectories from 2015-2050 in response to historical emissions and post-2017 projections



Source: Own elaboration

Additional SLCP mitigation could avert a large fraction of projected warming over the near term (figure 6.3 and table 6.1). By 2050, methane reductions contribute the largest share (table 6.1). Realizing the maximum emission reduction potentials for emissions of hydrofluorocarbons, thus going beyond what is envisaged in the Kigali Amendment to the Montreal Protocol, would lead to fourfold additional savings by 2030 (figure 6.1)[28]. The remaining half to one third of the benefits stem from the net impact of the measures targeting black carbon-rich sources.

Figure 6.1 illustrates the near-term mitigation potential for black carbon using 20-year global warming potentials. By 2030, such near-term mitigation potential is roughly three quarters that of methane. As noted, however, understanding the full impact of measures to mitigate black carbon requires an assessment of the impact of all pollutants affected. Compared to methane, changes in emissions of black carbon lead to faster changes in concentrations of black carbon. When the effects of organic carbon and carbon monoxide from black carbon-rich sectors are taken into account, the net impact on 2030 temperatures is also about three quarters that of methane. This fraction decreases over time, as methane concentrations adjust more fully to emissions changes. By 2050, the black carbon mitigation potential is approximately two thirds that of methane, but the temperature response is just over 50 percent (again, including co-emissions of black carbon). This shows that mitigation potentials using 20-year global warming potentials can be a useful, but only rough, guide to near-term temperature impacts. For the longer term, the 2030 additional mitigation potential for methane is about 3 $GtCO_2e$ per year (using a 100-year global warming potentials of 21), and roughly 5 $GtCO_2e$ per year (using updated 100-year global warming potentials of 34)[29].

The relatively large near-term warming mitigation potentials presented above are similar to those in several prior studies. Excluding hydrofluorocarbons, they are similar to the results presented in (UNEP/WMO, 2011) and Shindell *et al.* (2012). Warming mitigation values are slightly larger in 2050, consistent with the inclusion of additional mitigation measures in this analysis, along with the extension of SLCP mitigation through 2050, which offset the decrease in benefits associated with the later start in mitigation. Including hydrofluorocarbons, values for 2050 are similar to those reported elsewhere (Xu *et al.*, 2013)[30].

28 With hydrofluorocarbons, emissions reductions are phased in early: in 2050, additional gains would reach about 30 percent, which represents a much more moderate rate in reductions, compared to those achievable by 2030.

29 A reduction of that magnitude, sustained for 100 years, would be equivalent to reducing CO_2 emissions by 170 $GtCO_2$ in one year (Allen *et al.*, 2016).

30 Other research found smaller warming mitigation from SLCPs, although compared to reference cases with reduced SLCP emissions. For example, Smith and Mizrahi (2013) used a model that assumed that (i) all control measures with a negative cost automatically happen based on 'rational economic behaviour', and (ii) projected increases in wealth worldwide lead to automatic adoption of strict emission control standards. Therefore, in essence this study calculated benefits of additional efforts to remove SLCPs after many of the available emissions control had already happened. Another study explored many possible reference cases, unsurprisingly reporting smaller SLCP-related benefits in comparison to reference cases with relatively low SLCP emissions, and similar values in comparison with high-SLCP emission reference cases akin to those seen in the detailed modelling presented above (Section 6.2) (Rogelj *et al.*, 2014). In comparison with reference cases incorporating stringent climate mitigation policies focused on CO_2, that study found a substantial decrease in the mitigation potential for SLCPs. This reflects the overlap mentioned previously between stringent CO_2 controls that transition away from fossil fuel use (covering energy-related methane emissions and diesel-related black carbon emissions). Those results are consistent with the drop in black carbon emissions under the Shared Socio-Economic Pathway – narrative 3 3.4 W/m^2 scenario relative to the Shared Socio-Economic Pathway – narrative 3 reference scenario shown in figure 6.1, although such scenarios also include structural changes (for example, with regard to renewable sources of energy, energy access or electric vehicles), and increased energy access for the poor, which may be more difficult to realize than technical SLCP control measures, and would likely take longer to materialize.

Given the potential for enhanced SLCP reductions to reduce warming substantially in the near term, relative to current policies, such reductions could clearly help to close the emissions gap defined by long-term global mean annual average temperature. They could also help offset near-term warming caused by CO_2 mitigation strategies. Near-term SLCP mitigation is also a critical lever for slowing the rate of change in the next few decades, which is particularly important for reducing cumulative climate impacts, such as sea-level rise. Hu *et al.* (2013) found that curbing emissions of SLCPs immediately can reduce the rate of sea-level rise by approximately 18 percent by 2050, while immediate reductions in CO_2 would yield minimal benefits with regard to sea-level rise. Delaying SLCP mitigation by 25 years could decrease the impact of both CO_2 and SLCP mitigation on sea-level rise by approximately 30 percent. Not least, reducing near-term warming can also decrease risks of low-probability, high-impact climate change effects (Xu and Ramanathan, 2017).

6.5 Implications for the Sustainable Development Goals and other policy goals

This chapter assesses the role of SLCPs, including black carbon (a component of particulate matter) and methane, in bridging the emissions gap. In addition to the climate change mitigation benefits associated with curbing emissions of SLCPs, a reduction in emissions of these pollutants would contribute significantly to the achievement of several of the United Nations' Sustainable Development Goals (SDGs)[31].

The SDGs capture key human and planetary needs and challenges, and achieving them by 2030 requires coordinated actions on diverse fronts. Implementing SLCP mitigation measures can clearly contribute to the achievement of multiple SDGs, because of the impact of SLCPs on climate change and air pollution[32].

Residential combustion of solid fuels in traditional cooking stoves and the use of kerosene for lighting in the Asia-Pacific and African regions results in very high levels of indoor air pollution (Karekezi *et al.*, 2006). The World Health Organization has estimated that indoor and ambient air pollution cause 6.5 million premature deaths, recognizing it as "the single most important environmental health risk factor worldwide", and noting that it is driving a global health emergency (WHO, 2016). The provision of modern and clean energy forms for meeting these basic requirements, particularly those of rural households, would not only help reduce the emissions gap, but would also help achieve SDG 3 on ensuring healthy lives and promoting well-being, SDG 4 on ensuring inclusive education, SDG 5 on empowering women and girls, and SDG 15 on sustainable forests (Griggs *et al.*, 2014).

Tropospheric ozone is also harmful to human health. Recent estimates show that the significance of this pollutant as a cause of premature mortality is higher than had previously been estimated (Malley *et al.*, 2017). In addition, tropospheric ozone is the pollutant that causes the most significant crop yield losses. Therefore, early action on sources of SLCPs could lead to a rapid reduction in these adverse impacts.

Another key area of global concern is the increasing levels of pollution in urban areas. Urbanization is a global megatrend, and it is expected that nearly 70 percent of the world's population will be living in urban areas by 2050 (compared with 54 percent in 2014). The major causes of urban air pollution, namely transportation and industrial activity, are also major contributors to SLCP emissions. Improving fuel and technology choices in the transport sector, banning the open burning of biomass and waste in urban areas, and improving energy efficiencies, all contribute to reducing SLCPs. In doing so, these initiatives would also contribute to achieving several SDGs (Cherian, 2015): SDG 2 on sustainable agriculture, SDG 3 on health, SDG 7 on energy, SDG 11 on inclusive and sustainable cities, and SDG 12 on sustainable production and consumption.

Actions to reduce SLCP emissions can be synergistic with efforts to improve energy efficiency. For example, when coupled with energy efficiency policies, measures to phase out hydrofluorocarbon-based refrigerants can save between 340 GW and 790 GW of peak power load globally, while also avoiding about 98 Gt of CO_2 emissions by 2050 (Shah *et al.*, 2015).

Despite widespread efforts to reduce emissions of several air pollutants, especially sulphur dioxide, nitrogen oxides, and particulate matter, in several regions air pollution will not improve enough to reduce the burden on human health (IEA, 2016). On the contrary, regional demographics, rising energy use and urbanization may lead to growth in the number of premature deaths due to outdoor air pollution, especially in Asia. However, introducing efficient reduction measures in the power sector, industry, and transport, and accelerating access to clean energy for cooking — measures that are compatible with an SLCP mitigation strategy — could reduce the number of premature deaths significantly (IEA, 2016). These results are consistent with those of Schmale *et al.* (2014), who estimated that, by halving the concentrations of SLCPs in the atmosphere, more than 40 million deaths from respiratory and cardiovascular diseases could be avoided by 2030.

Compared to introducing policies to mitigate SLCPs, introducing policies to implement the SDGs is often more feasible politically. For this reason, the latter can be used to exploit the opportunity of reducing emissions of SLCPs.

31 The majority of black carbon emissions are accounted for by the Asia-Pacific region (including China), followed by Africa. Emissions come largely from residential combustion of fuels and diesel burning in the transport sector. Sources of black carbon also emit a large proportion of precursors of tropospheric ozone globally. Methane is another significant precursor of the increasing background levels of ozone.

32 SLCP mitigation is also complementary to CO_2 mitigation: many SLCP mitigation strategies can yield CO_2 mitigation co-benefits, and vice versa (Haines and *et al.*, under review).

Reductions in emissions of SLCPs offer significant potential to slow the rate of near-term warming, contribute to the achievement of the long-term Paris Agreement temperature targets, improve well-being via improved air quality, and facilitate the achievement of several SDGs. Although technical control measures already exist and have been demonstrated, scaling up those measures to their full potential would require dedicated policy efforts beyond those embodied in either current policies or low-carbon policies. Ideally, by aggressively reducing both SLCPs and CO_2, policies would optimize the societal welfare associated with efforts to curb climate change, improve air quality and achieve sustainable development.

6.6 Key messages

Large reductions in emissions of short-lived climate pollutants (SLCPs) are an important part of mitigation efforts in virtually all scenarios that meet the 2°C target, and especially those that meet the 1.5°C target.

Reductions in SLCP emissions cannot be considered equivalent to reductions in long-lived greenhouse gases, as many impacts are not directly proportional to global mean temperature change at a given point in time. For this reason, climate change mitigation policies need to consider these two classes of emissions separately.

Early reductions in SLCP emissions would provide substantial health benefits, limit the short-term rate of climate change, slow self-amplifying feedbacks, and facilitate the achievement of the Paris Agreement's long-term temperature target.

Significant SLCP mitigation potential, beyond existing commitments, is available via proven technologies. However, to unlock that potential requires dedicated policy action to strengthen legal frameworks and institutional capacities. This is because many SLCP mitigation strategies are distinct from strategies to reduce CO_2 emissions.

Over the period 2018–2050, stringent SLCP reductions based on existing, demonstrated technical measures could reduce warming by between 0.3°C and 0.9°C relative to current emissions projections. Roughly half of the mitigation potential is associated with methane, one third with black carbon, and the remainder with hydrofluorocarbons. As some policies that reduce CO_2 emissions also reduce SLCP emissions, a substantial portion of SLCP reductions could be achieved through CO_2 mitigation efforts. However, compared with policies specifically targeting SLCP controls, the reductions in SLCP emission resulting from CO_2 mitigation efforts would be slower.

Reduction of SLCP emissions, specifically black carbon, might play an important role in mitigating the regional impacts of climate change.