TACKLING BLACK CARBON: HOW TO UNLOCK FAST CLIMATE AND CLEAN AIR BENEFITS

CONTRIBUTORS

Report endorsed by: Climate & Clean Air Coalition to reduce short-lived climate pollutants — a UNEP convened initiative

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ABOUT CLEAN AIR FUND

Clean Air Fund is a global philanthropic organisation that works with governments, funders, businesses and campaigners to create a future where everyone breathes clean air. We fund and partner with organisations across the globe that promote air quality data, build public demand for clean air and drive action. We also influence and support decision makers to act on air pollution.

Cover photo: Traditional boats in Dhaka's busy harbour function alongside industry ©iStock (Photo ID:1470603430)

CONTENTS

ACRONYMS & ABBREVIATIONS

AQM: Air Quality Management

AR6: Assessment Report 6 under the Intergovernmental Panel for Climate Change

CCAC: Climate and Clean Air Coalition

CEDS: Community Emissions Data System

CO: Carbon monoxide

CO_2: Carbon dioxide

CO_{2eq}: Carbon dioxide equivalent

ECAs: Emission control areas

EU: European Union

GFED: Global Fire Emissions Database

GTP20: Global Temperature Change Potential at the 20-year mark

GWP100: Global Warming Potential in a 100-year timeline

HFO: Heavy fuel oil

IMO: International Maritime Organization

ISO: International Organization for Standardization

IPCC: The Intergovernmental Panel for Climate Change

kt: Kiloton

LRTAP: Long-range transboundary air pollution

MARPOL: International convention for the prevention of pollution from ships

MDBs: Multilateral development banks

MEPC: Marine environment protection committee

mm/day: Millimetre/day

mK: Milli-kelvin

N_2O: Nitrous oxide

NCAP: National Clean Air Programme

NDCs: Nationally Determined Contributions

NO_x: Nitrogen oxides

O_3: Ozone

$PM_{2.5}$: Fine particulate matter (particles with aerodynamic diameters of 2.5 µm or less)

PM_{10}: Respirable particulate matter (particles with aerodynamic diameters of 10 µm or less)

SDG: Sustainable Development Goals

SLCPs: Short-lived climate pollutants

SO_2: Sulphur dioxide

TM5-FAAST: A global atmospheric source–receptor model for rapid impact analysis of emission changes on air quality and SLCPs

Tg CO_{2eq}: Teragrams of carbon dioxide equivalents

UNECE: United Nations Economic Commission for Europe

UNFCCC: United Nations Framework Convention on Climate Change

WHO: World Health Organization

Flames approaching Highway 50 during Caldor Fire in California
Credit:Kcapaldo | Adobe Stock

EXECUTIVE SUMMARY

Reducing black carbon alongside other super pollutants is the fastest, most effective way to achieve near-immediate climate gains while improving air quality, public health, and the economy. The case for action is clear—proven solutions exist to cut emissions rapidly and at scale, but greater attention and urgency are essential.

Focusing on the sources of black carbon, characterised by dirty fuels and inefficient burning, offers an opportunity to deliver substantial climate, health, and social justice benefits at pace. By prioritising the most affected regions and communities, ranging from the billions of people relying on polluting fuels in their homes to Arctic Indigenous Populations and those living in wildfire-prone areas, we can make significant strides in both mitigating climate change and improving quality of life. Alongside deep decarbonisation, a targeted focus on black carbon draws together action on climate change and clean air, allowing efforts in one area to amplify progress in the other.

This report sets out to explain why and how we must maximise the dual benefits for people and the planet by more effectively tackling black carbon.

What is black carbon and why is it damaging?

Black carbon is a powerful climate and air pollutant. More commonly known as 'soot', it comprises the visible, dark fumes emitted from vehicles, wildfires, household activities such as cooking with traditional fuels, and industries such as brick manufacturing. While black carbon particles only remain in the atmosphere for a few days to a few weeks, they play a unique and powerful role in the Earth's atmosphere. Black carbon simultaneously drives climate change as a short-lived climate pollutant (SLCP) and worsens public health as an air pollutant. The major effects of black carbon emissions are listed here:

Global warming: Black carbon is known as a 'super pollutant' because its emissions warm the planet at a far more potent rate per tonne than carbon dioxide (CO_2) emissions. Black carbon is one of the super pollutants alongside methane that are responsible for half of the global warming witnessed to date. Targeted action on super pollutants can mitigate climate change four times faster than decarbonisation alone.

Local and regional climate impacts: Black carbon accelerates ice melting in the Arctic and the glaciers, ice sheets, icebergs, and sea ice that make up the wider cryosphere. Black carbon emissions also disrupt Asian and West African monsoon precipitation, leading to increased flooding that adversely impacts agriculture, lives, and livelihoods, and contribute to localised warming and extreme heat.

Public health: As a component of fine particulate matter ($PM_{2.5}$), black carbon contributes to ill health and the >8 million premature deaths caused by air pollution each year.

Economic and sustainable development: Black carbon also contributes to the $8 trillion economic costs of air pollution each year, with its impacts particularly felt among the poorest and most marginalised households and workers.

Black smoke from burning of associated gas
Credit: Leonid Ikan | Adobe Stock

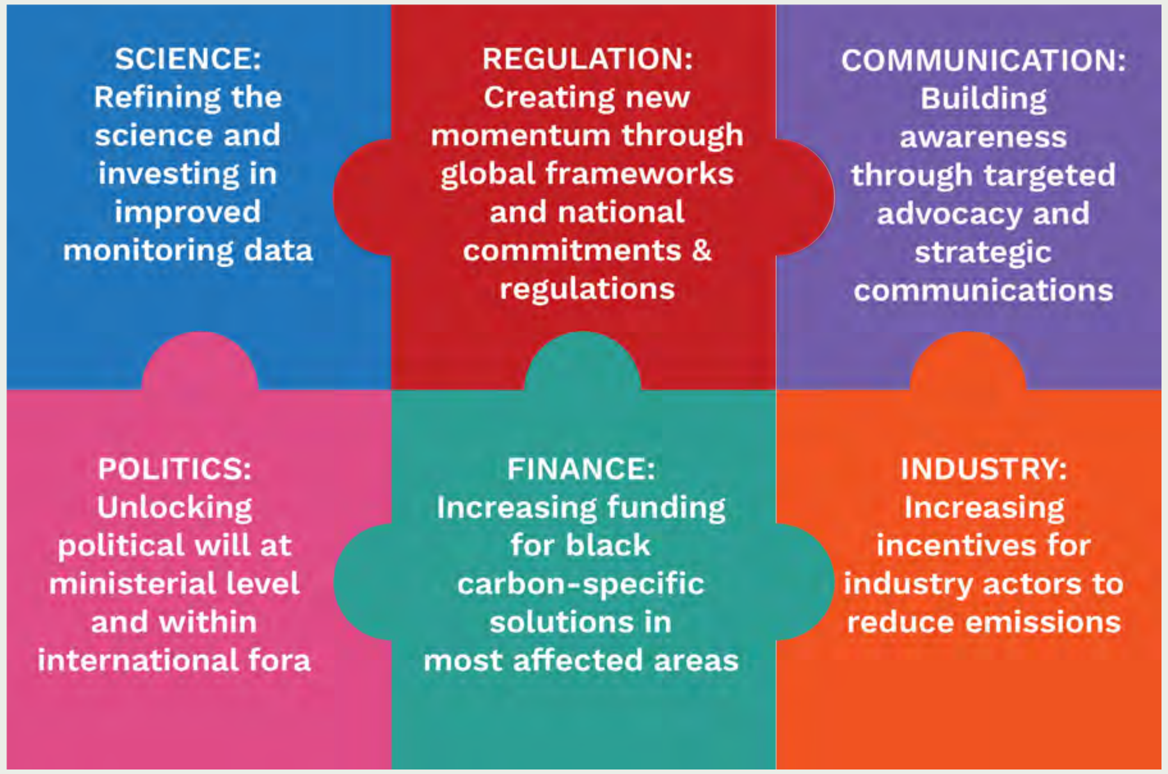
What has prevented greater progress in tackling black carbon?

Evidence of the negative impacts of black carbon and on the case for action has grown since the 1970s. Yet, experts and policy makers have found it challenging to adopt the regulations and measures needed to reduce emissions. Progress has largely been driven by efforts to curb CO_2 and $PM_{2.5}$. A business-as-usual approach is forecast to deliver a merely 3% global emission reduction of black carbon over the next decade, while solutions that already exist make an 80% reduction technically feasible by 2030 from 2010 levels. This analysis found that a combination of six barriers related to politics, science, finance, regulation, industry, and communication have blocked progress on reducing black carbon emissions.

The considerable influence of powerful countries, companies, and institutions has directly contributed to inaction. For example, most international development donors provide no direct support for projects explicitly tackling black carbon; in total, less than $18 million was spent by just eight donors on black carbon-focused projects from 2018 to 2022. Powerful industry actors also block progress by lobbying against regulation on emission targets or measures in inter-governmental forums.

The good news is, solutions to address black carbon already exist and are ready to be adopted or scaled up, particularly across six areas where we have identified opportunities for swift and equitable action (Figure ES1).

Figure ES1: Macro-level opportunities to catalyse action on black carbon



What should be prioritised to tackle black carbon as quickly as possible?

Our analysis shows that policy makers and experts should focus on three core areas:

1. **Target the climate-related effects of black carbon, particularly in the cryosphere and other most impacted regions**, to protect snow and ice and reduce rainfall disruptions and extreme heat. A good starting point is tackling black carbon-rich sectors in and around the Arctic (focusing on gas flaring, the shipping sector, and residential heating), accelerating a clean energy transition in and around the Himalayas and Andes, and financing cleaner brick kilns in the Indo-Gangetic Plain.

2. **Prioritise black carbon in clean air and energy policies** by focusing on black carbon-rich sectors that will yield the greatest climate benefits, while delivering the health and economic benefits of reduced $PM_{2.5}$. This includes clean air policies in on- and off-road transport, supporting a just transition to cleaner energy for cooking, heating, and lighting and targeting informal industries and businesses that contribute to air pollution. Measuring and regulating black carbon, alongside $PM_{2.5}$, in these interventions is key to understanding and maximising the climate benefits.'

3. **Take coordinated action on super pollutants** by targeting sectors with significant black carbon and other super pollutant emissions, such as holistic waste management solutions that cut both black carbon and methane and sustainable agriculture solutions that consider emissions of methane, nitrous oxide, and black carbon together.

Which approaches are needed to overcome blockages and prioritise black carbon reduction?

Tackling the black carbon challenge will require a coalition of key stakeholders, including international organisations, governments, financing institutions, philanthropic funders, and civil society actors to work together. Crucially, it will also require collaboration across climate change, air pollution, and health fields, with leaders working together to achieve multiple benefits. Stakeholders must adopt the following actions:

- Form a global caucus of countries committed to black carbon emission reductions and exhibit leadership to bridge the gap in global climate strategies and fast-track mitigation.
- Advance the development of binding and international frameworks on black carbon targeting opportunities in both global climate processes and regional environmental and air quality frameworks.
- Funds should be targeted towards scientific research to reduce observational and modeling uncertainties, and to produce more country-level black carbon emission inventories and enhance emission estimates.
- Rapidly scale up funding for black carbon emission reduction efforts across transport, industry, residential, and other sectors.
- Integrate specific black carbon targets into national action plans and NDCs, detailing implementation, funding, and progress measurement mechanisms.

Bricks kiln in Pakistan
Credit: Tamseel Ahmad | Wikimedia Commons

A GUIDE TO THIS REPORT

The case for taking action on black carbon has been made[1], comprehensive action plans exist[2], and despite a long period of stalled action, momentum is once again building. Now is the time to address why progress has been insufficient and to unlock positive impacts for climate, health, and economic and social justice.

Target audience: This report is intended to support the efforts of policy makers (at the global, national and city levels), funders, climate and air quality experts, and civil society actors to accelerate progress on black carbon emission reduction.

Structure of the report: The report provides an overview of global emissions and trends, including where black carbon is doing the most damage (Section 1); presents a deep dive into the barriers that have prevented progress and outlines opportunities for stakeholders to work together at the macro level (Section 2); suggests solutions that can deliver rapid impact at scale in the most influential sectors (Section 3); and makes the case for an equity- and justice-focused approach (Section 4). The recommendations in Section 5 outline measures that will support overall black carbon reduction strategies, maximising climate and health benefits.

Methodology: This study combined elements of a problem-driven political economy analysis with a technical analysis of the feasibility and impact of a wide range of policy levers designed to reduce black carbon emissions. This work was complemented by a deep dive analysis on black carbon emissions and sectoral solutions in India, Nigeria, and the Arctic region.

This report addresses two key questions:

1. What factors have prevented greater action on black carbon, whether in terms of politics, policy, legislation, financing, or other aspects, globally and in priority geographical areas?
2. What are the available solutions that could reduce black carbon emissions from the highest emitting sectors and in the most affected countries in the short term?

Over 80 key stakeholder consultations were conducted with a wide range of experts, including academia, policy makers, government officials, and representatives of affected communities, alongside an in-depth document review of primary and secondary sources.

The main argument of the report is as follows:

The effects of black carbon are **devastating**, with significant impacts on climate, tipping points and health.

The black carbon **puzzle**: Progress on explicitly tackling black carbon emissions has stalled, despite knowledge of necessary actions existing for over 15 years.

Barriers in six key areas have prevented further action to date, but also present **opportunities for action**.

If key stakeholders capitalise on these opportunities and prioritise **sectoral solutions** that will have the biggest impact in the **short term**...

and if **equity and justice** considerations are prioritised across all efforts to reduce black carbon emissions, it is possible to...

unlock swift emissions reductions through policy action and funding in three key areas: the cryosphere, in clean air and energy policy, and through coordinated action on super pollutants.

1. WHERE BLACK CARBON HAS THE GREATEST IMPACT AND WHAT HAS BEEN THE PROGRESS SO FAR

Black carbon is both a climate and air pollutant. Also known as a short-lived climate pollutant (SLCP) due to its short life span (1–2 weeks in the atmosphere), it is one of the most powerful super pollutants, along with methane, tropospheric ozone, nitrous oxide, and hydrofluorocarbons. Despite its short-lived nature, its effects are devastating across both climate and health.

Its particles in the air absorb the sun's warmth, heating our climate and disrupting local weather patterns, affecting floods, monsoons, and extreme heat. When these particles settle on snow and ice, they darken the surface and accelerate the melting of glaciers and sea ice. Black carbon also pollutes the air in our communities, significantly damaging our lungs and contributing to millions of premature deaths and illness from air pollution[3].

These negative impacts disproportionately affect the most marginalised communities, particularly those in the Global South who are most often exposed to black carbon emissions while cooking and heating their homes. Decreasing black carbon emissions, therefore, presents a significant opportunity for achieving multiple benefits in terms of climate, health, economics, and social justice.

What is black carbon?

Black carbon, a key component of fine particulate matter ($PM_{2.5}$), is the sooty material emitted along with other air pollutants and greenhouse gases during the incomplete combustion of fossil fuels, biomass, and waste. Key sources include residential energy (cooking, lighting, and heating), diesel engines (e.g. trucks and generators), brick kilns, open burning and wildfires. It is emitted alongside other warming climate forcers, including CO_2, carbon monoxide, non-methane volatile organic compounds, and cooling agents such as organic carbon.

Tackling black carbon presents an opportunity to unlock simultaneous climate mitigation, public health, social justice, and economic benefits.

Local to global impacts of black carbon

Global and regional climates

- Black carbon has contributed substantially to historic global warming, with an estimated mean global radiative forcing of +0.11 W/m^2[4] It is co-emitted alongside other warming (e.g. carbon monoxide and non-methane volatile organic compounds) and cooling (e.g. organic carbon) climate forcers.
- Deposited black carbon darkens snow and ice, accelerating melting in the Arctic, Himalayas, Andes, and other cryosphere regions. It is estimated to account for 39% of the Yala glacier's mass loss in the Tibetan Plateau[5].
- Black carbon and co-pollutants disrupt hydrological cycles, affecting rainfall patterns as well as flood and drought risk.[6]
- Black carbon can worsen extreme heat conditions, causing a direct impact on heatwaves and increasing the heat island effect in cities.[7]

Climate tipping points

- The Arctic is warming three to four times faster than the global rate[8], leading to the irreversible retreat of ice sheets. As the radiation-reflecting ice layer melts, darker layers of land and water are exposed, which hasten the melting rate. Black carbon's unique impact on snow and ice fuels Arctic amplification, which has far reaching effects on the Earth's climate including the Indian monsoon and aridification of California.[9]
- Black carbon's impact on hydrological cycles affects monsoon shifts in South Asia[10,11] and West Africa[12], which have widespread consequences on extreme rainfall, flood risk, drought, and agricultural practices for billions of people.

Air pollution, health, and economy

- Black carbon is a component of fine particulate matter ($PM_{2.5}$), accounting for approximately 5%–25% of ambient $PM_{2.5}$ concentrations.[13] $PM^{2.5}$ is linked to more than 8 million premature deaths,3 more than 500,000 deaths of children under five,3 economic losses equivalent to 6.1% of the global GDP,[14] and 1.2 billion workdays lost each year.[15]
- Black carbon is directly associated with an increased risk of cardiovascular diseases, high blood pressure, chronic respiratory diseases, adverse birth outcomes, and heatwave-related mortality.[16,17]
- Exposure to black carbon during pregnancy has been linked to multiple adverse birth outcomes including low birth weight.[18,19]
- Black carbon contributes to rising heatwave temperatures and worsens air pollution, both of which increase heat-related mortality. This creates a dangerous feedback loop, amplifying climate and health risks.[6]

Resilience and social justice

- Economically and socially disadvantaged groups are most likely to be exposed to black carbon and suffer its negative health impacts. For example, women in low-income households are highly exposed to pollution from traditional or inefficient biomass stove use.[20]
- Low-income communities are often disproportionately exposed to air pollution, as they are more likely to live near busy roads where diesel trucks and buses emit harmful pollutants, leading to long-term exposure.[21]
- Reducing black carbon emissions will improve the food, energy, and water security of billions of people in the Global South who rely on glacier-fed rivers and monsoon rain for their livelihoods.[22]
- Reducing black carbon emissions can help communities adapt to the climate crisis, turning down temperature rise, reducing heat stress,[23] and improving human and ecosystem health.[22]

1.1. Sectoral and geographic distribution of black carbon emissions

Black carbon emissions are concentrated regionally in East Asia, South Asia, and North and East Africa, primarily from the residential, transport, and industrial sectors. Forest fires are also a significant contributor to emissions, particularly in Russia, Brazil, and Central Africa.

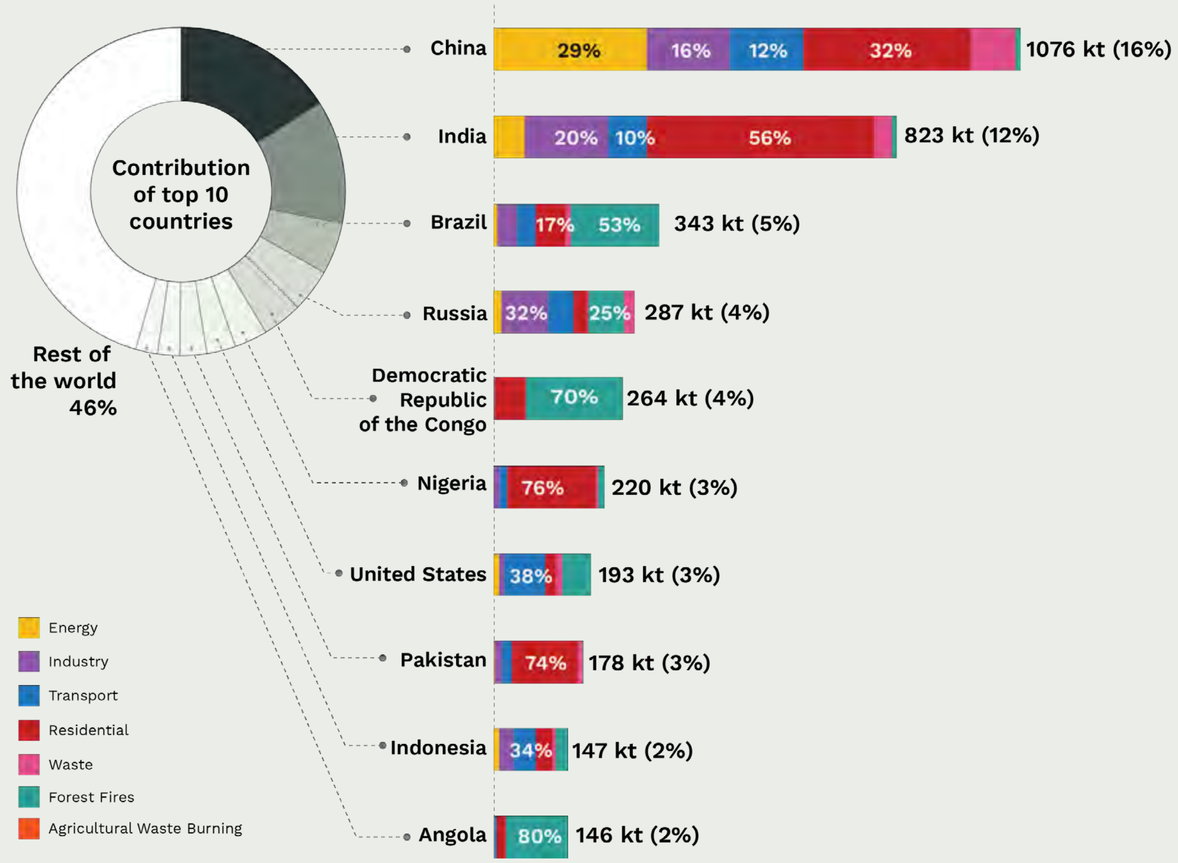
Black carbon is emitted during the incomplete combustion of carbon-based fuels, such as coal, oil, gas, and biomass, as well as solid waste and open biomass burning. The amount of black carbon and co-pollutants emitted depends on the type of fuel, the mode of combustion, and presence of a filtration system[24].

When fuels burn inefficiently (due to lower temperatures, less oxygen availability, higher moisture content etc.), higher levels of black carbon, organic carbon, volatile organic compounds, methane, and carbon monoxide are emitted. The composition of what is burnt, in terms of sulphur, nitrogen, and other components, affects the breakdown of the resulting emissions. Specific ‘fuel–combustion’ pairings can drive extremely high black carbon emissions, such as the use of kerosene in wick lamps that emit almost completely black carbon and CO_2. The link between incomplete combustion and black carbon for multiple types of fuels means that the pollutant has a varied source profile across different regions and different economic sectors.

Global emissions: Global anthropogenic black carbon emissions were estimated to be 5,330 kt in 2022, according to the Community Emissions Data System (CEDS)[25], a decrease of 14% (891 kt) from 2012. Including forest fire black carbon emissions (as estimated by the Global Fire Emissions Database (GFED)[26]), the total emissions are estimated to be 6,758 kt.

Emissions by country: Figure 1 displays the top 10 black carbon-emitting countries as of 2022 and their sectoral contributions. The residential sector is the primary source of black carbon emissions in both China and India, whereas wildfires are the largest source in Russia and transport in the United States.

Figure 1: Top 10 black carbon-emitting countries with their sectoral contributions



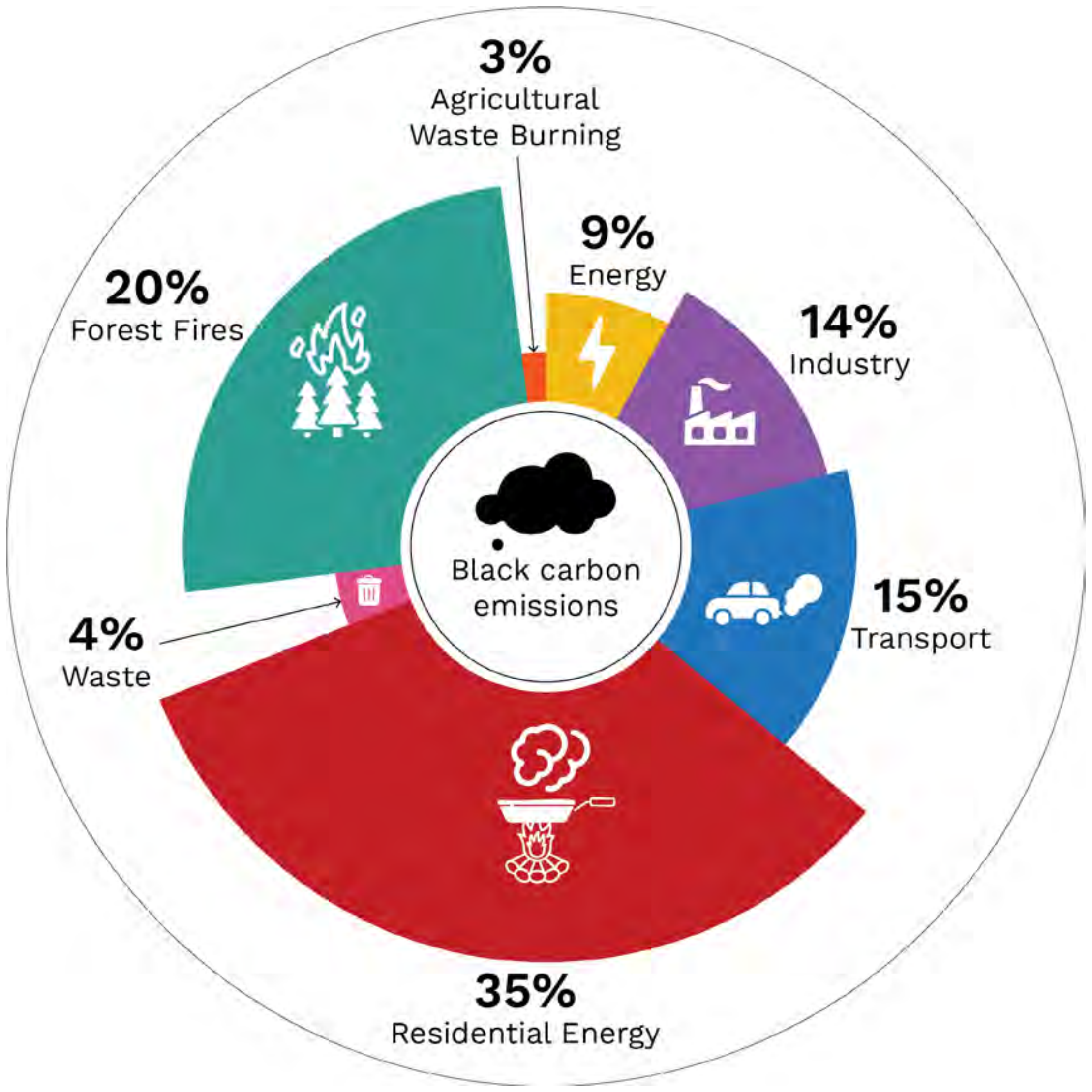
Source: Based on the combined data from the Community Emissions Data System (CEDS)[25] and the Global Fire Emissions Database (GFED)[26] for 2022

There have been notable changes in emission profiles since 2012. For instance, 69% of the global black carbon emission reduction took place in China (612 kt). Black carbon emissions were reduced in India by 10.7 kt (1.2%), in the USA by 50 kt (5.6%), in South Africa by 14.7 kt (1.6%), and in Brazil by 33 kt (3.7%). In other countries, however, black carbon emissions have increased, e.g. by 20 kt (2.2% of the net change) in Nigeria and by 1.7 kt (0.2%) in Russia.

Overall emissions by sector: Major sectors contributing to black carbon emissions in 2022 include the residential sector (35%), forest fires (19%), transport (15%), industry (14%), energy (9%), and waste (4%) (Figure 2). These sectors include sub-sectors that are considered ‘black carbon-rich’, which means that their particulate matter emissions have high levels of black carbon (for instance, brick kilns, diesel combustion, and wood/dung burning; more detail in Section 3). In some cases, the sectors also co-emit other super pollutants alongside black carbon (e.g. methane from municipal solid waste burning), indicating that sectoral measures can tackle multiple potent pollutants at once. Technology and fuel transitions in the residential, industrial, and transport sectors have contributed to 14% of black carbon emission reductions in the last 10 years (with sector-specific reductions of 12% in residential, 18% in transport, and 22% in industrial sectors)[25].

This demonstrates that reductions in black carbon-rich sectors are possible if investments in cleaner technology transitions are sustained and scaled up.

Figure 2: Black carbon emissions by sources (2022)

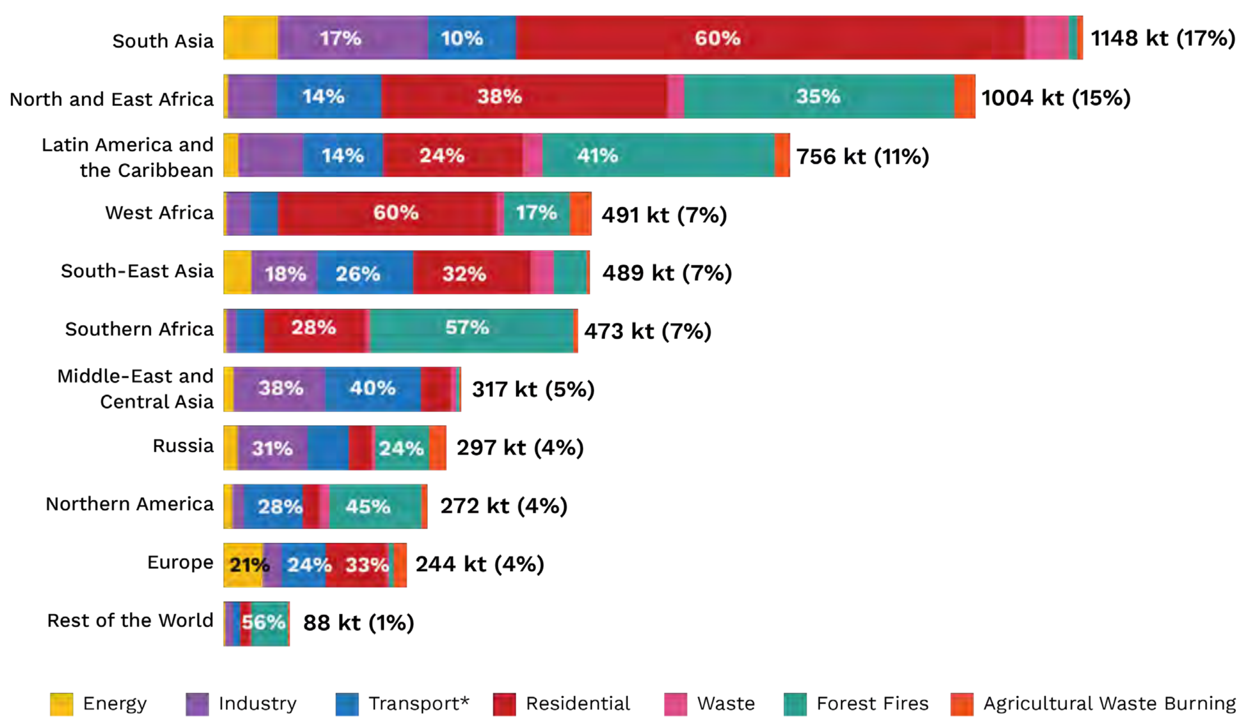


Source: Based on the combined data from the Community Emissions Data System (CEDS)[25] and the Global Fire Emissions Database (GFED)[26] for 2022

Emissions by region and sector: In terms of regional contribution (Figure 3), black carbon emissions were highest in East Asia (17%; 1178 kt), South Asia (17%; 1147 kt), and North and East Africa (15%; 1003 kt) in 2022. Countries in these regions rely substantially on traditional fuels for residential cooking, heating, and lighting activities that leads to the incomplete combustion of solid fuels, such as biomass and coal, and usage of liquid fuels including kerosene, causing high levels of black carbon emissions along with fine particulate matter. Residential cooking and heating from continued reliance on biomass burning contribute to 59% of emissions in South Asia, 31% in East Asia, and 38% in North and East Africa.

Due to the variety of sectoral contributions to black carbon emissions, there cannot be a one-size-fits-all solution for its mitigation. Efforts to mitigate black carbon emissions must be country- and region-specific, addressing the primary sectoral sources to achieve effective reductions in black carbon emissions globally.

Figure 3: Annual black carbon emissions by region and sector



Source: Emissions from Community Emissions Data System (CEDS)[25] and Global Fire Emissions Database (GFED)[26] (forest fires) for the year 2022. Note: Country-wise distribution according to the regions in the TM5-FASST model.[27]

**Shipping and aviation are not included*

- In **Africa**, forest fire emissions of black carbon alone amount to 810 kt/yr (41% of the continental total), surpassing the combined emissions of Europe and Russia.
- In **East Asia**, power plants, steel production, cement manufacturing, and other industries account for an estimated 45% of black carbon emissions.
- Industries in **South Asia**, such as brick production, rice mills, and sugar industry, also contribute significantly to black carbon emissions.
- In **Russia**, black carbon emissions are primarily emitted from forest fires and industry. One recent estimate suggests that gas flaring alone contributes approximately 68 kt/yr of black carbon emissions[28]. While this represents just over 11% of the wider region's total black carbon emissions, which includes forest fires, it accounts for a significant 39% of Russia's anthropogenic emissions.
- In **North America**, forest fires are the largest contributors to black carbon emissions, followed by transport emissions.
- In **Europe**, black carbon is emitted mainly from residential heating, followed by the transport and energy sectors.

Air pollution crisis in city from diesel vehicle exhaust pipe on road
Credit: toa555 | Adobe stock

1.2. Translating black carbon emission reductions into impacts

Reducing black carbon and co-pollutant emissions presents an opportunity to address climate change and air pollution at multiple scales—from reducing exposure to harmful pollutants in individual households to minimising regional rainfall disruptions and mitigating global warming over a 20-year period. The short-lived nature of black carbon and its co-pollutants indicates that these effects are not linear and that globally averaged metrics, as often used for well-mixed greenhouse gases such as CO_2, do not tell the full story. Black carbon's climate impacts vary because of differences in regional climates, regional fuels, and emission sources.

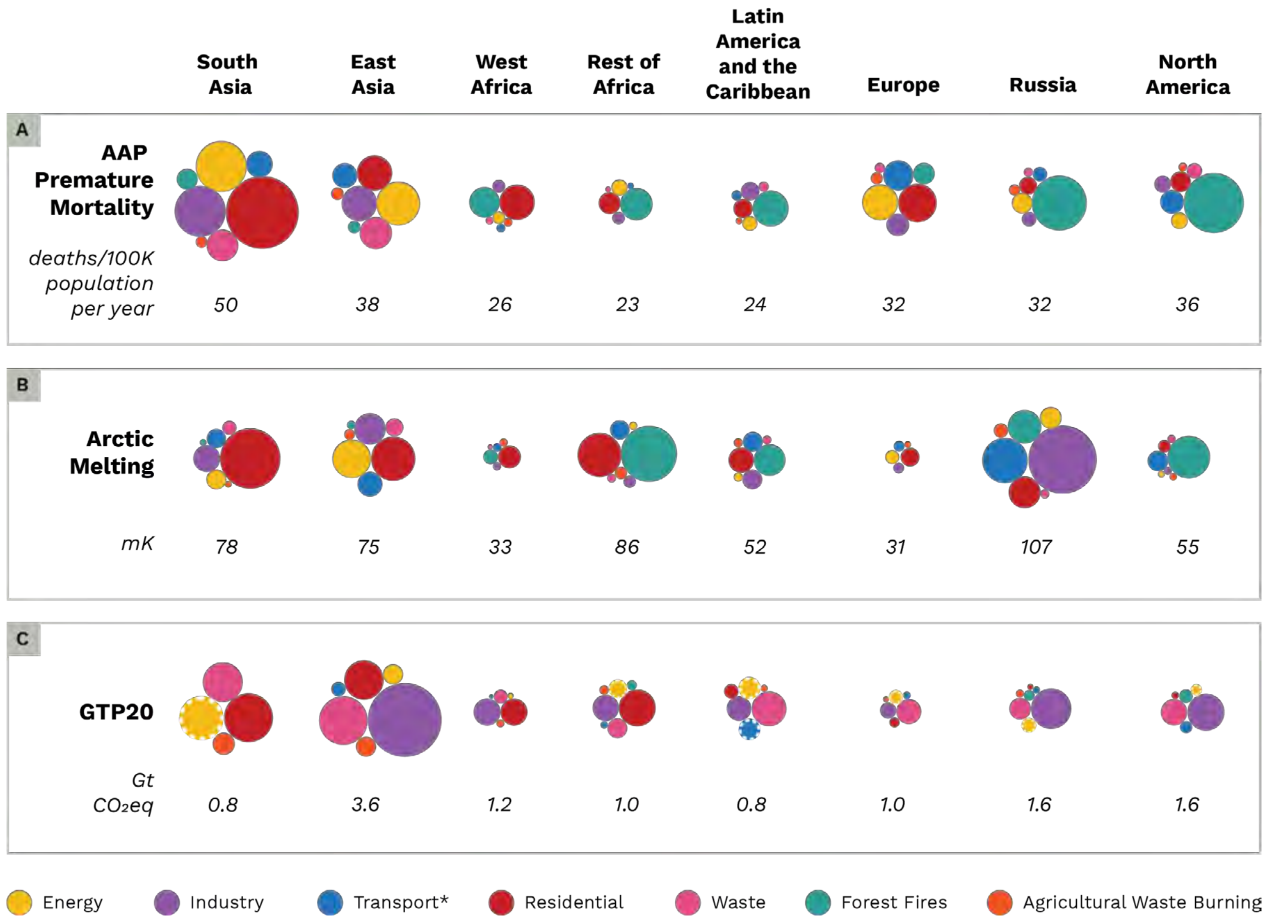
Here, we present estimations of the multiple impacts of black carbon by modelling scenarios wherein emissions are cut from all black carbon-rich sub-sectors. Figure 4 illustrates the impacts of black carbon-rich sectors, with coloured bubbles representing different sector–region pairs and their sizes indicating the estimated relative impact of emissions in these sectors. This analysis also captures co-emitted pollutants[i] from the same emission sub-sectors (see Annex 1). While the interpretation of this analysis is influenced by the datasets and models used and their associated uncertainties and limitations, it highlights the importance of black carbon emission reductions from various impact perspectives. Focusing first on black carbon as part of policy-decision making offers an opportunity to use black carbon-rich sectors as a prioritisation mechanism to (i) improve health outcomes by decreasing premature mortality and ill health, (ii) slow Arctic melting, (iii) decrease near-term global warming, and (iv) tackle local and regional climate effects such as monsoon and rainfall changes.

In terms of precipitation patterns, Shindell et al. (2012)[162] found that when black carbon emissions are reduced, precipitation increases over Western Africa and Europe but reduces over South Asia. Similarly, Westervelt et al. (2020)[163] found that increasing black carbon emissions increased rainfall over India. Reanalysing the the model run by Westervelt et al. (2018)164, we found that zeroing out black carbon emissions from India causes a net increase in precipitation of 0.073 mm/day over South Asia during the monsoon months (June-September). Zeroing out European black carbon emissions increases annual precipitation over Europe by 0.0135 mm/day. Hence, to determine the actual impact of potential black carbon mitigation measures (which can also depend on their spatial distribution), regional climate modelling reflecting specific changes is required.

i Other short-lived climate forcers included are sulphur dioxide, nitrogen oxides, ammonia, primary organic aerosols, carbon monoxide, and methane. For instance, the waste and energy sectors contribute significantly to GTP20 due to methane reductions, while the energy sector's particulate matter emissions have substantial health impacts in South Asia.

Cumulatively, (a) residential energy use in the Global South; (b) forest fires in Africa, Latin America, and Russia; (c) industries in East Asia and South Asia; (d) the transport sector in East Asia, South Asia, and North and East Africa; and (e) the energy sector in East Asia contribute to 75% of black carbon emissions. These sectors are estimated to account for 63% of premature mortality, 39% of warming (Global Temperature Change Potential at the 20-year mark [GTP20]), and 68% of Arctic melting as a proportion of the total impact from the sub-sectors.

Figure 4: Benefits of reducing black carbon emissions by region and impact areas



Note: Bubble size represents the magnitude of impact (the bigger the bubble, the greater the benefits of the black carbon reductions). The modelled impact areas include (A) ambient air pollution-related premature mortality (as avoided thousand deaths per year), (B) monsoon impacts (annual precipitation change in mm/day), (C) arctic melting (surface temperature change in milli Kelvin (mK), the same as 0.001 K or 0.0010°c), and (D) Global Average Temperature Change Potential (GTP20[ii] in Tg CO_{2eq}). For GTP20, starred borders indicate that the emissions from the sector have a net cooling effect (due to the overall impact of co-emitted climate cooling pollutants).

**Shipping and aviation are not included.*

ii GTP20 represents the Global Temperature Potential metric (GTP20) and accounts for the warming effect of black carbon and other short-lived climate pollutants (SLCPs) over a 20-year time frame (expressed here as the equivalent CO_2 emissions that would produce the same effect, Tg CO_{2eq}).

Scientific interpretation of the modelled impacts

- *Premature mortality:* Of the 4.2 million global premature deaths from ambient air pollution estimated by the WHO[30], the black carbon-rich sectors reported in Figure 4 contributed to nearly half of these deaths. In South Asia alone, the number of premature deaths was estimated at 1.05 million. This toll would be higher when also considering the premature mortality from exposure to household air pollution (not included in this analysis), and it affects all regions.
- *Arctic melting:* Observation records over the Arctic show warming trends of 0.77 K/decade during 1979–2014, which is a total of 2.7 K in the 35-year period[32]. Our analysis shows a combined warming of 0.6 K from all black carbon-rich sectors. Of note, Arctic warming is most sensitive to black carbon aerosols among all aerosol species[33].
- *Near-term warming:* SLCP emissions from the source sectors and regions shown in Figure 4 cumulatively contribute 15.8 Gt CO_{2eq}, mostly from black carbon and methane. Black carbon-rich sectors alone contribute 8 Gt CO_{2eq}. By comparison, fossil-fuel industries, thermal power plants, and transport release 45 Gt CO_2 globally[34].

Limitations: Figure 4 highlights the multiple impacts of black carbon emission reductions, but the results are highly dependent on the emissions data and model applied. The results show important trends, but regional-scale climate modelling is needed to generate more accurate estimations. In addition, the current estimation involved some standard assumptions, which are applicable at a regional scale. At a local level, exact values might differ.

Implications for policy makers

The analysis highlights that tackling black carbon and other short-lived climate forcers (SLCFs) not only improves public health but also helps mitigate global warming and local and regional climate impacts. This is a key concept that warrants further attention across integrated climate and clean air policy. Figure 4 provides policy makers who approach the black carbon puzzle from various angles with a rapid assessment tool for delivering action aligned with their own agendas.

- For those primarily interested in **addressing the health burden of air pollution**, particularly the contribution from black carbon, it is essential to focus on programmes addressing the residential sector, especially in South and East Asia, as this is where the majority of health impacts from black carbon exposure originate.
- For those focused on **reducing the warming impacts on the cryosphere and Arctic regions**, forest fires in Russia and North America emerge as significant contributors to Arctic melting. These sources need to be considered alongside other efforts to reduce black carbon emissions affecting the Arctic. While residential energy use also plays a key role in Arctic melting, its impact is linked to emissions from nearly all global regions, rather than being predominantly driven by Asia, as is the case for health-related impacts.
- For those focused on **food security and climate adaptation**, reducing black carbon emissions across Asia and West Africa is an important consideration for tackling the shifts in monsoon and rainfall patterns. Addressing residential, industrial, and transport sources may help minimise rainfall disruptions and avoid rainfall extremes, flooding, and drought. If the focus is on near-term warming mitigation, it is essential to prioritise black carbon reduction programmes across various geographies and source sectors. This aligns with the multi-sector nature of Air Quality Management (AQM) planning and highlights the opportunity for AQM stakeholders to maximise synergies with climate action planning. By targeting black carbon-rich source sectors (those in the geographies shown in the bottom row of Figure 4), air quality interventions can achieve near-term cooling, potentially mitigating any 'unmasking effect[iii]' while advancing the broader objective of reducing PM2.5 levels globally29. Thus, the top and bottom rows of Figure 4 can be used as a prioritisation lens, through which air quality interventions can be designed to maximise climate and health benefits.

iii The 'unmasking effect' refers to specific scenarios wherein clean air strategies have led to a reduction in cooling climate forcers, and therefore, acted to 'unmask' global warming.

Children and Waste burning
Credit: Nigel Bruce

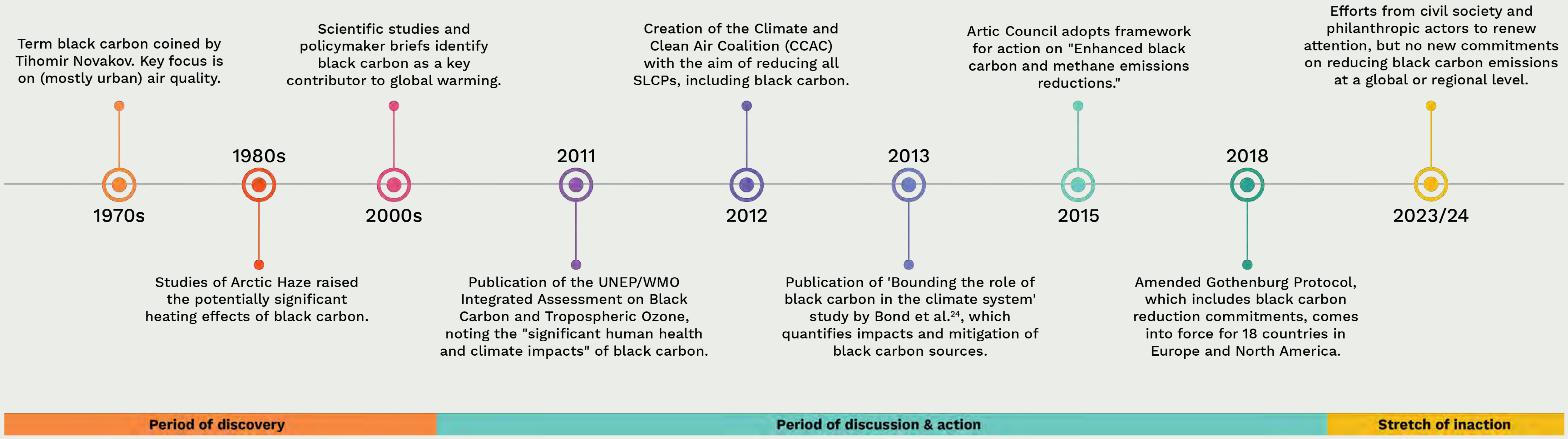
1.3. How progress stalled, and why we must act nowon black carbon

Despite the action galvanised by the publication of the Integrated Assessment report on Black Carbon and Tropospheric Ozone in 2011[35] by the UN Environment Programme (UNEP) and the World Meteorological Organization (WMO), further progress in addressing black carbon emissions from both climate and air quality perspectives has stalled. Figure 5 provides a brief history of efforts to address black carbon, highlighting a recent stretch of inaction that must be overcome.

Action has stalled because of six key barriers—political, scientific, regulatory, financial, industrial, and advocacy/communications challenges—outlined in detail in Section 2.

As the above timeline shows, the importance of black carbon has been known for decades. The international stakeholders and national/sub-national governments must recognise the need to act on black carbon emissions because '*drastically cutting black carbon and other climate super pollutants is the only known way to slow warming in the near term and we need to exploit this advantage to the fullest'*[9]. The negative climate effects are particularly acute in the cryosphere (which refers to snow and ice regions and includes ice sheets, glaciers, snow, permafrost, sea ice, and polar oceans), where black carbon has a warming effect estimated to be approximately three times more potent than that of CO_2[36].

Figure 5: Brief history of key black carbon moments



Note: Authors compilation from multiple sources

As detailed in Section 4, black carbon emissions disproportionately affect countries in the Global South, as well as marginalised populations in both the Global South and North. Failing to reduce black carbon emissions now decreases the chances of an equitable and just outcome for these populations.

The good news is, solutions to address black carbon already exist and are ready to be adopted or scaled up (see Section 3). Under current scenarios, global anthropogenic black carbon emissions are expected to decrease by approximately 3% this decade[35]. However, estimates have shown that maximum technically feasible mitigation could achieve as much as an 80% reduction by 2030 from 2010 levels[35].

Despite this clear case for action, a concerted policy approach and large-scale funding to reduce black carbon emissions have not yet fully materialised. No global policy framework exists for black carbon in either climate or air pollution; only 13 countries include black carbon in their Nationally Determined Contributions (NDCs) (Table 1); and there is limited funding for black carbon-specific interventions, particularly in heavily affected countries in the Global South.

From a climate perspective, the 28th session of the Conference of the Parties (COP28) saw increased momentum on and interest in super pollutants, including a call to action in the outcome text for governments to substantially reduce non-CO_2 emissions, particularly methane emissions. In contrast, COP29 saw a limited focus on super pollutants, including black carbon, particularly outside of the Arctic region. Many air quality programmes recognise black carbon reductions as an important and synergistic component of $PM_{2.5}$ reduction. However, they do not yet use black carbon as a prioritisation lens for designing AQM programmes, which will also yield the greatest climate co-benefits, minimise the ‘unmasking effect’ (more detail in Section 2), and potentially yield the greatest health benefits[37].

However, there is some momentum. There are specific opportunities for including a renewed focus on black carbon at key intergovernmental fora, such as the United Nations (UN) Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC). Sectoral bodies, such as the World Health Organization (WHO) and the International Maritime Organisation (IMO), and regional entities and agreements, such as the Arctic Council’s Expert Group on Black Carbon and Methane and the Gothenburg Protocol revision process (including consideration of a specific black carbon target), are increasingly recognising that black carbon is critical to solving the climate crisis and improving air quality globally. See Annex 2 for a comprehensive list of regulatory frameworks that include black carbon. Several other forums and initiatives also address black carbon emissions. These include the Climate and Clean Air Coalition (CCAC), convened by the UN Environment Programme (UNEP), which focuses on reducing SLCPs including black carbon and comprises 80 countries and over 80 non-state actors[38], and the Forum for International Cooperation on Air Pollution, established in 2019 to provide a platform for global collaboration on transboundary airpollution solutions.

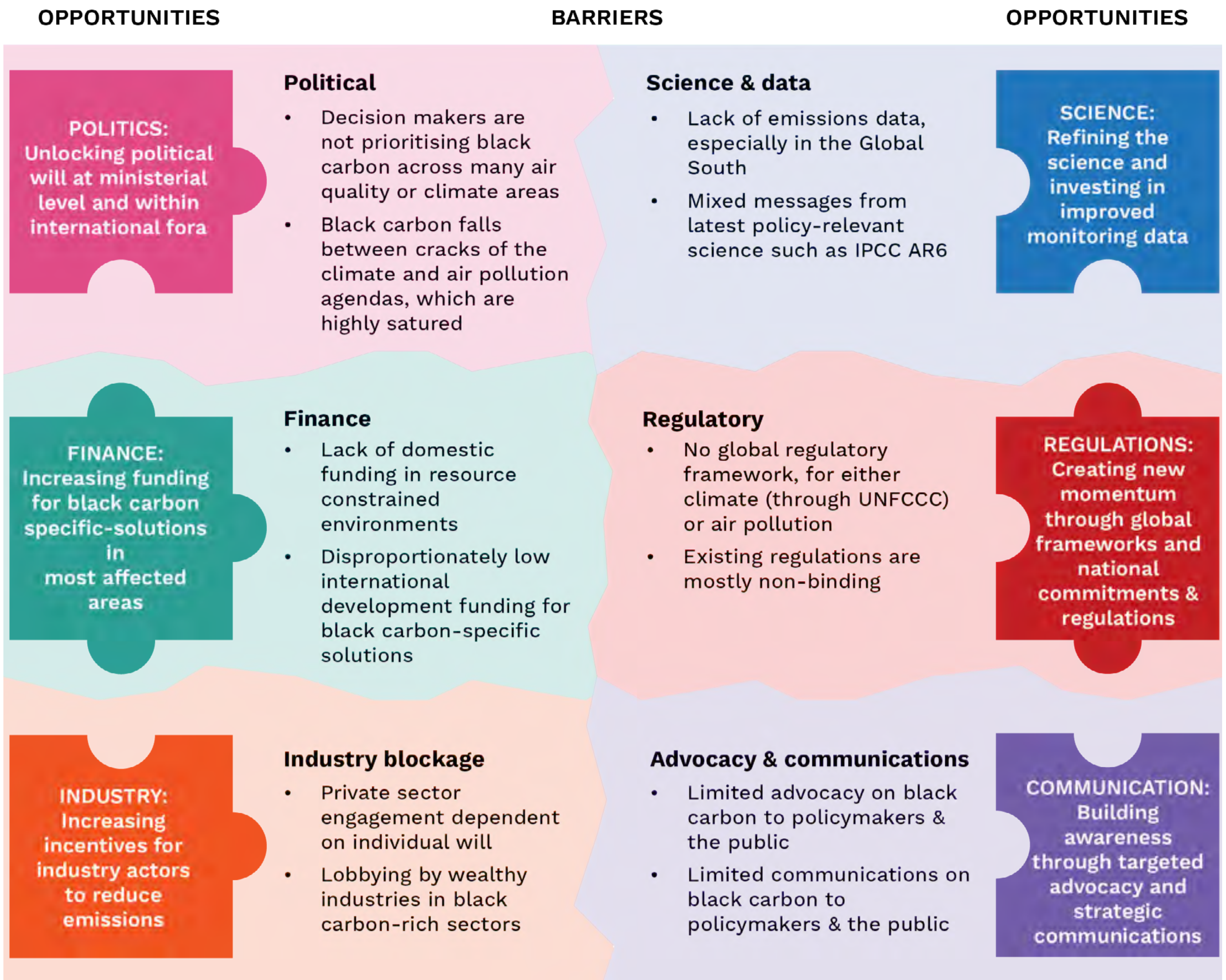
Smoky school kitchen in Kenya
Credit: Nigel Bruce

2. OPPORTUNITIES TO OVERCOME BARRIERS TO TACKLING BLACK

Despite a strong case for action on black carbon, interconnected barriers have hindered progress on reducing emissions. However, opportunities exist to overcome them.

Policy makers, scientists, representatives of affected communities, and civil society organisations have identified opportunities to overcome barriers classified into six categories: political, scientific, financial, regulatory, industrial, and communications challenges (Figure 6).

Figure 6: Overview of the key opportunities to tackle black carbon and their intersection with the barriers that are inhibiting progress'.



Opportunity 1: Politics – Unlocking political will at ministerial level and within international fora

Commonly-cited barriers:

1. **Black carbon falls between the cracks of climate and air pollution:** Despite being a major health and climate risk, black carbon has fallen between the cracks of the global climate and air pollution agendas. Its ambiguous classification often means that neither international frameworks nor government departments take full ownership, which contributes to inaction. The classification of black carbon as an aerosol rather than a greenhouse gas has made it challenging to integrate it into the existing climate framework under the UNFCCC.

2. **Mixed messaging on the climate-related effects of black carbon:** Mixed messaging about the global climate impacts of black carbon since the publication of the IPCC Assessment Report 6 (AR6) in 2021[4] has been a key factor behind the lack of action by national governments. Overall, its radiative forcing in AR6 was reduced compared with the earlier AR5 report.

3. **Crowded policy agendas often mean little room for black carbon:** National policy makers often recognise the importance of black carbon when presented with compelling evidence. However, the crowded climate and health agendas make it challenging to highlight a new concern, hindering efforts to allocate national attention and resources to address black carbon as a standalone issue. Additionally, some stakeholders worry that clean air strategies could reduce cooling climate forcers, such as organic carbon and sulphur dioxide, potentially 'unmasking' global warming.

4. **Exclusion and blockage of black carbon from global climate initiatives:** In some cases, influential countries have deliberately excluded black carbon from international climate initiatives, prioritising other super pollutants such as methane. While addressing all super pollutants is essential, black carbon must be prioritised in its own right because of its numerous harmful effects and well-evidenced regional impacts that contribute to climate tipping points.

Opportunities:

1. **Grow attention on black carbon as a climate issue:** The UNFCCC's Global Stocktake report at COP28 called on countries to accelerate and substantially reduce non-CO_2 emissions worldwide. As a result, action on black carbon—alongside other super pollutants—could become more closely linked to the UNFCCC through Article 2 of the Convention. This article emphasises the need for climate action "*within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner*"[39]. Given black carbon's short-lived nature in the atmosphere, addressing it is essential to meeting these goals. Additionally, the IPCC is currently working on a Methodology Report on Inventories for Short-Lived Climate Forcers (SLCF)[40], due in 2027. This will provide standardized guidelines for measuring SLCF emissions, including black carbon, improving inventories and supporting more effective mitigation effort

2. **Address the 'unmasking effect' head on by ensuring that action on climate change and air quality is integrated:** At present, most countries focus on $PM_{2.5}$ as a way to reduce negative health outcomes from air pollution, with no black carbon considerations or under the assumption that black carbon will be proportionally reduced as a component of $PM_{2.5}$. That is often not the case. Data indicate that some clean air strategies (e.g. for the shipping sector) have led to a reduction in cooling climate forcers, which has acted to 'unmask' (i.e. increase) global warming[41]. This is why adopting an 'all-pollutants' approach and anticipating any potential unmasking effect are crucial. Countries have an opportunity to focus first on black carbon-rich sectors as a prioritisation scheme for AQM planning to simultaneously reduce toxic elements of $PM_{2.5}$ and to counteract or minimise any unmasking due to a reduction in 'cooling' aerosols co-emitted with or components of $PM_{2.5}$[42,43]. In addition, there is an urgent requirement to improve aerosol observation and include component-specific targets in international agreements as definitive ways to target both climate and clean air action.

3. **Establish effective ministerial coordination between health and environment:** Countries where ministries of environment or climate change and health collaborate on tackling the effects of air pollution and climate change, with consideration of black carbon, have had greater success in creating national plans or setting emission reduction targets. Chile is an example, with such integration helping establish black carbon targets in the country's 2020 NDC[44]. Rather than pigeonholing black carbon as either a health or climate issue, there is an opportunity to combine government efforts and tackle all of its negative effects simultaneously.

4. **Use cryosphere negotiation tracks as a starting point:** Cryosphere-focused activities are on the agenda of the UNFCCC and many national governments owing to the key role of snow and ice in mitigation and adaptation, for instance, through the Ambition on Melting Ice high-level group, Adaptation at Altitude, and the Arctic Council Expert Group on Black Carbon and Methane. The UN General Assembly has also declared 2025 the International Year of Glacier Preservation. The climate impacts of black carbon across the cryosphere are well recognised and quantified[45], and this presents a unique opportunity for advocacy and action, including funding technical solutions to decrease black carbon emissions (see Section 3 for details).

5. **Create a global movement:** Making a difference on black carbon cannot rely on the actions of a few governments alone—joint action through international fora can unlock further progress. For example, air quality and climate change have been identified as priority concerns at South Africa's G20 Presidency for 2025. The CCAC has launched the Clean Air Flagship, a new effort for 2024–2026 to save lives, slow climate change, and maximise co-benefits, with a specific objective to mitigate climate change by taking advantage of win–win opportunities to reduce the emissions of SLCPs such as black carbon simultaneously with other harmful pollutants[46].

Country highlight: Finding synergies between climate and air pollution - Insights from China

China's dominant policy approach has been to manage air quality and climate change mitigation separately, with black carbon mitigation managed under $PM_{2.5}$ air pollution reduction measures. In 2014, the government declared a 'war on air pollution', and these measures led to a 41% reduction in air pollution between 2013 and 2022[47]. Recent developments provide an opportunity for combined approaches, such as the 2022 Implementation Plan for Synergistic Reduction of Pollution and Carbon Emissions[48] and 2024 *Technical Guideline for Integrated Emissions Inventories of Air Pollutants and Greenhouse Gases*[49] (trial implementation), which include guidance for black carbon inventories. In addition, the US–China diplomacy on non-CO_2 pollutants (such as the Summit on Methane and Non-CO_2 Greenhouse Gases convened at COP29) has also emphasised the benefits of enhancing synergies of measures to reduce climate and air pollutants.

Opportunity 2: Science – Refining the science and investing in improved monitoring data

Commonly-cited barriers:

1. **Interpretation and communication of climate-related scientific uncertainties:** The understanding of black carbon's effect on the climate is limited by uncertainties in (a) Wblack carbon emission inventories and (b) the representation of black carbon in climate models. Scientific uncertainties about the exact effects of black carbon emissions have been cited as challenges by both global and national-level policy makers when attempting to elevate black carbon on the climate agenda. However, the last major scientific assessment wherein both modelling and observations were considered is now over a decade old[35]. Studies have revealed large discrepancies between modelled and observed black carbon levels[50]. There is a need for an updated integrated assessment on black carbon to support active policy questions and move towards scientific consensus

2. **Lack of data, especially in the Global South:** Ground-based observational data on black carbon are currently limited, with major gaps in the Global South and cryosphere regions with the highest climate impacts. Black carbon monitoring is generally limited to advanced monitoring sites (source attribution; e.g. the SPARTAN network), government-mandated super sites (e.g. the requirement for monitoring in the European Union (EU)'s Ambient Air Quality Directive), or sub-national AQM plans wherein black carbon has been prioritised (e.g. Bogotá's monitoring network). This makes it challenging to accurately design interventions that will have the maximum emission reduction potential considering the regional effects of black carbon. There is a need to develop a consistent measurement protocol and reduce uncertainties by collecting high-quality data and better integrating satellite and ground-based observations[51].

3. **Relative toxicity to PM$_{2.5}$:** The true magnitude of relative toxicity of aerosols such as black carbon relative to PM$_{2.5}$ is still not robustly determined in epidemiological studies[52]. Studies suggest that black carbon has direct health impacts and may be more toxic than PM$_{2.5}$[17,53]. The latest update of the WHO Air Quality Guidelines recognised black carbon as a pollutant of concern and issued a good practice recommendation, emphasising its significant impact on air quality and human health[54]. In response to the growing evidence of its harmful effects, the WHO has commissioned an updated systematic review in 2025 to further assess black carbon's health implications[55]. However, in the absence of broader scientific consensus and comprehensive health-based evaluations, the case for prioritising black carbon solely from a health perspective remains weak.

Opportunities:

1. **Fund coordinated scientific research to further deepen the evidence base:** New research, along with a systematic compilation of existing evidence, is needed to reduce the uncertainties associated with black carbon and co-emitted pollutants (while acknowledging that there is sufficient scientific certainty to take swift action). Priority research areas may include (a) regional climate modelling focused on black carbon mitigation pathways and local impacts such as drought, extreme heat, and glaciers; (b) developing climate and health metrics that better account for the local environmental and social costs of black carbon and other SLCF emissions; (c) compiling or updating emission inventories and improving emission factors and parametrisations underlying high uncertainty bars on black carbon and other SLCFs in climate forcing estimates for Earth system models; and (d) performing health impact assessment of black carbon relative to PM$_{2.5}$.

2. **Invest in opportunities to gather high-quality data:** Countries that have developed robust black carbon emission inventories and an engaged scientific community have been more successful in sustaining political and policy momentum to address black carbon and other SLCFs. In Mexico and Colombia, for instance, national black carbon inventories have served as key reference points for setting emission reduction targets. To address data uncertainty, new funding for scientific research should prioritise scientists and institutions in the Global South, especially in countries with high black carbon emissions. As outlined above, the announcement of IPCC emissions guidance on SLCFs, including black carbon[40], has already incentivised some countries to take this step, including South Africa.

Opportunity 3: Regulations – Creating new momentum through global frameworks & national regulations

Commonly-cited barriers:

1. **No global black carbon framework/ mechanism**: As outlined above, the absence of global policy mechanisms, frameworks, or protocols on black carbon has hindered greater national-level political action. Incentives to integrate black carbon into global climate frameworks, namely, the UNFCCC, have been especially hindered by the fact that it is an aerosol rather than a greenhouse gas[56].

2. **Non-enforceable agreements:** Existing frameworks and agreements that include black carbon (for example, the Fairbank Declaration and the Gothenburg Protocol) are often difficult to enforce in practice, which makes it challenging to achieve concrete progress on reducing black carbon emissions. Lessons could be learned from better enforced agreements such as the Montreal Protocol, a treaty that has succeeded in completely reducing nearly 100 ozone-depleting chemicals[57].

3. **Integrating black carbon into NDCs has not been prioritised to date:** The integration of black carbon targets and measures into NDCs might prove especially challenging for resource-constrained countries, where the commitments outlined in NDCs do not include the finance needed to implement the targets or explicitly note the need for international development finance to support implementation. Despite these challenges, Global South countries are leading on the integration of black carbon into NDCs. This promise can be further unlocked through increased funding support.

Opportunities:

1. **Embed black carbon into regional frameworks and processes, with a particular focus on air pollution:** Given the challenges of integrating black carbon into the global climate regime, prioritising relevant legal frameworks on preventing air pollution can help unlock further progress[56]. For example, the inclusion of a specific black carbon target in the Gothenburg Protocol revision process (see Annex 2) could result in a binding target across as many as 51 countries, generating significant climate and health benefits. The EU's National Emission Reduction Commitments Directive could include stronger and mandatory black carbon standards. Similar regional frameworks are in progress and under development worldwide.

2. **Identify sectoral entry points to create impact:** The IMO's new guidance on best practices for cutting black carbon emissions from ships operating in the Arctic was put forward at the Marine Environment Protection Committee in October 2024 (MEPC82). This resulted in the proposal for new regulations under MARPOL (mandating a polar fuel standard[58] developed by the International Organization for Standardization [ISO]) to be approved in April 2025 (and adopted by 2026). MEPC82 has also adopted (voluntary) guidelines on goal-based control measures for black carbon emissions, as well as measurements, monitoring, and reporting. Other influential organisations are considering further work.

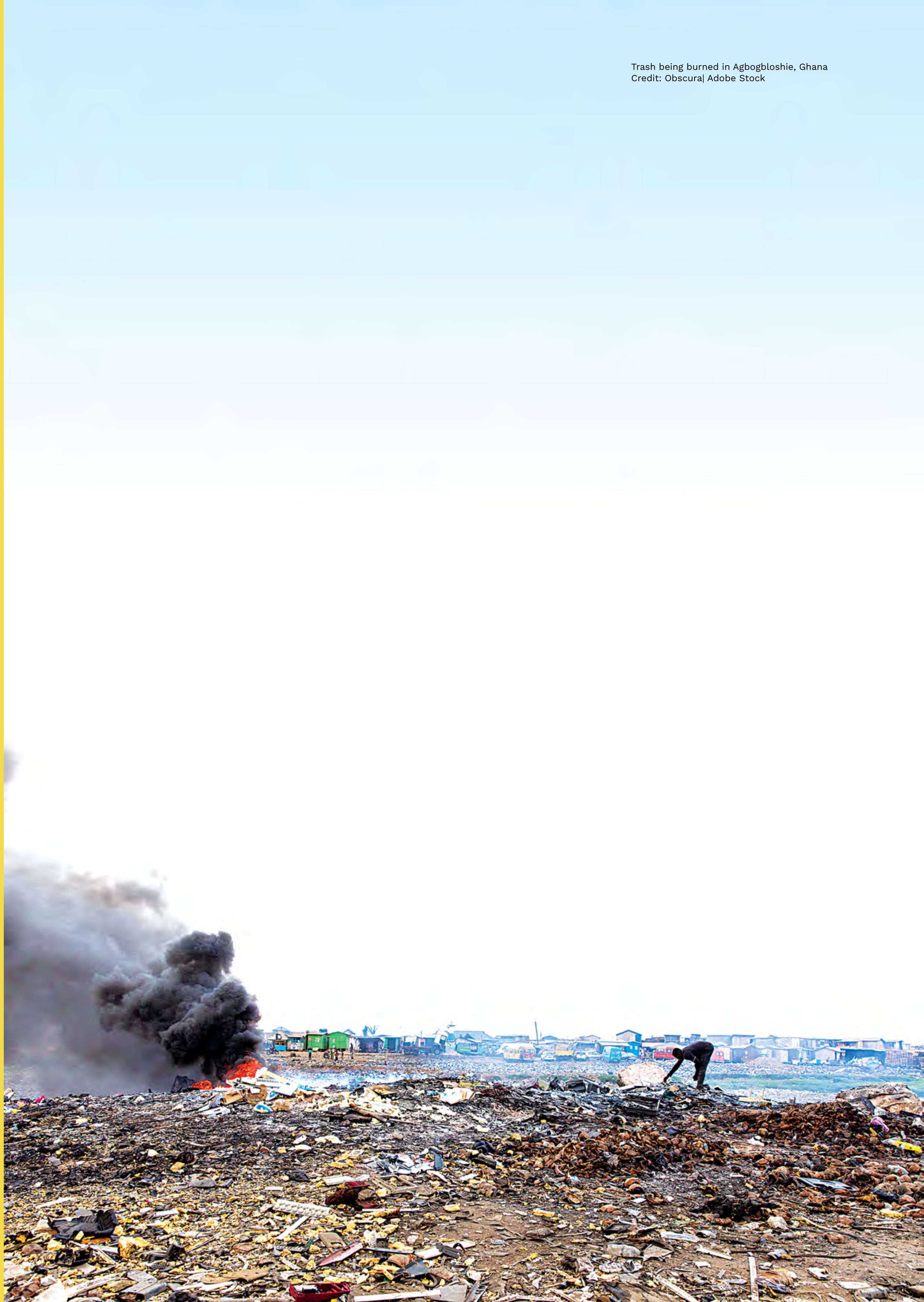
3. **Integrate black carbon into NDCs 3.0:** The 2025 revisions of NDCs present a critical opportunity for countries to integrate black carbon as a strategy for limiting global warming to 1.5°C and improving public health[59]. Several countries have already recognised the importance of black carbon in their NDCs, either by addressing its impact or by setting specific reduction targets (details outlined in Table 1). Integrating black carbon into their NDCs provides an opportunity to tackle near-term warming and crucial public health challenges together. Platforms such as the NDC Partnership and CCAC can be leveraged for support[60].

4. **Adopt a sub-national approach, where relevant, for action:** In cases where incorporating country-wide action plans and targets into NDCs is challenging owing to a lack of political will and/or finance, countries can identify opportunities for sub-national entities, such as states or provinces and sub-national agencies or departments, to work on reducing black carbon emissions.

Country highlight: Taking action at the sub-national level - Insights from India

Black carbon mitigation is often a secondary outcome of efforts to reduce air pollution rather than a primary objective of policy decisions in India. However, some state governments and institutions have implemented both direct and indirect measures to address black carbon emissions. For example, Punjab's 2024 State Action Plan on Climate Change (SAPCC)[61] explicitly recognises black carbon impacts and allocates funding for research on heat stress and aerosol burdens across the Indo-Gangetic Plain. Bihar's investment and training programmes to transition to zig-zag brick kilns[62] are directly tackling a key black carbon-emitting sector. Other state governments have included black carbon in monitoring and air pollution mitigation efforts. For example, Uttar Pradesh is pushing to tackle air pollution at the airshed level (in recognition of rural household emissions), and an initiative by the West Bengal Pollution Control Board[63] focuses on identifying gross polluting vehicles[iv] through remote sensing devices. This demonstrates that engagement with state governments can unlock black carbon reduction measures and add to wider efforts on super pollutants in India.

iv Gross polluters are vehicles in which emission control equipment has been disconnected or are poorly maintained leading to disproportionately high emissions.



Trash being burned in Agbogbloshie, Ghana
Credit: Obscura| Adobe Stock

Table 1: Examples of black carbon inclusion in NDCs and national plans

Country	**Reference to black carbon in NDCs (as of December 2024)**
Bangladesh*	Full implementation of the plan is expected to reduce black carbon emissions by 40% in 2030 compared with a business-as-usual scenario[64,65].
Benin	Measures in the energy sector are projected to lead to a 14.2% reduction in black carbon emissions by 2030, with the residential sector also named as a source[66].
Central African Republic	The impacts of black carbon emissions are acknowledged as part of the needs for SLCP reductions (no specific target)[67].
Chile*	Target of reducing black carbon emissions by 25% by 2030 compared with 2016 levels[68].
Colombia	Target of reducing black carbon emissions by 40% by 2030 compared with 2014 levels[69].
Costa Rica*	Target of reducing black carbon emissions from industrial and transport sectors by 20% by 2030 compared with 2018 levels[70].
Côte d'Ivoire*	Target of a 58% reduction in black carbon emissions by 2030 compared with a baseline scenario[71].
Dominican Republic	Implementing the NDC action plan could reduce black carbon emissions by 6% in 2030 compared with a baseline scenario[72].
Eswatini	Mentions SLCPs including black carbon (no target)[73].
Ghana*	The NDC notes that improved cookstoves and electric vehicles should reduce black carbon emissions for better public health outcomes[58].
Mali	Notes that black carbon contributes to negative impacts on human health, and plans to form a technical team to monitor SLCPs[74].
Mexico*	Unconditional target of reducing black carbon emissions by 51% by 2030 compared to a business-as-usual scenario[75].
Micronesia	Target to reduce black carbon and methane emissions related to diesel electric generation by more than 65% below 2000 level by 2030[76].
Nigeria*	Highlights a potential 42% reduction in black carbon emissions by 2030 if mitigation measures are fully implemented[77].
Togo	The full implementation of the updated NDC should reduce black carbon emissions by 80% in 2030 compared with the reference scenario[78].
Uganda	Includes a section on the co-benefits of implementing measures against SLCPs. Plans to create a national SLCP emission inventory, including black carbon[79].
Zimbabwe	Black carbon is mentioned (no target)[80].
Country	**Black Carbon in national action plan**
Canada	Canada and other Arctic States have committed to a collective, aspirational goal to reduce black carbon emissions by 25%–33% below 2013 levels by 2025[74].
Kenya	Launched its National Action Plan to Reduce SLCPs in 2023 and is committing to promoting clean cooking solutions[81].
Norway	Norway and other Arctic States have committed to a collective, aspirational goal to reduce black carbon emissions by 25%–33% below 2013 levels by 2025[74].

Note: (*) Indicates countries that have also included black carbon in national action plans.

Opportunity 4: Finance – Increasing funding for black carbon specific-solutions in most affected areas

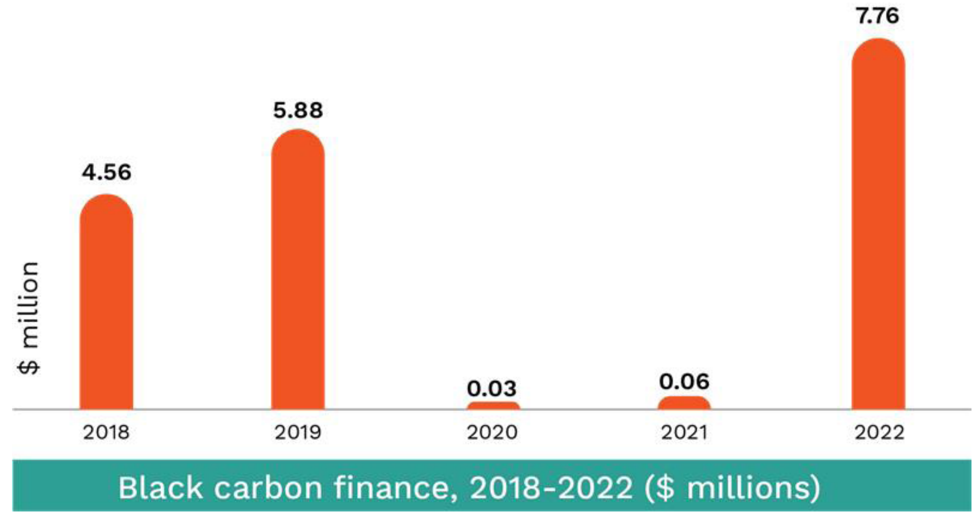
Commonly cited barriers:

1. **Lack of funding in resource-constrained environments:** While high-income countries have been able to deploy a range of policy instruments to reduce emissions, most resource-constrained countries find finance as a barrier to implementing black carbon mitigation goals due to limited resources. Some NDCs with specific goals and targets for black carbon have no corresponding financing commitments (for instance, Nigeria and Côte d'Ivoire), suggesting that ambition for this agenda does not always align with the availability of resources needed to deliver impact.

2. **Disproportionately low international development funding for black carbon-specific solutions:** Lack of dedicated and targeted funding for black carbon makes it challenging for resource-constrained countries to access international finance for black carbon mitigation efforts. Black carbon is almost invisible in international development and climate finance and even more so in overall international development finance. Targeted black carbon finance (projects where black carbon/soot was explicitly mentioned in the project description) comprised only 0.1% of the outdoor air quality funding provided by international development funders between 2018 and 2022 (a total of $18 million)[82]. As Figure 7 shows, there was almost no funding specifically for black carbon between 2020 and 2022. This reflects an overall decline in international development finance, which had a disproportionate impact on already low levels of finance for black carbon. International development funders provided $2.8 billion for projects addressing black carbon-rich sources in the same period, largely for energy- and transport-related projects, which represents less than 1% of international public climate finance over the same period[82].

3. **Limited pool of international development funders:** A very small pool of international funders provide targeted black carbon finance, with just eight donors identified as of 2022 and no multilateral development banks (MDBs) among them. Despite the creation of a 2015 Black Carbon Finance Study Group convened by the CCAC and led by the World Bank[83], the recommendations from this group were never implemented and progress stalled.

Figure 7: Black carbon finance, 2018–2022 ($ millions)



Source: The State of Global Air Quality Funding 2024[82]

Opportunities:

1. **National air pollution-related taxes:** At a national level, introducing taxes and levies on polluting activities can raise funds to reinvest in emission reduction measures. Among Organization for Economic Cooperation and Development countries, air pollution-related taxes raised $498 billion in 2022, representing over two-thirds of environmentally related tax revenue (67%)[84]. Most of the revenue was raised from taxing energy (55%), particularly motor fuels and transport. Examples of air pollution-related taxes include the Czech Republic's air pollution tax, which began in 1967 and has been adapted over the years; Sweden's carbon tax (introduced in 1991); and Norway's sulphur tax. In many cases, these can be combined with tax incentives for clean fuels to support industry transitions.

2. **Developing new international financial mechanisms:** There are opportunities to better integrate black carbon in climate and clean air projects across MDBs and especially within the World Bank, which has implemented shifts to make particulate matter a stronger priority. MDBs can also develop new financial mechanisms to reduce risks and burden on borrowers; black carbon solutions such as clean transportation or clean cooking in the Global South are risky because of various reasons including currency fluctuations, high upfront costs, and higher chances of default. Risks associated with the implementation of black carbon technological solutions in Global South countries could be mitigated by financing mechanisms that reduce borrower risk. For example, in the early phase of a project, funders can work together to share and distribute risks.

Regional entry point: World Bank Indo-Gangetic Plain project - Catalytic financing for projects that have direct implication on the reduction of black carbon

The exceptionally low levels of international development finance for black carbon creates an opportunity for a small group of countries and institutions to come together and significantly increase the availability of grant-based or concessional finance, structured to have a catalytic effect. The World Bank has a history of policy thinking on black carbon and is particularly well placed to take on a leadership role on this agenda. The World Bank Group has a pipeline of projects, both at the state and country level, across the Indo-Gangetic Plain–Himalayan Foothills region, which has some of the world's most polluted air[85]. The projects under preparation in Uttar Pradesh and Haryana in India, as well as in Bangladesh, Nepal, and other target countries, have a strong focus on cost-effective and transboundary approaches. They will also support actions that have considerable climate change co-benefits through reductions in CO_2, black carbon, and methane. There is further scope within these projects to prioritise and **focus first on black carbon-rich sectors** to maximise benefits for both climate and air pollution.

3. **Unlocking private sector finance:** In the context of growing calls for 'investible NDCs' (including from the We Mean Business Coalition and the Institutional Investors Group on Climate Change), governments can unlock private finance for black carbon by integrating black carbon-specific targets into their climate plans. Through the Alliance for Clean Air[86], the World Economic Forum has emphasised the potential to drive action and unlock financing by increasing private sector engagement in incorporating black carbon emission reduction targets and plans into NDCs. The Alliance for Clean Air supports companies to quantify their air pollutant emissions and develop mitigation scenarios and is beginning to increase interactions between the private sector and national governments[86].

Opportunity 5: Industry – Increasing incentives for industry actors to reduce emissions

Commonly cited barriers:

1. **Private sector engagement dependent on individual will:** Although there is potential to engage large private sector actors directly in reducing black carbon emissions, motivation to adopt changes is currently dependent on individual company willingness and how material air pollution is to the operations of a particular business. In addition, there is a first-mover challenge—in industries such as shipping or gas flaring, companies are only motivated to take action if their competitors are doing the same.

2. **Existing industry regulations are often non-binding or have loopholes:** Some efforts to regulate black carbon emissions from the private sector exist, but they often lack enforcement power. For example, non-binding legislation related to shipping in the Arctic coupled with the lobbying power of the shipping industry has stalled progress in reducing black carbon emissions in the region. In June 2021, the IMO announced a ban on the use and transportation of heavy fuel oil (HFO) in the Arctic, which came into effect on 1 July 2024. However, this measure currently has several loopholes that exempt ships with fuel tank protections and allows countries with an Arctic coastline to issue waivers to vessels flying their flags[87]. These issues may persist until 2029, with a study by the International Council on Clean Transportation showing that 74% of the HFO-fuelled fleet could continue to operate in the Arctic due to exempsions and waivers[88].

Opportunities:

1. **Support opportunities for increased interaction and collaboration with peers:** Opportunities to connect industry actors on reducing black carbon emissions are growing. The Alliance for Clean Air was launched at COP26 in 2021 by the World Economic Forum and the Clean Air Fund. It brings together business leaders to measure and reduce value chain air pollutant emissions and invest in innovation and is generating positive outcomes among its member companies. These types of initiatives can help overcome any hesitation from companies on being a first mover. In addition, mandatory measures on black carbon can assure companies that their peers will be bearing any costs associated with a transition or lack thereof, if there is a penalty.

2. **Introduce stronger global standards and enforcement:** At the UN General Assembly in 2024, the Prime Minister of the United Kingdom, Keir Starmer, called for a new global emissions levy on international shipping, intended to put a price on the true costs of air pollution emissions, with the proceeds used to tackle climate change and cut emissions. Given the contribution of international shipping to global black carbon emissions, there is a strong case for a global levy to be used for projects to cut black carbon emission, especially in the Arctic and regions most affected by international shipping.

3. **Partner with industry to pilot new technologies:** There is an opportunity for industry actors to pilot new technologies that have the potential to reduce black carbon emissions (for instance, low-carbon fuel use in vehicles and electrification of heavy-duty vehicles) in coordination with scientific institutes/think tanks to boost their research and development. Viable projects could be scaled up and implemented.

Ferry tourist boat air pollution Credit: Skyimages | Adobe Stock

Opportunity 6: Advocacy and Communication – Increasing awareness of the effects of black carbon

Commonly cited barriers:

1. **Ineffective or limited advocacy on the effects of black carbon:** There is a lack of targeted advocacy on the specific effects of black carbon, especially to raise awareness among the public. This is driven by a combination of the barriers listed above: (a) the science related to black carbon's climate-related effects is complex and regionally specific; (b) there is a lack of financing not only for black carbon emission reductions projects but also for advocacy on black carbon; and (c) international fora for directly advocating on black carbon are absent.

2. **Inability to communicate using climate metrics:** The commonly used climate metrics do not work for black carbon. Under the Paris Agreement, countries agreed to use Global Warming Potential values with a 100-year time horizon (GWP100). However, this has limitations when applied to black carbon and other SLCPs owing to their short-lived nature. Therefore, communicating the climate impact of black carbon to policy makers is challenging, further diminishing demand from the public to solve the problem.

Opportunities:

1. **Frame communications for success in each context:** To effectively communicate the case for action on black carbon, advocacy and communications strategies should be framed as follows: focus on localised messaging to reflect specific contexts; emphasise the potential for co-benefits; be specific about the positive effects on health outcomes; highlight the speed with which the benefits of emission reductions can be felt; and deliver motivating messages with solutions, ideas, and support for government action.

2. **Diversify the messengers when crafting advocacy campaigns:** Creating a coalition of diverse communicators will be most effective in driving home the importance of tackling black carbon. Each stakeholder group may play a different role; for example, scientists and academics can provide impactful data and statistics, civil society actors can launch both local and global advocacy campaigns, the media can more explicitly reference black carbon when communicating on the effects of general air pollution or super pollutants, healthcare professionals can serve as trusted messengers on the health-related effects of black carbon in community settings, and the general public can urge governments to act on these concerns.

3. PRIORITY ACTIONS TO MAXIMISE THE IMPACT OF TACKLING BLACK CARBON

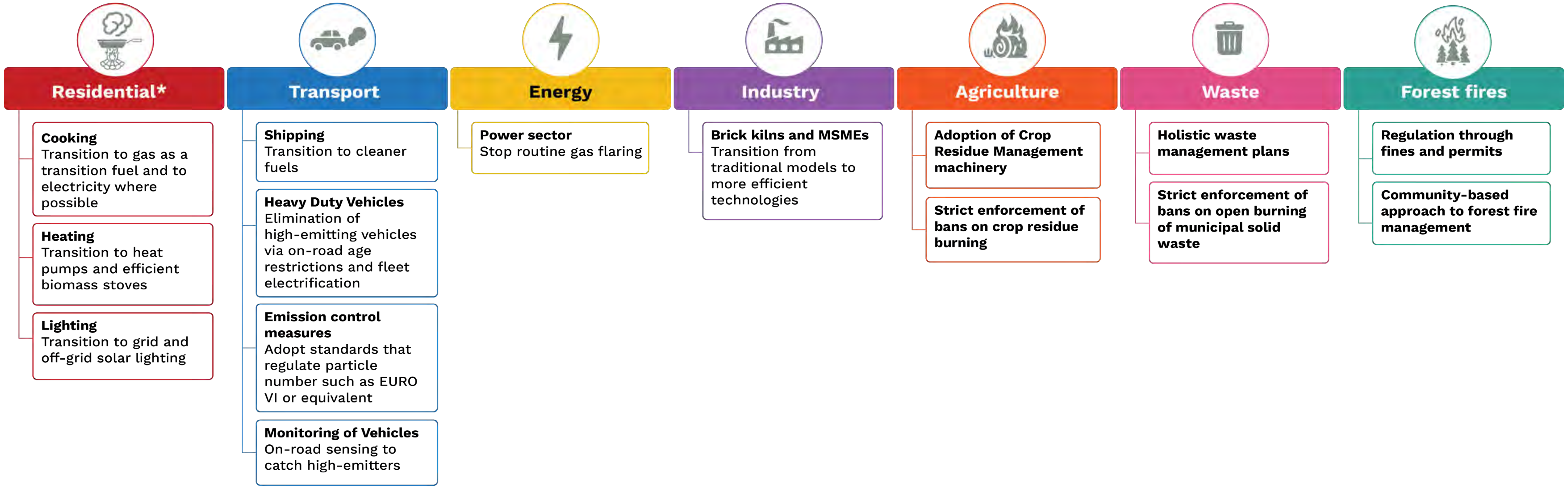
To overcome barriers and take advantage of opportunities, we need a targeted focus in three areas: 1) rapidly cut black carbon emissions affecting the cryosphere, 2) integrate black carbon into clean air and energy policies, and 3) take coordinated action on super pollutants.

Black carbon is co-emitted with other harmful pollutants and is a component of $PM_{2.5}$, so its solutions often align with existing efforts on decarbonisation and air pollution. However, the barriers outlined in Section 2 inhibit targeted attention on the dual impacts of black carbon on climate and health, and this drives a gap in our approach and prioritisation of solutions.

The status quo of indirect action on black carbon through other priorities is not driving down emissions fast enough in most places and is a missed opportunity to tackle climate and health together. This section explores what it means to act on black carbon across all relevant sectors and solutions and presents a framework for how this can be delivered alongside and as a complimentary to existing efforts.

Because black carbon emissions are the result of dirty fuels and open or inefficient burning, the solutions lie in the transition to cleaner fuels and technologies, the uptake of more stringent emission standards, and reduction of harmful burning practices. Action is needed across all key black carbon-rich sectors, as summarised in Figure 8.

Figure 8: Selected interventions across black carbon-rich sectors



*Including institutions and commercial settings

Table 2: Qualitative assessment of the impacts of selected interventions across black carbon-rich sectors in example regions

Sector	Sub-sector (example region)	Change required	Black carbon emissions reduction potential	Tipping points and other local climate impacts	Short-term climate impact	Long-term climate impact	Air pollution and health benefits
Residential	**Cooking (South Asia)**	Transition from biomass to LPG in the near-term, with a long-term view to use bio-LPG when fully commercial	light green	dark green	light green	orange	dark green
		Transition from biomass to biogas technology in livestock-owning households in rural areas	light green	dark green	light green	orange	dark green
		Transition from biomass to renewably generated electric cooking and hydroelectricity	dark green	dark green	dark green	light green	dark green
	Heating (Europe)	Replacing boilers with heat pumps for residential space heating	orange	light green	light green	light green	light green
		Adoption of tighter ecodesign emission standards, including for black carbon	orange	light green	light green	light green	light green
	Heating and lighting (Himalayas)	Displacing biomass fuels and diesel generators with off-grid solar and small-scale hydropower systems	light green	dark green	dark green	light green	dark green
	Lighting (Sub-Saharan Africa)	Displacing the use of kerosene wick lamps with solar lighting	orange	orange	light green	light green	dark green
Transportation	**Shipping (Arctic)**	IMO to establish a black carbon emission standard for shipping in Arctic waters	orange	light green	orange	grey	orange
		Installation of diesel particulate filters on ships	orange	light green	orange	grey	orange
	Diesel vehicles and mobile machinery (East Asia)	Eliminating on-road and off-road super-emitters in transportation and freight	light green	light green	light green	orange	dark green
Energy	**Gas flaring (Arctic)**	Stop routine flaring by exporting the Norwegian model (strict regulations and taxes) to other countries	orange	dark green	light green	orange	orange
Industry	**Brick kilns (South Asia)**	Transition to improved low-emission brick kilns	light green	dark green	dark green	orange	light green
		Worker upskilling on improved technologies (tailored to specific country contexts).	light green	dark green	dark green	orange	light green

Sector	Sub-sector (example region)	Change required	Black carbon emissions reduction potential	Tipping points and other local climate impacts	Short-term climate impact	Long-term climate impact	Air pollution and health benefits
Agriculture	**Adoption of Crop Residue Management (South Asia)**	Develop profitable alternative markets (*ex-situ* options) to incentivise stubble management applications	Uncertain	Uncertain	Uncertain	Uncertain	Medium-high
		Streamline access to happy seeders and super seeders via custom hiring centers (*in situ-management*)	Uncertain	Uncertain	Uncertain	Uncertain	Medium-high
Waste	**Open burning of solid waste, including e-waste (Africa)**	Adopt holistic waste management systems and bans on open burning	Uncertain	Uncertain	Uncertain	Uncertain	Medium-high
Forest Fires	**Wildfire Management (Latin America)**	Promote wildfire management in Latin America	Very high	Very high	Uncertain	Very high	Medium-high
	Wildfire management (West Africa)	Promote wildfire management in West Africa	Very high	Medium-high	Uncertain	Very high	Medium-high

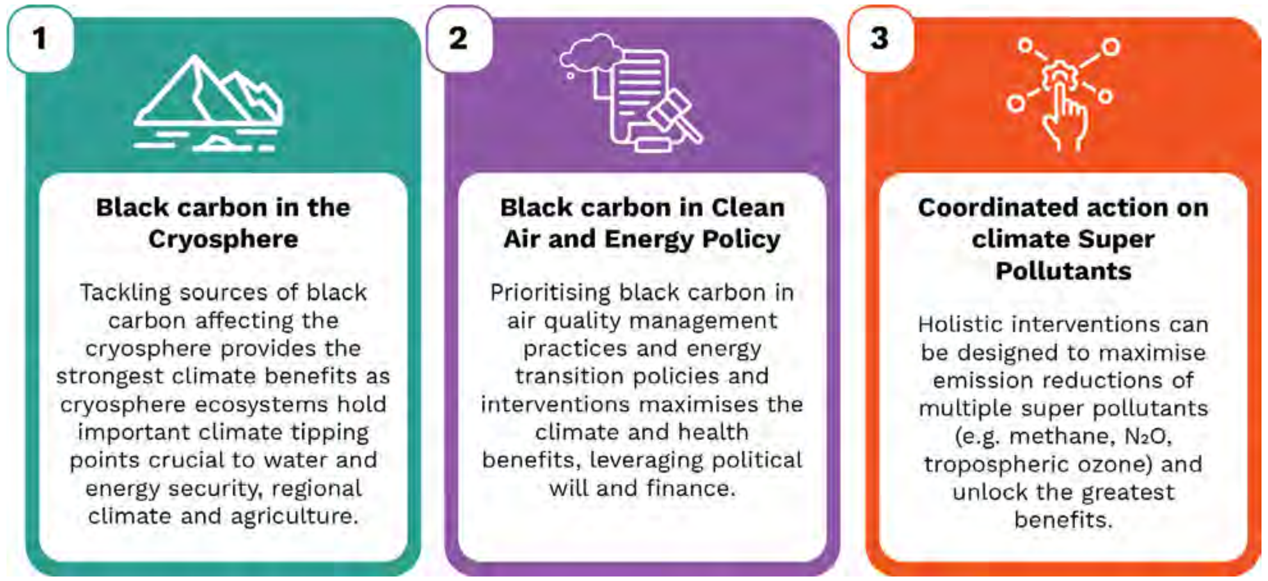
Key: Very high positive impacts; Medium-high positive impacts; Uncertain positive impacts; Insufficient information to determine impacts

Many of these solutions are already on the agenda of governments and other institutions to varying extents, largely driven through other closely related agendas. Yet, in most places, progress is too slow. We are generally failing to draw the connection between these solutions and their multiple benefits. Black carbon should be leveraged as a tool to understand and unlock the connection between climate, health, and social justice.

Black carbon links all these interventions, but multi-pollutant and locally relevant analyses are needed to break down their impacts at a granular scale. This is illustrated in Table 2 using regional examples, through a qualitative assessment of their emission reduction potential, local climate effects, short-term climate effects, long-term climate effects and potential health benefits. Refer to Annex 3 for further details.

Tackling black carbon, therefore, means better understanding the climate and health impacts of emission reductions. It presents new priorities and action areas from local to global scales. Here, we summarise what this means for climate and health through three top priorities as set out in Figure 9.

Figure 9: Priority action areas to tackle black carbon



3.1. Reducing black carbon in the cryosphere

Tackling black carbon emissions that have significant cryosphere effects represents a huge opportunity to garner near-term climate benefits. The opportunity for action sits in the Arctic, Himalayas, Andes, Alps, and beyond.

Black carbon emissions are linked with 20% of snow and ice loss in the Arctic over the 20th century and also has a direct impact on glacier melt in the Himalayas, Alps, Tibetan Plateau, and Rockies[5,89]. Changes in snow and ice cover risk triggering irreversible climate tipping points and have wider effects on the global climate. With the Arctic warming four times faster thanthe rest of the world[8] and with almost a billion people dependent on glacier-fed rivers in South Asia, the quick win of cutting down black carbon emissions (within days or weeks) is a major missed opportunity in climate strategies. This section outlines sector-specific interventions that could deliver these quick wins.

Global warming climate change melting ice lake glacier in New Zealand
Credit: Nigel Bruce | Climate Visuals

3.1.1. Tackling black carbon-rich sources in the Arctic

Action in the Arctic requires a combination of technical solutions and regulatory changes that address key emitting sectors in tandem.

Energy: The energy sector is the highest contributor to black carbon emissions from anthropogenic sources in the Arctic region according to CEDS 2022[25,90]. This includes emissions from electricity and heat production, as well as fugitive and flaring emissions from fuel production and oil refining[91]. While gas flaring contributes to approximately less than 3% of global black carbon emissions, it has an amplified effect on the Arctic, with gas flaring accounting for 42% of all the annual mean black carbon surface concentrations in the Arctic region[92]. Emissions released during gas flaring and other oil and gas exploration activities on the Arctic shelf contribute to regional warming, affecting biodiversity and the livelihoods of at least five million people, including Indigenous Arctic communities[93]. Some countries have adopted measures to tackle gas flaring; for example, 36 national- and sub-national governments, including Canada and Norway, and 59 oil companies have endorsed the World Bank's Zero Routine Flaring Initiative, and the USA and Norway have supported the World Bank's recent Global Flaring and Methane Reduction Partnership.

Transport and Shipping: The transport sector is the second-highest contributor to anthropogenic sources of black carbon emissions in the Arctic region[25,90]. Although shipping contributes less to the overall black carbon emissions in the Arctic, its impact is significantly greater. This is because black carbon emissions from shipping have greater proximity to the surface and the sea ice, which increases the likelihood of the deposition of black carbon particles on ice and snow, leading to a more pronounced effect[94]. Melting ice is opening more waters to freight and other shipping activities, generating a dangerous feedback loop. Black carbon emissions from shipping in the Arctic doubled from 2015 to 2021 and are growing 10 times faster than those in the rest of the world[88]. The Clean Arctic Alliance has noted that switching from dirty residual fuels, such as HFO, to lighter distillates could reduce black carbon emissions by 50%–80%, depending on the type of engine[58].

Sectoral spotlight: More stringent regulation for Arctic shipping

Black carbon is an active agenda item in the IMO, and several solutions have been put forward[95]. However, black carbon emissions from ships are currently not directly regulated by the IMO. While the IMO's fuel sulphur regulation indirectly addresses black carbon, it is not specifically designed to do so. This regulation reduces black carbon only when the sulphur limit is met by switching to cleaner fuels (rather than through the use of ultra-low-sulphur fuels or heavy fuels with scrubbers).

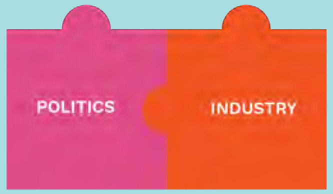
Entry points:

- The IMO could regulate black carbon by **amending MARPOL Annex VI**[96] to require ships operating in/near the Arctic (north of 60° N) to use distillates / cleaner fuels ('polar fuels'), following the recent ban on HFO.
- In the context of the Arctic, the IMO could set a **black carbon emissions standard for international shipping**. Compliance with such a much-needed standard can be achieved using low black carbon / methane fuels (e.g. marine distillate fuels) or technologies such as diesel particulate filters in ships' engines. The latter are currently facing challenges in widespread adoption owing to cost, fuel compatibility, and operational complexities, but as the maritime industry transitions toward zero-emission technologies, they could be treated as an interim measure, especially for smaller vessels.
- **Emission control areas (ECAs) for international shipping could be expanded**. A transatlantic ECA connecting North America with the European ECAs could prevent between 2,900 and 4,300 premature deaths among indigenous coastal communities between 2030 and 2050, with the cumulative economic value of these health benefits projected at €19–€29 billion over the same period[97]. The establishment of ECAs also allows countries to prioritise emission standards domestically, contributing to the overall improvement of air quality.

Residential heating: Residential burning of solid fuels such as wood and coal is third-highest contributor to anthropogenic emission sources in the Arctic region, contributing to 18% of black carbon emissions[25,90]. Residential heating in the EU significantly contributes to Arctic warming, particularly from Eastern and Northern European countries. Approximately 80–90 million European households use solid fuel heating appliances, with more than 4 million such appliances sold annually in the EU[98]. Converting heating appliances in 14 EU countries to cleaner fuels and boilers could cut black carbon and co-pollutant emissions by 94% and reduce the Arctic temperature impact by 85%[99].

Smokey roofs Gatlang
Credit: Nigel Bruce

Regional entry point: Leveraging the Arctic Council's leadership



As an intergovernmental forum, the Arctic Council fosters cooperation and coordination among Arctic states and observers, Indigenous People, and other Arctic communities on a range of regional issues. Through science diplomacy, the Council serves as a platform for technical collaboration and the creation of non-binding agreements among its member states. However, the decision-making process, which requires consensus from all eight member states (Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden, and the United States), can make policy outcomes more challenging to achieve[100].

In April 2015, the Council adopted the '**Enhanced Black Carbon and Methane Emissions Reduction: An Arctic Council Framework for Action**', prioritising key sources such as diesel engines, methane leakage, residential combustion, and wildfires[101]. The 2017 Fairbanks Declaration set a goal to cut black carbon emissions by 25%–33% below 2013 levels by 2025, with Arctic states already achieving a 20% reduction by 2018[102] but witnessing a rise in marine fuel consumption in past years, threatening overall progress[103].

Entry points:

- Establish a **new black carbon emission reduction target post-2025**.
- Encourage members and observer nations to **improve black carbon emission measurements and reporting** to take meaningful action to reduce emissions.
- Given that a significant portion of Arctic shipping involves routes to or from EU ports, the Arctic Council could advocate for stronger **inclusion of black carbon regulations in the next revision of the *Fuel EU Maritime Regulation***. Supporting EU efforts to reduce shipping emissions would promote coordinated action on black carbon.

3.1.2. Accelerating a clean energy transition in the Himalayas

Interventions focused on cleaner energy in the Hindu Kush Himalaya region can deliver a triple win for local climate, health, and sustainable development through investments in clean cooking, heating, and lighting solutions.

Residential and institutional biomass and coal burning for cooking, lighting, and heating are major health and equity issues, which also have significant climate impacts. Based on data from 2013, residential solid fuel burning and brick kilns together account for 45%–66% of the anthropogenic black carbon deposition in the Hindu Kush Himalaya region, which encompasses parts of eight countries (Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, India, and Pakistan)[104]. This deposition is responsible for as much as 50% of the accelerating glacier and snow melt in the Hindu Kush Himalaya mountains[105]. These glacial processes affect water resources in the downstream areas of the Indus, Ganges, and Brahmaputra River basins, home to 750 million people and providing fresh water, hydroelectricity, and agricultural irrigation. Given these severe climate impacts, a transition to clean energy is needed in all three residential sectors (cooking, lighting, and heating), which will also generate significant co-benefits for air quality and improved health outcomes in the region (as highlighted in Section 3.2 below).

Sectoral spotlight: Replacing diesel generators with off-grid solar or hydropower

Diesel generators are a relatively small source of black carbon emissions but with significant climate impact when used in close proximity of Himalayan and other cryosphere regions. Currently, they are used to power primary healthcare centres in remote locations, which exposes vulnerable populations to significant levels of air pollution and black carbon. Replacing diesel generator sets with off-grid solar (e.g. as the SELCO Foundation is doing with support from India's Ministry of Health and Family Welfare and the World Health Organization in India[106]) is a promising and scalable solution.

Entry points:

- Displacing diesel generators with hydropower, following the successful implementation of small hydropower plants providing reliable, low-cost electricity in rural areas of Bhutan and other South-Asian countries. India has an estimated potential of 21,133 MW from small hydropower plant projects across over 7,000 sites, with half of this potential located in its Himalayan states[107]).
- Continuing the expansion of off-grid solar in the region

Karawang, West Java, 07/30/2018 A worker of a limestone processing plant to put pargets to a traditional kiln.
Credit: Eriz Razak | iStock

3.1.3. Cleaner brick kilns in the Indo-Gangetic Plain

Increased financing and scaled training programmes for brick kiln owners and operators could support the transition to cleaner kilns, in addition to enforcement inspections.

Traditional brick kilns are a significant contributor to the regional economy, particularly within the informal sector where they provide local employment opportunities, but they are also a major source of black carbon emissions in the region. Concentrated mainly in the Indo-Gangetic Plain, traditional kilns worsen local air pollution, deplete fertile soil, and accelerate Himalayan glacier melt. Their inefficiencies highlight the need for modernisation and cleaner production methods.

In India, estimates from 2017 showed stack emissions of black carbon from brick kilns in India to be more than 100,000 tonnes/year, accounting for approximately 80% of all black carbon emissions from brick kilns in South Asia[108]. Brick kilns in India and South Asia largely operate in an unorganised manner. For instance, research from 2024 showed that 90% of brick kilns in the Delhi National Capital Region violate a density-based policy[109].

The Government has acknowledged the issue, and in 2022, the Indian Ministry of Environment, Forest, and Climate Change mandated that new kilns adopt either zig-zag or vertical shaft technology or use gas as a fuel[110]. Additionally, existing kilns were required to upgrade within 2 years. However, high conversion costs ($35,000–$50,000), limited financing, and a lack of skilled workers have slowed the progress. There is still potential for growth with better incentives and targeted support for the informal sector. Furthermore, there is a growing opportunity to transition to cleaner kiln technologies, such as zig-zag or more advanced systems, supported by government measures including emission limits, improved stack designs, and stricter regulations.

3.2. Prioritising black carbon in clean air and energy policy

Targeting black carbon as an air pollutant is key to improving global health and maximising climate benefits. This requires a focus on black carbon-rich sectors, not just particulate matter overall.

Black carbon is a major component of air pollution, an issue which is felt more acutely by the public than climate change in many parts of the world. Air pollution is often a larger driver of political will and government ambition than climate change.

AQM processes and frameworks worldwide typically focus on particulate matter as a whole rather than its components or characteristics (Table 3). As a result, clean air policies are often designed to reduce PM2.5 and/or PM10, and thus, some interventions can have limited effect on black carbon or their effect on black carbon is often unknown or unreported.

Prioritisation of efforts to reduce black carbon in AQM is needed to maximise climate benefits of these policy actions. Black carbon is the component of particulate matter with the largest negative impact on climate change. The amended Gothenburg Protocol already requests parties to prioritise black carbon-rich sources when delivering on their $PM_{2.5}$ commitments111 (Annex 2).

Overall, it is critical to maximise the black carbon reduction benefits of air quality measures and accelerate growing interest in addressing black carbon as part of the air pollution problem. Similarly, mitigation of black carbon emissions is a direct benefit of energy policies promoting an equitable and just transition to clean and modern energy for residential and institutional energy needs, especially among countries in the Global South. This can be achieved by embedding black carbon in national and sub-national AQM practices with a focus on addressing the following:

- Black carbon/$PM_{2.5}$-rich sources (such as heavy-duty vehicles, non-road machinery, gas flaring, waste burning, and agricultural burning)
- Continued reliance on black carbon-rich fuels (such as coal, diesel, oil, kerosene, charcoal, and wood).

Table 3: Effectiveness of climate and health regulation on selected aerosol or particulate matter types and components

Particulate matter type	Source characteristics	Health regulation effectiveness	Climate regulation effectiveness
PM_{10} (≤10 μm)	Coarse particles, relatively more natural (e.g. desert dust and sea salt) and mechanical (e.g. construction and road dust) sources, and less influenced by combustion processes	**Moderate:** Reducing PM_{10} improves respiratory health but is less crucial than finer particles	**Limited:** It is composed of many particles with varying climate effects.
$PM_{2.5}$ (≤2.5 μm)	Subset of PM_{10}, fine particles, relatively more combustion sources (e.g. fossil fuels and biomass burning), and includes secondary particles formed from the emissions of non-methane volatile organic compounds, SO_2, and NOx	**Very high:** Significant impact on reducing respiratory, cardiovascular, and other diseases and conditions.	**Limited:** It is composed of many particles with varying climate effects.
Black carbon	Component of $PM_{2.5}$, emitted from incomplete combustion of carbon-based fuels (e.g. wood, diesel, coal, and kerosene)	**High:** Part of $PM_{2.5}$ and independently linked to cardiovascular and respiratory diseases	**High:** Major climate forcer; reducing black carbon has strong short-term mitigation effects (also important to consider other aerosol types, e.g. organic carbon)
Ultrafine particles (<0.1 μm) or **Particle number** (/m^3)	Subset of $PM_{2.5}$ and emitted directly from combustion, high-temperature industrial processes, and chemical reaction from precursor gases	**High:** An emerging concern; it can penetrate organs; less studied but likely significant	**Moderate:** It is composed of multiple particles with varying climate effects, but it is a better proxy for combustion sources.

Source: Authors' compilation

3.2.1. Clean air policy in the road transport sector

The road transport sector offers opportunities to significantly reduce black carbon emissions through interventions that align well with broader AQM policies, such as low-emission zones, and decarbonisation strategies, such as electrification.

Diesel, particularly from heavy-duty vehicles, is the largest source of black carbon in the transport sector. Off-road vehicles and machinery (e.g. back-up diesel generators, road paving equipment, construction equipment, cranes, locomotives, ferries, and harbour boats) are also a key source[98].

As argued above, adopting a specific focus on black carbon (alongside existing focuses on all types of particulate matter) is crucial to achieving climate-relevant emission reductions in the road transport sector. For example, while commercial vehicle emission standards (e.g. EURO in the European area) or similar emission standards have successfully reduced particulate matter emissions, they do not always guarantee a proportional reduction in black carbon. Significant cuts in black carbon emissions were achieved only after particle number (a better proxy for black carbon) was regulated alongside particle mass. This shift from EURO V to EURO VI was a result of targeted advocacy by European Union civil society bodies, which pushed for black carbon and other emission standards beyond $PM_{2.5}$.

The push for electrification has rightly received significant funding in recent years. However, phasing out super-emitting diesel vehicles remains critical. Over the past decade, the Indian government has introduced policies to promote electrification, backed by significant financing and stricter emission standards. However, diesel use remains high, with electrification hindered by high costs and insufficient charging infrastructure. Strengthening voluntary scrappage policies for vehicles over 15-years old is essential. Additionally, on-road remote sensing to detect black carbon plumes can help identify super-emitters for repair or scrappage.

Country spotlight: Reducing emissions from off-road vehicles - Insights from China

In China, off-road diesel equipment, such as construction and agricultural machinery, accounts for over half of the particulate matter emissions from mobile sources and consumes more than one-third of the country's diesel fuel[112]. To address this, regulatory agencies in key regions have established timelines mandating the transition to zero-emission equipment, complemented by ongoing pilot projects. Numerous zero-emission models are already available in the market, and major manufacturers continue to unveil new prototypes[113]. This is part of an increasingly synergistic approach to air quality management and climate change mitigation. Notably, in July 2023, Stage 6b (largely equivalent to EURO VI) of the National VI emission standards for automobiles was implemented nationwide to promote the synergistic control of air pollutant and greenhouse gas emissions from vehicles[114].

An old steam tractor with smoke billowing plows a farm field
Credit: David Halgrimson | Adobe Stock

3.2.2. Clean energy policy in the residential sector

Effective energy policies that address black carbon emissions are crucial for achieving Sustainable Development Goal 7 (SDG7), as they promote clean, affordable, and sustainable energy solutions while improving public health and mitigating climate impacts.

National energy policies and plans, even when not focused on black carbon, can play a crucial role in reducing black carbon emissions. Here are some examples from the cooking, heating, and lighting sectors:

Residential Cooking: Residential emissions, especially from the cooking sector in low- and middle-income countries, account for a significant share of global black carbon emissions, alongside a heavy mortality toll and ill health from household air pollution. Residential energy policies in countries should promote a twin-track approach (gas and electricity) for household and institutional cooking, wherein a full transition to renewable electricity is not foreseeable in the near-term, and support continued reliance on biomass fuels only through the adoption of fully tested and ISO-certified improved efficiency stoves[115]. Gas options include renewable alternatives such as biogas from animal manure for rural areas and green or bio-liquefied petroleum gas (LPG) derived from municipal solid waste. Bio-LPG holds significant promise as it is fully compatible with existing LPG distribution and user infrastructure, but production is still at a nascent stage[116].

Residential Heating: Black carbon emissions from heating could be reduced by prohibiting the sale and use of oil- and coal-fired appliances and by promoting more stringent wood-burning appliance regulations in Global North countries, while supporting low- and middle-income countries in transitioning to cleaner heating alternatives. In the EU, for example, current ecodesign regulations have led manufacturers to design stoves that satisfy particulate matter standards, yet there is a missed opportunity to further reduce black carbon emissions. Data show that while new log wood stoves typically emit less particulate matter than old ones[117], they produce a higher relative amount of black carbon in $PM_{2.5}$ due to oxygen deficiency and sub-optimal burning temperatures, leading to incomplete combustion[118].

Residential Lighting: Kerosene wick lamps have been replaced by grid and off-grid solar lighting in hundreds of millions of households across Africa and Asia, cutting down both black carbon and CO_2 emissions in the process. Under the World Bank Lighting Africa / Lighting Global programmes, replacing kerosene lamps has avoided 24,000 metric tonnes of black carbon emissions since 2009[1]. In the past decade, 32 million high-quality off-grid solar lighting products were sold across Sub-Saharan Africa, providing clean lighting to over 400 million people[122]. This work is being scaled through Lighting Global, focusing on rural and remote homes. By 2030, 600 million more people could benefit from off-grid solar lighting, aligning with SDG7[122]. Additional investments are needed to shape the sector's evolution.

Women lighting a kerosene lamp
Credit: Nigel Bruce

Sectoral spotlight: Residential heating improvements in the Nordic region

REGULATIONS

Finland's National Air Pollution Control Programme introduces measures that aim to improve air quality by **reducing emissions from small-scale wood burning**[119], which is the largest source of black carbon in Finland[120]. To complement this programme, research is being carried out to develop emission-measurement methods and an emission-based eco-label for wood-sauna stoves.

Denmark has developed protocols and conducted black carbon emission testing for heat stoves to promote ecolabelling and other voluntary black carbon standards for heat stoves. It placed a **ban on the installation of oil-fired boilers and natural gas** boilers in new buildings from 2013 onwards[121], and the **existing electrical heating tax was reduced to the EU minimum rate**, incentivising the transition to renewable electricity over fossil fuel energy sources.

Sectoral spotlight: Financing mechanisms for the adoption of clean residential energy

FINANCE

There are a multitude of strategies that support a transition to cleaner energy in the residential sector, especially across Global South countries. However, as highlighted in Section 2, raising finance to support these strategies can be a challenge.

Entry points:

- **Tax structure regarding various fuels and technologies:** Through energy policies, governments can use taxes and/or subsidies to incentivise the use of cleaner energy that produces lower amounts of black carbon emissions. They can also penalise and disincentivise the use of energy sources that significantly contribute to black carbon emissions. While bans on specific types of polluting fuels and energy sources are often difficult to enforce and provide mixed results, targeted value added taxes and subsidies have been generally successful in influencing consumer behaviour and energy usage.
- **Carbon markets:** Facilitate the rollout and demonstration phases of an updated black carbon methodology associated with metered and measured energy cooking devices (under development by the Modern Energy Cooking Services programme for release in 2025), which can constitute an add-on to current carbon accounting to incentivise investment in the cleanest cooking technologies. Philanthropic support could contribute to financial backing, in-kind contributions, and convening opportunities.

3.2.3. Targeting informal, locally relevant industries contributing to air pollution

Actions to target black carbon emissions related to informal, mostly unregulated industries could result in significant impacts for women and marginalised populations.

Targeting informal, locally relevant industries that contribute to air pollution, such as commercial street cooking and fish smoking in coastal communities of Africa and South and Southeast Asia, is important because these sectors often operate outside regulatory frameworks, exacerbating $PM_{2.5}$, black carbon, volatile organic compounds, and other harmful pollutant emissions[123]. Intervening in these informal industries and operations by promoting cleaner technologies that align with local needs and practices can reduce exposure to health-damaging pollutants for vulnerable populations. Addressing these sources not only improves air quality and public health but also supports climate goals by mitigating significant sources of SLCPs that are often overlooked.

Outdoor haze from fish smokeries in Cameroon
Credit: Nigel Bruce

Fish smoking
Credit: Nigel Bruce

Sectoral spotlight: Targeting fish-smoking informal industry in West Africa

FINANCE

Traditional biomass-fuelled smokers contribute significantly to air pollution across West Africa (where an estimated 6 million fish smokers work[123]). They are important as a livelihood for coastal communities, but the inefficiency of these kilns exacerbates air pollution, black carbon emissions, and environmental degradation. The health risks of emissions from the fish-smoking industry disproportionately affect women, who make up the majority of workers in the sector.

Entry point:

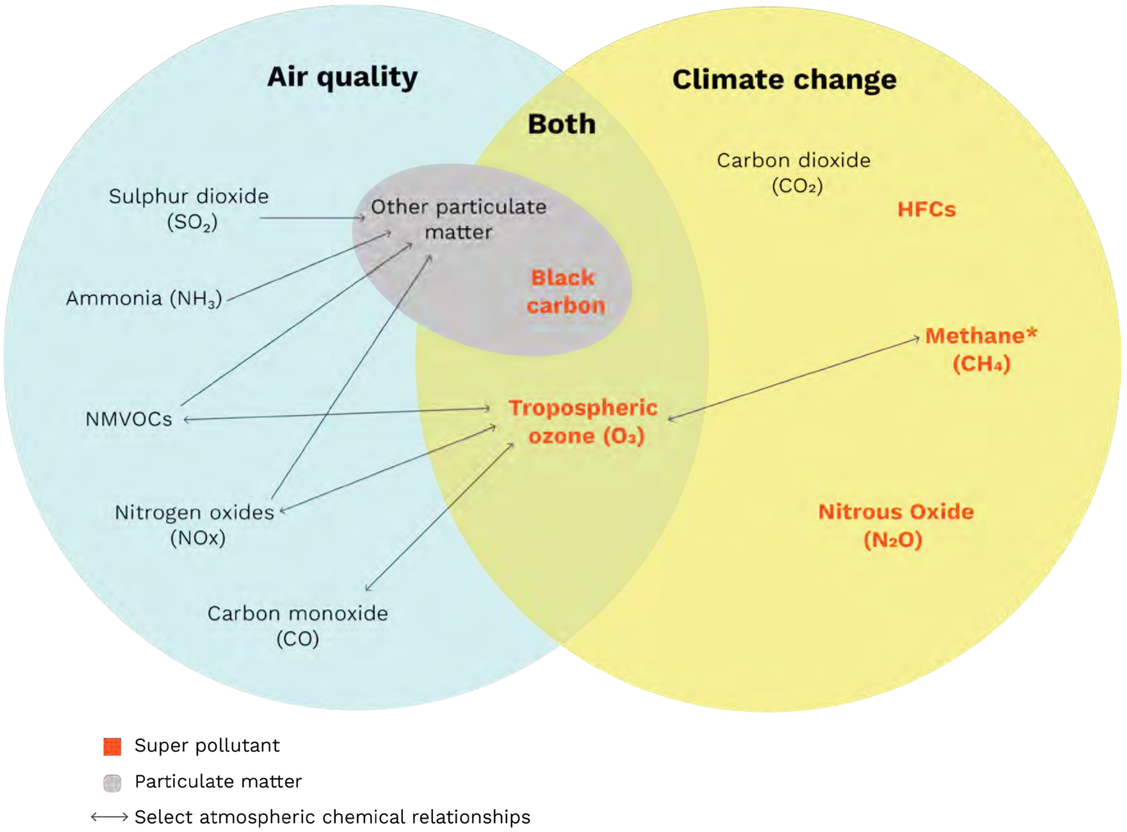
- Adoption of improved technologies along with training: Transitioning to improved kilns and reducing reliance on biomass burning can significantly lower health risks from smoke exposure while boosting economic stability by cutting fuel costs and enhancing fish quality. To achieve this, financing plans must be paired with training programmes for fish smokers.

3.3. Coordinated action on super pollutants

By coordinating action across all super pollutants, we can deliver significant black carbon emission reductions as part of a package of measures to mitigate near-term warming.

It has become increasingly evident that mitigating climate change pre-2050 will require dedicated action on super pollutants[124] (Figure 10), a group that is increasingly referred to as being responsible for the 'other half of warming'[125]. While methane has been at the fore of the conversation[124], concerted action across all super pollutants (tropospheric ozone, nitrous oxide, hydrofluorocarbons, methane, and black carbon), is needed. This will require interest, commitment, and finance for priority interventions across countries, particularly those with high levels of black carbon and other co-pollutant emissions. Some promising areas for particular attention are outlined below.

Figure 10: Visualisation of the super pollutants, their typical categorisations, and key relationships with select other air and climate pollutants



3.3.1. Combined action on black carbon and methane in the waste and agricultural sectors

Waste sector: The waste sector produces both black carbon and methane emissions. This sector produces about 4% of black carbon emissions globally[25] and contributes to about 18% of the total global anthropogenic methane emissions[126]. Segregating waste (organic and dry waste) at source, effective landfill management, and recycling result in black carbon emission reduction from open waste burning and minimise methane emissions from landfills. A Clean Air Fund and Global Methane Hub-funded project with GAYO in Ghana is a key example of effective waste segregation and recycling, for which GAYO was awarded the 2024 Earthshot Prize[127].

Sectoral Spotlight: Tackling electronic waste (e-waste)

According to the Global E-waste Monitor 2024, African countries generate around 2.9 million tonnes of e-waste annually, yet less than 1% of this is formally collected and recycled1[28]. E-waste poses significant health risks, particularly to vulnerable groups such as children and pregnant women. Workers in the e-waste sector, especially those recovering valuable materials such as copper and gold, may be exposed to over a thousand hazardous substances1[29].

Nigeria's informal e-waste sector plays a significant role in black carbon emissions through open burning, commonly used to extract valuable metals. This method is a major source of pollution, contributing to poor air quality and associated health risks. With the e-waste recycling infrastructure being inadequate globally, trafficking is increasing through sophisticated smuggling tactics. The Basel Convention aims to regulate this[130], but non-participation by major exporters such as the US hinders progress. Informal recycling also exposes vulnerable populations to severe health risks[131].

Entry points:

- **Reduce the open burning of e-waste (specifically the removal of insulation on wiring and other metallic components that have substantial recycling value):** African governments can achieve this policy goal by creating incentives that make formal recycling centres more attractive than unregulated and hazardous methods, which would have a direct effect in addressing the environmental and health concerns associated with e-waste burning.

Other approaches include creating an **Extended Producer Responsibility** scheme for manufacturers and establishing **buy-back programmes**, through which individuals can sell e-waste to licensed recycling centres.


Electronics waste in Ghana
Credit: Fairphone | Climate Visual

Agriculture: The agricultural sector contributes significantly to global methane emissions, and agro-residue burning can emit significant black carbon emissions[132]. Promotion of natural and sustainable agricultural practices such as mulching, no-tillage farming, crop rotation, and agro-forestry can reduce both methane and black carbon emissions by ensuring effective management of crop residue and improving soil health. In addition, post-harvest activities, such as eliminating open burning in agriculture through effective enforcement, capacity building for farmers, and providing alternative uses for stubble, directly reduce black carbon emissions.

3.3.2.Developing guidance to jointly tackle black carbon and tropospheric ozone

As a product of incomplete combustion, black carbon is co-emitted with carbon monoxide and volatile organic hydrocarbons, which along with methane are key precursors of tropospheric ozone. Tropospheric ozone is another potent super pollutant that has contributed 0.23°C of warming to date[4].

Climate mitigation through tropospheric ozone is as overlooked in climate strategy as black carbon[133]. Designing AQM plans that tackle black carbon and tropospheric ozone offers a win–win for climate and health and aligns strongly with actions outlined in Section 3.2.

3.3.3. Promoting the uptake of biogas to reduce black carbon, methane, and nitrous oxide

Biogas can help reduce methane, black carbon, and nitrous oxide emissions while producing cleaner fuel for cooking and lighting[134]. A family-size biodigester installation can replace the use of biomass for cooking in rural settings, where animal manure is abundant[135] (e.g. avoiding emissions up to 120 Mt CO_{2eq} per year over India)[136]. CCAC estimates suggest that effective manure management by well-maintained biogas plants can reduce global greenhouse gas emissions by 10% and deliver 50% of the Global Methane Pledge by 2030[134]. In addition, bio-slurry, the final waste product from biogas processes, is essentially an organic fertiliser that can significantly reduce the cumulative nitrous oxide emissions from 17% to 25% from soil[137].

4. TAKING AN EQUITABLE APPROACH TO TACKLING BLACK CARBON

Solutions for black carbon emission reductions must take into account equity and justice to ensure that the needs of the most affected people and communities are central to policy and finance decisions.

As highlighted throughout this report, the negative impacts of black carbon disproportionately affect countries in the Global South, as well as marginalised populations in both the Global South and North. These populations, which are most heavily affected by the negative impacts of these emissions, have the least power to reduce them. Thus, an equitable and just approach to reducing black carbon would ensure that such sections do not bear the primary burden of black carbon mitigation.

4.1. Equity and justice in the black carbon context

Each of the barriers to addressing black carbon outlined in Section 2 have contributed to the perpetuation of inequitable outcomes, particularly for regions, countries, and communities most affected by the climate and health impacts of black carbon emissions. These communities are also often excluded from key decision-making fora. As awareness of the importance of black carbon began to grow decades ago, so did concerns from some countries in the Global South that a focus on black carbon would take attention away from the need for Global North countries to decarbonise. These concerns, expressed by heavily affected countries in the Global South, reflected that the overwhelming responsibility for historic CO_2 emissions sits with the Global North and that the root cause of most black carbon emissions in many Global South countries is related to poverty rather than consumer choices.

As outlined in Section 1, in many Global South countries, the residential, transport, industrial, and waste burning sectors constitute the largest source of black carbon emissions—the root cause of which is often high levels of livelihood struggles. Residential sources of emissions include the fuels used for cooking, lighting, and heating homes, responsible for 35% of global black carbon emissions (Figure 2). Most citizens in Global North countries have access to clean cooking technologies (advanced electric and gas appliances), whereas people in the Global South often do not. Only 10% of the population in Sub-Saharan Africa, 21% in Southeast Asia, 27% in South Asia, 36% in East Asia, and 56% in Latin America and the Caribbean have access to clean/ modern cooking solutions[138]. According to the International Energy Agency, total investments in the clean cooking sector are still far short of the estimated $8 billion needed to achieve universal access to clean and modern energy for all by 2030, especially in Sub-Saharan Africa[139].

This illustrates a vicious circle of inequity: high levels of poverty in the Global South are both a root cause of black carbon emissions and the reason why countries have limited ability to finance black carbon solutions on a mass scale. This is compounded by high levels of debt distress, which further diminishes the availability of resources to tackle black carbon emissions, which in turn is driven by an unequal global, political, and economic system that disproportionately benefits Global North countries.

Inequities also persist within countries, where even in advanced economies, there is evidence to show that the poorest and often racialised communities face the highest exposure to high black carbon-rich sectors. Studies conducted in Boston, US, show that exposure to black carbon is directly correlated with lower levels of socioeconomic and racial privilege, controlling for household income level[140]. Research in the US has shown that the negative impacts of gas flaring fall disproportionately on marginalised communities, in particular People of Colour (who reside within 5 km of an oil or gas well)[141]. Similarly, Norway has higher black carbon emissions in the northern Barents Region, which has the highest Indigenous population[142].

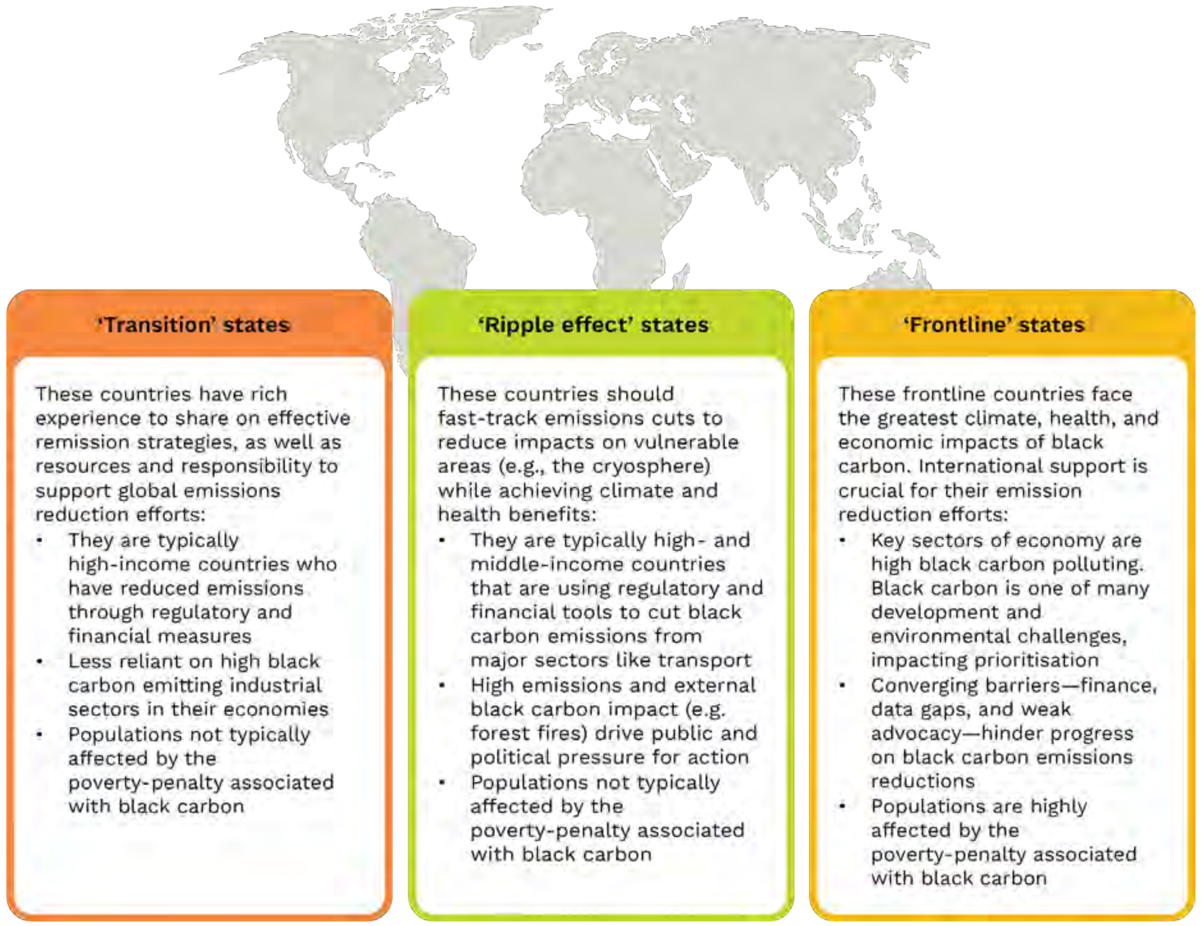
Including affected communities in decision-making.

Indigenous communities in the Arctic are significantly impacted by black carbon emissions, primarily because of increased shipping and oil spills. Black carbon accelerates ice melt and rising sea levels, expanding Arctic shipping routes and extending the operational season for vessels. This increased activity threatens Indigenous communities by restricting access to ancestral lands and vital resources essential for their livelihood, health, and food security[143]. For shipping, in particular, it disrupts fragile ecosystems that these communities depend on for traditional practices such as hunting, fishing, and harvesting. The expansion of industrial extractive industries also forces them to adapt or relocate, transforming their social and economic way of life[144]. Despite global conservation efforts, Indigenous voices at forums since COP26 emphasise the rising discord due to economic pressures and the need for sustainability in the Arctic[145].

4.2. Adopting equitable approaches to reducing black carbon emissions

Given the above context, an equitable approach to reducing black carbon emissions requires countries to adopt differentiated roles based on their income level, geographical location, and the existence of black carbon-rich sectors in their economies. These factors affect their experience of black carbon impacts at a domestic level as well as their ability to finance and implement effective policy responses. Figure 11 illustrates how these roles could be determined. Black carbon 'transition' states include countries best placed and most motivated to play a leadership role to promote international cooperation on black carbon emission reduction. Black carbon 'ripple effect' states include high- and middle-income countries with policy and financial tools in place to curb black carbon emissions and thus have the greatest opportunity for action. Black carbon 'frontline' states face the most barriers and need the maximum financial support to reduce emissions.

Figure 11: Determining country roles and responsibilities in reducing black carbon emissions



Tackling root causes: Interventions that address fundamental issues linked to energy poverty, which leave communities with limited options for accessing affordable, clean alternative energy sources, will have higher chances of long-term success. For example, the World Bank's Lighting Africa and Lighting Global programmes have supported access to affordable off-grid solar lighting since 2009, displacing kerosene wick lamps and eliminating the emissions of black carbon from this source across several Global South countries[122]. There are now over 99 different solar devices that are quality-certified by Lighting Africa[146]. This variety enables access to modern energy services for households with different income levels.

Country highlight: The Canadian Clean Energy for Rural and Remote Communities programme

Equity considerations were a driving factor behind the Canadian Clean Energy for Rural and Remote Communities programme, which moves communities away from relying on diesel generators and funds Indigenous-owned clean energy projects that deliver significant community benefits. An example is the 2.35 MW solar project in Fort Chipewyan, Alberta. This project unites three Indigenous communities under Three Nations Energy, an organisation that has been leading efforts on community energy planning using solar in remote cabins and replacing diesel with biomass, leading to further sustainable projects and community pride[147].

The Canadian government ensured that the appropriate infrastructure was in place to support communities as they led the transition projects. For example: The programme also supported projects aimed at empowering Indigenous Women and Youth to become future clean energy leaders (e.g. the Shining Lights: Energy Literacy and Language project in the Northwest Territories, with engagement across 22 communities[148]).

5. RECOMMENDATIONS FOR ACTION

Black carbon has fallen through the cracks of climate and air quality strategies. Coordinated and urgent action is critical to unlocking immediate climate, health, and social justice benefits.

Black carbon threatens both human and planetary health, yet its emissions remain largely untracked and unregulated. Often overlooked in climate and air pollution policies, black carbon reduction strategies remain under-resourced despite the potential to accelerate integrated climate and clean air action. The good news is that existing technologies and established practices can cut emissions, unlocking climate, health, and justice benefits while driving new commitments and funding for solutions. Recommendations for action are broken down here as (i) the three immediate priorities to maximise the impact from tackling black carbon now and (ii) the steps that policy makers, businesses, and other stakeholders can take to overcome barriers to action.

Tackling black carbon effectively means reorienting action to where we can unlock the greatest combined climate and health benefits:

1. Reduce black carbon in cryosphere regions, including the Arctic, Himalayas, and Andes regions

Black carbon accelerates snow and ice melting in a way that is distinct to any other pollutant. We recommend urgent policy and regulatory reforms to rapidly reduce black carbon emissions that affect highly vulnerable cryosphere regions.

- Member states of the Arctic Council should commit to a new collective black carbon emission reduction target post-2025.
- The IMO should implement urgent reforms to address long-standing weaknesses in the regulation of the shipping industry and halt the rapid increase in black carbon emissions from international shipping, which heavily impacts the Arctic.
- Policy makers and financial institutions should support interventions that accelerate the clean energy transition in the Himalayas and other cryosphere regions, with a core focus on cooking, lighting, and heating, and support the transition to cleaner brick kilns.

As we continue to better understand the local climate effects of black carbon and its co-pollutants on monsoons, extreme rainfall, drought, and extreme heat, similar local and regional initiatives on black carbon must be applied across other most affected regions.

2. Prioritise black carbon in clean air and energy policies

Policies targeting air quality, especially $PM_{2.5}$, often overlook the distinct benefits of reducing black carbon-rich emissions versus other particulate sources. To maximise climate, health, and environmental gains, policy makers at all levels should explicitly prioritise black carbon reduction within clean air and energy policies. For example, road transport regulations such as EURO VI focus on particle number, a better proxy for black carbon. Similarly, the Gothenburg Protocol urges parties to target black carbon-rich sources and should go further through its ongoing revision process to set black carbon emission reduction commitments. Greater awareness among policy makers and stronger prioritisation of black carbon in clean air and energy strategies are essential for meaningful progress.

3. Take coordinated action on super pollutants

Super pollutants including black carbon are responsible for half of the global warming witnessed to date and present the world's best opportunity to secure a near-term 'win' against climate change. Policy and decision makers must build on the momentum and progress achieved from a strong focus on methane in recent years and move towards a more integrated and coordinated approach to super pollutants as an issue.

This includes focusing on sectors with high levels of black carbon and other super pollutant emissions, for instance, holistic waste management that reduces both open burning and landfill emissions and the promotion of natural and sustainable agricultural practices that reduce pre-harvest methane emissions and post-harvest crop burning. At the forthcoming COP30 negotiations in Brazil, governments and other funding bodies should recognise the urgent need to tackle all super pollutants and commit the funding needed to make progress and deliver holistic solutions.

Glacier melting
Credit: Gevende | iStock

Supporting actions in these areas and tackling the key barriers that have stopped progress to date:

1. **A global caucus of countries committed to tackling black carbon is needed.** This group must be aware of some of the political barriers that have stalled progress to date and work tactically with intergovernmental, non-governmental, and private sector stakeholders to advance progress, especially in cryosphere regions and other affected geographies.

- **Show international leadership by elevating black carbon and other super pollutants in global climate processes**, filling a gap in global climate strategy, spotlighting opportunities for fast climate mitigation, and drawing links to the health and economic benefits of clean air:
  - Push for black carbon and other super pollutants to be robustly included within UNFCCC processes and reporting, building on the outcome of the UN's 2023 Global Stocktake that calls on parties to contribute to an accelerated and substantial reduction of non-CO_2 emissions by 2030. Entry points include discussions through the Bonn Research Dialogue or Mitigation Work Programme.
  - Champion the development and uptake of the 2027 IPCC Methodology Report on Inventories for SLCFs[40]. Countries that already have sophisticated and greenhouse gas–air quality-integrated emission inventories should see themselves as 'early adopters'.
  - Integrate specific black carbon emission reduction targets as part of the next NDC development and submission. Targets on black carbon should be ambitious and include measures in addition to those targeting CO2 and other greenhouse gases. Additionally, countries should outline how they will implement and fund the delivery of the black carbon targets and measures in their NDCs, including through development cooperation. They should also design and tailor policies suited to local contexts and emission sources, leading to implementation at national and sub-national levels.
- **Advance the development of binding and enforceable international frameworks on black carbon emission reduction** to address the gaps in the existing regulatory frameworks that have, to date, failed to deliver effectively in some of the highest-emitting industries.
  - Adopt, support, and strengthen regional and airshed approaches to tackling air pollution and adopt specific mandates on black carbon. Opportunities include setting binding and ambitious emission reduction commitments on black carbon through the Gothenburg Protocol revision process (for countries in the UN Economic Commission for Europe region) or spotlighting black carbon in other regional programmes such as the UN Economic and Social Commission for Asia and the Pacific's Regional Action Plan on Air Pollution and the UN Environment Assembly-mandated Africa Clean Air Programme.
  - Develop and strengthen regional agreements in areas most affected by black carbon. For example, the Arctic Council must set a new and ambitious collective target on black carbon post-2025, following the Fairbanks Declaration.

2. **National and sub-national governments should take an integrated, multi-pollutant approach to climate change and air pollution**, with specific focuses on super pollutants including black carbon.

- Develop black carbon emission inventories to help policy makers quantify emissions, inform black carbon reduction strategies, and track progress in emission reductions over time. This is an essential first step for effective national-level action, alongside existing country inventories on greenhouse gases and inventories measuring health-related pollutants.
- Undertake exposure assessments and source apportionment for black carbon in relevant jurisdictions to better protect vulnerable population segments from the health effects of short- and long-term exposure to black carbon sources.
- Enable effective cross-government collaboration to facilitate an integrated approach to openly share and monitor black carbon and other super pollutants to inform both air quality and climate change mitigation plans.
- Engage in the Climate and Clean Air Coalition to share best practices and learnings on tackling black carbon and other climate super pollutants.
- Accelerate the move to cleaner energy sources by shifting away from the use of dirty fuels, transitioning away from harmful burning, and building ministerial coordination on the implementation and enforcement of stricter emission standards across all air pollutants and super pollutants, including black carbon.

3. **Funding bodies should rapidly scale up funding for tackling black carbon**. Recent commitments on methane highlight how momentum behind tackling super pollutants can catalyse significant increases in finance. A step change in funding towards black carbon science and solutions is needed.

- **International development funders should rapidly scale up funding for black carbon reduction efforts**. Development funders allocated just $3.6 million per year on average in development funding for explicitly tackling black carbon emissions between 2018 and 2022[82]. This leaves an opportunity for governments, development banks, and philanthropy to step into this space, massively scale up the available funding, and leverage this investment for a resource mobilisation campaign to advocate for other donor governments to begin or expand support to black carbon emission reduction.
    * Identify and implement opportunities to scale up financing for air quality and climate programmes that target black carbon-rich sectors (see Section 3), incorporating black carbon in financial instruments.
    * Mitigate risks associated with black carbon solutions in Global South countries by fostering new financial mechanisms to reduce risks and burden on borrowers and improving access to finance for black carbon mitigation projects, while highlighting the economic benefits and addressing the overall low financing of black carbon reduction efforts.
- **Fund targeted scientific research** on black carbon to reduce observation and modelling uncertainties and build the evidence base, with a focus on the Global South, cryosphere regions, and regions most affected by black carbon. New investment in research will help move towards a greater scientific consensus on black carbon, which in turn may help unlock more financial and political action.
    * Develop improved emission factors and robust black carbon emission inventories including the development of local emission factors for black carbon and co-pollutants.
    * Increase funding for observational studies and continuous monitoring networks and make data openly available in real time, where possible.
    * Support global and regional-scale modelling studies, especially focusing on scenario analysis for understanding the mitigation impact in black carbon-rich sectors over sensitive ecosystems and climate tipping points.Support improvement in parametrisation of black carbon in Earth system models to better represent black carbon aging and morphology.
    * Build the evidence base on black carbon's health impacts, with a view towards informing the World Health Organization Air Quality Guidelines to provide updated policy advice and guidance on tackling black carbon.

4. **Businesses must show leadership on climate and health by reporting on black carbon and other super pollutant emissions in their value chains**. Guidance is available on how to report on black carbon and other emissions alongside greenhouse gas emissions[149,150]. Multinational companies can follow the lead of organisations in the World Economic Forum Alliance for Clean Air[86] on reporting and acting on these emissions, unlocking a new area for corporate sustainability.

Brick kiln Pakistan Asia
Credit: Sakhan Photography | Adobe Stock

ANNEXES

Annex 1: Methodology underpinning black carbon emission calculations and impacts

The underlying data and assumptions to generate the data presented in this report (see Section 1) are described below.

A1.1 Black carbon emission calculations

Base emissions: The base simulation emissions use Community Emissions Data Systems (CEDS)[25,151] anthropogenic emissions and the Global Emissions Database (GFED)[26] v4.1 for the year 2022 (at the country and sector levels). Emitted pollutants include sulphur dioxide, nitrogen oxides, ammonia, primary organic aerosols, total primary $PM_{2.5}$, non-methane volatile organic compounds, carbon monoxide, and methane, along with black carbon.

Experiments: A reduced-form source-receptor model (TM5-FASST) developed by van Dingenen et al.[27] is used to calculate the change in concentration at a receptor (country or region) due to reductions in source emissions. Pollutant concentrations are affected by emissions, wind transport, dry and wet deposition (onto surfaces and through precipitation), and chemical reactions. These processes are simplified in reduced-form models, which can have consequences in predicting impacts for large emissions perturbations. Using the FAst Scenario Screening Tool (FASST) (see https://tm5-fasst.jrc.ec.europa.eu/), seven experiments for each of the sectors listed below are conducted: energy production (ENE), industry (IND), transport (TRA), residential cooking/heating (DOM), waste management and incineration in landfills (WST), forest and grassland fires (FORESTS), and agricultural waste burning (AWB).

For a sectoral experiment, the base emissions for the specific sector are set to zero. This implies that all species emissions, including gaseous precursors, ozone precursors, and primary $PM_{2.5}$ emitted from the sector, are set to zero.

Region and sector classification: The countries are classified into working regions based on TM5-FASST regions and UNDP's country classification, when the two overlap. Some world regions (e.g. the Middle East, Central Asia, Southeast Asia, and Australia) were excluded owing to a lack of data for estimating Arctic warming sensitivity and precipitation change or because of lower black carbon emissions.

Primary activities are combined into common sectors, which include industry, energy, transport, residential, waste, forest fires, and agricultural residue burning. For example, we have not included 'agricultural non-combustion activities' (e.g. fertiliser, manure management, and soil dust) or non-carbonaceous primary particulate emissions from power plants and industries (e.g. fly ash or metals). In the transport sector, data on emissions from shipping and aviation were not available and have not been included.

A1.2 Underlying assumptions informing the black carbon impact analysis

The assumptions underlying Figure 4 by the category of impact are summarised below.

Pollution reduction, health benefits, and global temperature change: The FAAST model assesses not only pollution reduction but also the associated impacts on human health and climate. It evaluates mortality rates resulting from air quality improvements, specifically by quantifying the reduction in premature deaths due to lowered pollutant exposure. Additionally, the model estimates changes in the global mean temperature relative to CO_2 emissions using the Global Temperature Change Potential (GTP20), which accounts for the warming effect of black carbon and other short-lived climate pollutants over a 20-year time frame[v].

In terms of the modelled premature mortality, the results presented in Figure 4 uses the 2019 Global Burden of Disease data[152,153] and refers to ambient $PM_{2.5}$ only, i.e. it does not include the mortality attributed to household air pollution or desert dust (both particularly relevant for the African continent).

Arctic temperature impacts: The warming effect of black carbon is particularly significant in the Arctic owing to its ability to absorb sunlight and heat up the surrounding air and snow-covered surfaces[89]. To estimate how reducing black carbon emissions impacts Arctic warming, the emission reductions are multiplied by a sensitivity factor (K/[Tg/year]) derived from Sand *et al.*[154]. This factor represents how much the Arctic surface temperature would decrease per unit of black carbon emissions reduced. By applying this method, the benefits of emission cuts from specific sectors and regions can be quantified in terms of their contribution to slowing Arctic temperature rise. Sand *et al.*[154] observed that emissions from Asian nations are the largest contributors to Arctic warming due to the vast quantity of black carbon they release. However, the Arctic is particularly sensitive to emissions from certain activities, such as gas flaring from Arctic nations. Although these activities emit smaller quantities of black carbon, their proximity to the Arctic region causes a disproportionately high impact on local warming per unit of emissions.

v Other development benefits such as change in crop yields are also tracked by the model.

Precipitation changes: The effects of black carbon reductions in India, Europe, and the USA on monsoon precipitation over South Asia (June-September) and annual precipitation over Europe and North America, respectively, are determined using the long-term model output (100-140 years of monthly precipitation values) from the Community Earth System Model (NCAR-CESM1) presented in Westervelt et al. (2018)[164]. The precipitation response is the difference in precipitation from the scenario run (zeroing out black carbon in India, Europe or the USA), and a control experiment with baseline (no reduction) black carbon emissions. The average change (scenario-control) in the precipitation over the long term helps us estimate how emission reductions lead to shifts in precipitation, particularly over monsoon-affected regions, which are highly sensitive to changes in atmospheric pollutants.

Limitations of the model and approach used: Pollutant concentrations are affected by emissions, wind transport, dry and wet deposition (onto surfaces and through precipitation), and chemical reactions. These processes are simplified in reduced-form models, which can have consequences in predicting impacts for large emissions perturbations. Another important limitation of TM5-FASST_v0 is that it relies on data from a single meteorological year and source–receptor relations from one chemistry-transport model, with fixed fields for natural $PM_{2.5}$. The evaluation by van Dingenen et al.[27] showed that non-linearity effects in $PM_{2.5}$ and O_3 metrics generally cause higher bias for stringent emission reductions (towards −80% and beyond) than for strong emission increases relative (+100% and beyond) to the base case. However, the impacts remain within acceptable limits (30% biases between CTMs and FAAST) due to the low weight of uncertainty in low pollutant levels (below threshold) from strong emission reductions in exposure–response functions.

Annex 2: Frameworks for regulating black carbon emissions

Currently, there is no global agreement or framework specifically regulating black carbon emissions. However, various regional and sectoral policies acknowledge black carbon either as a component of fine particulate matter ($PM_{2.5}$) or as a distinct pollutant. One key agreement in this context is the revised Gothenburg Protocol under the United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (LRTAP)[155].

A2.1 The Gothenburg Protocol

The Gothenburg Protocol, established in 1999 under the UNECE LRTAP Convention, aims to reduce air pollution and combat acidification in participating countries111. In 2012, the Protocol was amended to include fine particulate matter and explicitly recognise black carbon as a component of $PM_{2.5}$[155]. This amendment, which came into force in 2019, marked the first binding international agreement to target $PM_{2.5}$ emissions while acknowledging black carbon's climate impact. Under the Protocol, ratifying member states must implement domestic policies to achieve emission reduction targets. Additionally, the Convention's Long-term Strategy for 2020–2030 emphasises the importance of reducing black carbon emissions, further reinforcing the Protocol's role in addressing both air pollution and climate concerns.

In December 2023, the UNECE LRTAP Executive Body agreed to further revise the Gothenburg Protocol, with the updated version expected by the end of 2026[156]. One of the seven priority areas for revision is enhancing efforts to reduce black carbon emissions. Strengthening black carbon-specific targets and integrating black carbon as a key factor in AQM under the Protocol could set a strong precedent for other regional air pollution agreements. This revision presents an opportunity to refine policies and encourage broader international action on black carbon mitigation.

A2.2 Other agreements and initiatives

Below is a list of other agreements and opportunities to regulate black carbon emission reductions:

- The non-binding Arctic Council 2015 framework for action on '*Enhanced black carbon and methane emissions reductions*' lays out a common vision for Arctic States, with an enhanced ambition to reduce black carbon emissions at the national level through the development of national action plans[101]. This sits alongside the *Fairbanks Declaration* from 2017, which recognises the effect of black carbon on human health and includes an aspirational collective goal to reduce black carbon emissions by at least 25%–33% below 2013 levels by 2025[102]. The European Union supports the Arctic Council's target and encourages all Arctic states to reduce black carbon emissions.
- The 2016 Global Strategy to Introduce Low Sulfur Fuels and Cleaner Diesel Vehicle is the first global roadmap to reduce $PM_{2.5}$ and black carbon emissions from the global on-road diesel fleet by over 90%[157]. The strategy is said to have major health and climate benefits through the reduction of short-lived climate pollutants.
- *The National Emission Reduction Commitments Directive*, adopted by the European Union in 2016, established national emission reduction commitments for EU Member States. It requires Member States to report on five key air pollutants, including $PM^{2.5}$, and encourages countries to report on black carbon emissions if data are available. These reduction commitments align with those made by Member States under the amended Gothenburg Protocol[158].
- The European Union's April 2024 *Ambient Air Quality Directive* includes a special emphasis on black carbon air pollution.
- *The Regional Air Quality Action Plan* (2022–2025), developed by the Intergovernmental Network on Atmospheric Pollution for Latin America and the Caribbean, is a regional cooperation initiative aimed at tackling air pollution. It acknowledges the impact of black carbon emissions and the associated health and climate benefits of reducing emissions[159].

- *The African Ministerial Conference on the Environmental (AMCEN) 17th Session* (2019) called for fast action on short-lived climate pollutants, including black carbon for climate mitigation[160].

Other national initiatives focus on $PM_{2.5}$ and PM_{10} more broadly without directly mentioning black carbon; however, they target black carbon-rich sources. An example includes the National Clean Air Programme (NCAP), launched in January 2019 by the Government of India, which aims to tackle air pollution across the country[161]. Initially targeting a 20%–30% reduction in PM10 levels by 2024 using 2017 as the baseline, the programme's timeline was extended in 2022 to achieve a 40% reduction by 2026. The NCAP focuses on cities, and efforts towards monitoring, mitigation, and financing often include residential emissions, which are a large source of black carbon in India.

Annex 3: Impact indicators methodology for selected interventions

The impacts for the interventions presented in Table 2 and Table A4 have been estimated through a semi-quantitative and qualitative approach.

The following indicators have been used:

- *Black carbon emissions reduction potential:* The magnitude of emissions and potential for emissions reduction has been assessed from each sector/sub-sector (e.g. transport, residential energy etc.) using CEDS emission inventory (2022)[25], as well as local/regional emission inventories for some selected black carbon sources (e.g. https://www.ncapcoalesce.iitb.ac.in/resources/smog-india-emission-inventory/).
- *Tipping points:* The potential impact of an intervention on regional tipping points was assessed through a literature review and the TM5-FASST analysis[27]. Tipping points considered include faster warming of cryosphere regions, melting of snow, ice and glaciers in Arctic, Himalayan, Andes etc., and shifts in monsoon patterns in South Asia and West Africa.
- *Short-term climate impacts:* The near-term climate response of the interventions was assessed by estimating the fast (i.e. 10–20 years) climate response of the interventions. Information has been collated from a literature review, the TM5-FASST modelling for GWP20, and the black carbon/organic carbon ratio of each intervention (based on data availability). For broader sectors such as residential and transport, the global and regional mean temperature response over 10 years (following one year of present day [2014]) was also analysed based on the IPCC AR6[4].
- *Long-term climate response:* The long-term climate response of the interventions was assessed based on the associated changes in emissions of CO_2 and other greenhouse gases. The source contribution of CO2 from black carbon rich-sources has been analysed, alongside the potential for CO_2 emission reduction from the intervention and considering the global and regional mean temperature response over 100 years (GWP100), following 1 year of present day (2014) emission analysis by IPCC AR6[4].
- *Air pollution and health benefits:* This indicator focuses on the impact of interventions on $PM_{2.5}$/black carbon emissions and associated reduction in exposure to air pollution, considering associated health effects and proximity to populated areas. Estimated impacts have been evaluated through a literature review.

The different interventions' impacts have been evaluated through a 4-point rating scale described in Table A3 below.

Table A3 - Impacts categorisation and meaning of colour coding

Impacts	Colour classification
Tipping points	**Dark green** – High positive impact on mitigating tipping points **Light green** –Moderate positive impact on mitigating tipping points **Amber** – Low positive impact on mitigating tipping points
Black carbon emissions reduction potential	**Dark green** – Very high black carbon emissions reduction potential **Light green** – High black carbon emissions reduction potential **Amber** – Moderate to low black carbon emissions reduction potential
Impact on short-term climate warming	**Dark green** – High potential to reduce short-term climate warming **Light green** – Medium potential to reduce short-term climate warming **Amber** – Low or uncertain potential to reduce short-term climate warming
Long-term climate warming	**Dark green** – High potential to reduce long-term climate warming **Light green** – Medium potential to reduce long-term climate warming **Amber** – Low or uncertain potential to reduce long-term climate warming
Air pollution and health benefits of the intervention	**Dark green** – Very high reduction in exposure to air pollution leading to substantial health benefits **Light Green** – Medium reduction in exposure to air pollution and associated health benefits **Amber** – Limited reduction to exposure to air pollution and limited health benefits

Table A4 - Notes and references supporting the qualitative analysis shown in Table 2

Sector	Sub-sector (example region)	Change required	Notes
Residential	**Cooking (South Asia)**	Transition from biomass to LPG in the near-term, with a long-term view to use bio-LPG when fully commercial	The residential sector contributes to 35% of the total black carbon emissions globally and 60% in South Asia[i]. Biomass burning contributes to approximately 54% of black carbon in the Himalayas[ii]. Adoption to LPG and biogas leads to black carbon emissions reductions, proving a net short-term light green climate benefit. Shifting to renewably generated electric cooking will achieve more complete multi-pollutant emission reductions and hence greater climate benefit. An estimated 3.2 million deaths are associated with household air pollution from cooking globally.[iii]
		Transition from biomass to biogas technology in livestock-owning households in rural areas	
		Transition from biomass to renewably generated electric cooking and hydroelectricity	
	Heating (Europe)	Replacing boilers with heat pumps for residential space heating	Black carbon emissions from heating in the EU is less than 1% of global black carbon emissions. Replacing 60 million conventional heating devices to heat pumps will avoid 112 megatonnes of CO_2 emissions per year[iv]. Black carbon emissions from residential heating[v] significantly contributes to advanced snowmelt by 17 ± 6 days on average in the French Alps and the Pyrenees[vi]. Domestic heating is linked to extreme air pollution events in Europe.[vii]
		Adoption of tighter ecodesign emission standards, including for black carbon	
	Heating and lighting (Himalayas)	Displacing biomass fuels and diesel generators with off-grid solar and small-scale hydropower systems	Solid fuel contributes to 17-27% of black carbon deposition in the Himalayas.[viii] Space heating accounts for 20% of energy usage.[ix] Direct link to snow cover reduction and snow melting in the Himalayas has been established.[x]
	Lighting (Sub-Saharan Africa)	Displacing the use of kerosene wick lamps with solar lighting	Solar lamps have already substantially reduced the use of kerosene for lighting in Africa.[xi] No literature has been found highlighting the impact on tipping points such as the West Africa Monsoon. There is a high black carbon to organic carbon ratio and potential for CO_2 emissions reductions.[xii]
Transportation	**Shipping (Arctic)**	IMO to establish a black carbon emission standard for shipping in Arctic waters	Shipping contributes less than 5%[xiii] of the black carbon in the Arctic but leads to more significant deposition in snow and ice (up to 8%).[xiv,xv] Amber short-term climate impact due to limited literature available, also considering the effects of sulphates. Amber health benefit due to relatively lower population density.
		Installation of diesel particulate filters on ships	
	Diesel vehicles and mobile machinery (East Asia)	Eliminating on-road and off-road super-emitters in transportation and freight	Disproportionately high emissions from super-emitters in East Asia. On road sources contributes 13% of total black carbon emissions.[i] Off-road emissions for particulate matter constituent 39% of total emission from transport.[xvi] Fossil fuel combustion in China is linked to significant black carbon deposition in the Tibetan Plateau.[xvii] Diesel vehicles have a relatively high black carbon to organic carbon ratio.[xviii] Vehicular emissions contributed to ~78,000 premature deaths in three urban agglomerations in China from 2010 to 2020.[xix]
Energy	**Gas flaring (Arctic)**	Stop routine flaring by exporting the Norwegian model (strict regulations and taxes) to other countries	Gas flaring contributes to 3%[xx] of global black carbon emissions, but it has an amplified effect on the Arctic. It has been estimated to contribute up to 42% of surface black carbon in the Arctic.[xx] High short-term climate impact benefits as it also addresses methane.

Sector	Sub-sector (example region)	Change required	Notes
Industry	**Brick kilns (South Asia)**	Transition to improved low-emission brick kilns	Black carbon from brick kilns is linked to impacts on both Arctic warming[xxi] and Himalayan glacier melting.[xvii] One of the largest relative climate benefits in South Asia could be achieved through transitioning to cleaner brick kilns.[xxii]
		Worker upskilling on improved technologies (tailored to specific country contexts).	
Agriculture	**Adoption of Crop Residue Management (South Asia)**	Develop profitable alternative markets (*ex-situ* options) to incentivise stubble management applications	This sector contributes to less than 5% of black carbon emissions[xxiii] and accounts for less than an estimated 3% Himalayan black carbon deposition.[xxiv] Crop residue burning has a relatively has relatively lower black carbon to organic carbon ratio.[xxiii] The long-term red and short-term climate impacts are derived from IPCC AR6 table 6.16.
		Streamline access to happy seeders and super seeders via custom hiring centers (*in situ*-management)	
Waste	**Open burning of solid waste, including e-waste (Africa)**	Adopt holistic waste management systems and bans on open burning	Waste burning emits a relatively small total proportion of black carbon. No literature has been found linking tipping points or regional climate impacts. However, there is a well-established link to air pollution and health.[xxv]
Forest Fires	**Wildfire Management (Latin America)**	Promote wildfire management in Latin America	Black carbon drives larger reductions in precipitation during the dry season[xxvi], when higher levels of biomass burning occur in South America. Black carbon from wildfire in the Amazon is directly linked to Andes Glacier melting.[xxvii] Moreover, forest fires have also been linked to the Amazon tipping point.[xxviii] In recent years CO_2 emissions from forest fire have sometimes supersedes anthropogenic CO_2 emission in some countries.[xxix]
	Wildfire management (West Africa)	Promote wildfire management in West Africa	Wildfire is linked to West African Monsoon (WAM) anomaly along with other factors.[xxx] Additionally, African fires are associated with considerable methane emissions[xxxi].

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