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WORLD ECONOMIC FORUM

Black Carbon Reduction: A Rapid Action Plan

WHITE PAPER

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Contents

Executive summary

The impact of ultra-warming black carbon (BC) on seasonal Arctic ice melt, Himalayan glacier run-off and the timing and intensity of the Indian monsoon has been known for decades. The deadly health effects of ultra-fine BC, both on its own and as a component of fine particulate matter under 25 microns in diameter (PM2.5), are also well established. There is extensive, well-documented evidence highlighting the significant climate, health and social benefits of reducing BC emissions. So why has the global policy response been so muted and incomplete?

To answer that question, this white paper examined five national case studies (Brazil, China, India, Nigeria and the United States) to discern the primary obstacles to BC mitigation in those settings. Next, the team summarized the common barriers to implementation. Based on this review, the following became evident:

– **The problem starts at the top.** The United Nations Framework Convention on Climate Change (UNFCCC), the foremost international framework working to combat climate change, continues to undervalue the importance of short-lived climate forcers, so there is little incentive to pursue BC abatement in nationally determined contributions (or countries' climate action plans). The Climate and Clean Air Coalition (CCAC), which is a voluntary partnership between governments and non-governmental organizations with a focus on reducing short-lived climate pollutants, cannot single-handedly close this gap.

– **Air quality drivers are helpful but not sufficient.** Conventional air quality programmes capture some BC emissions (e.g. from polluting diesel vehicles) but not all. To maximize climate returns, BC needs to be a direct target of government interventions.

– **The technical guidelines for addressing BC emissions are still in their infancy.** There are no universally recognized guidelines for building an emissions inventory, monitoring ambient BC concentrations, measuring direct BC exhaust, modelling the behaviour of BC in the atmosphere or confirming compliance with regulatory schemes.

– **The role of BC mitigation in economic development is undervalued.** Controlling BC emissions moves individual households, private contractors (e.g. truck drivers) and small businesses up the energy ladder – to cleaner, more efficient fuels – while concurrently reducing exposure to hazardous emissions. But that pay-off is not typically part of the policy conversation.

– **More creativity around subsidy schemes is needed.** Most BC emissions sources are in the hands of relatively poor individuals or small commercial operations. These parties are unable to upgrade to cleaner technology and/or fuels without government assistance of some kind.

– **Climate finance is key to deploying affordable technologies that modernize energy use in low-income regions.** While most BC mitigation technologies, such as clean cookstoves, modern brick kilns and clean lighting solutions, are widely available, their cost remains a barrier for poorer communities. Prioritizing climate finance in these areas is essential for a global just transition.

– **Health ministries and public health professionals are vital partners**, particularly but not only regarding indoor sources of BC. Health officials and medical professionals are more aware of the acute risks to children, women and the elderly from indoor solid fuel combustion. They also lend legitimacy to government interventions and, in some cases, may be more likely to act than environmental ministries.

– **Regional collaboration is essential** to disseminate best practices, share the lessons learned, replicate successful interventions, and achieve BC mitigation at scale. Peer-to-peer exchanges are especially useful in building trust and the willingness to act.

To prompt forward momentum, this paper describes some incremental steps to reducing BC emissions from each major source category. This section is intended to help countries evaluate where they stand on each trajectory so they can plan and take the next logical step(s). This paper also identifies the ultimate endgame for each source type to stimulate deeper thought around the potential for leapfrogging.

The paper ends with recommendations to the global climate community, since no single country or region can overcome all the implementation barriers. It needs global buy-in that BC mitigation matters, with a corresponding investment in legal frameworks, technical tools and financial mechanisms to make that possible.

Introduction

Decades of research have established the impact of black carbon (BC) on local, regional and global climate and public health. Yet, global progress in reducing BC emissions has been slow.

Air quality measures for fine particulate matter (PM2.5) worldwide have reduced BC emissions, but the reductions are far short of what is needed given the multiple benefits of BC mitigation. Many climate scientists have called for enhanced and targeted BC measures to address the climate crisis in the near term. Yet, something is impeding progress.

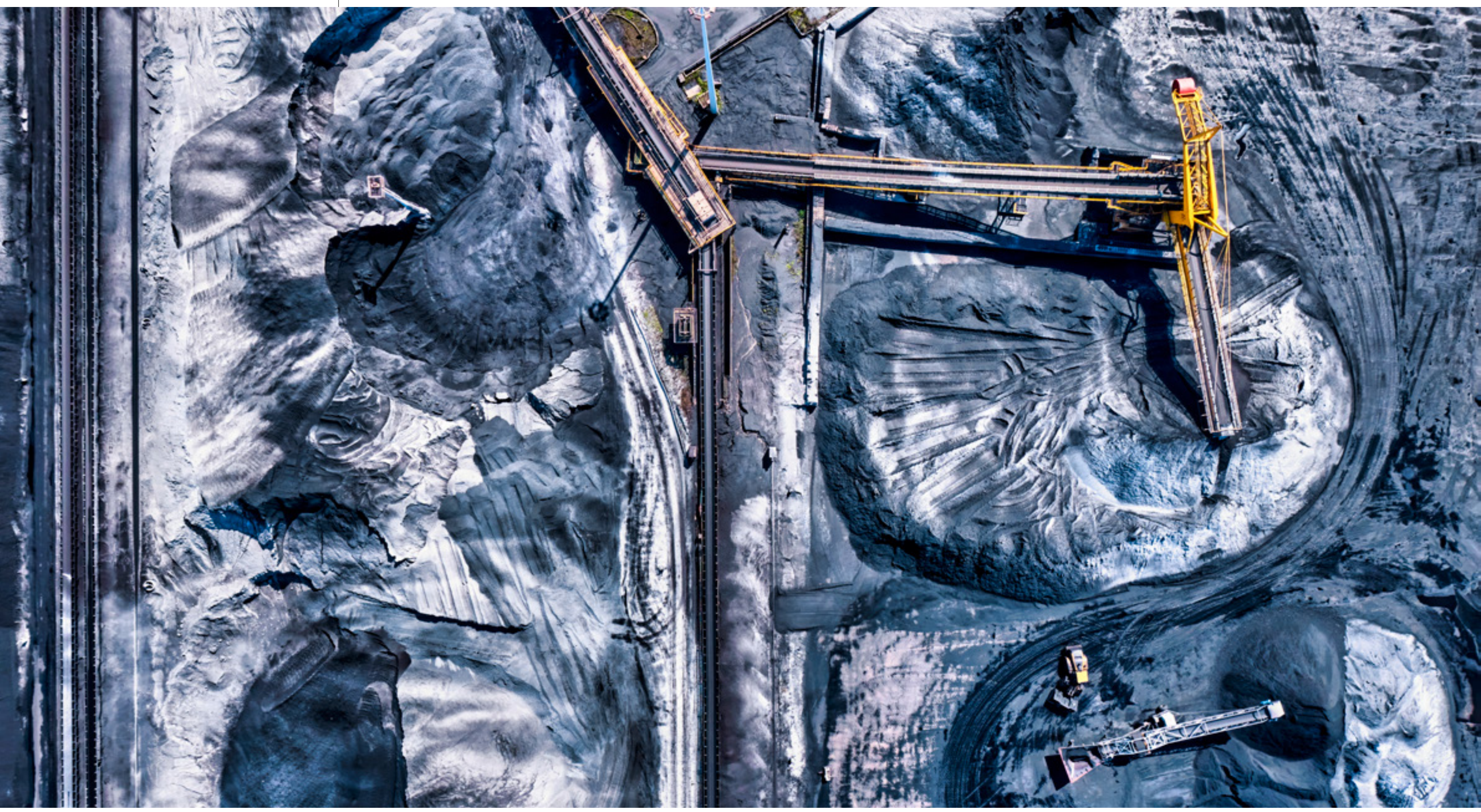
What is standing in the way, and what can be done about that?

The key to unlocking BC mitigation is to understand what motivates governments to act, the economics of BC control and the practical barriers to be overcome. A substantial proportion of anthropogenic BC emissions stem from household and business activities in lower-income, less-organized and under-capitalized sectors – smaller, less efficient brick kilns, for example, or the household use of solid fuels for cooking and heating.

This can make BC mitigation quite challenging, in the sense that it requires changing many small decisions rather than focusing on fewer, larger, industrial point sources. However, it also makes it very attractive as a development action – an aspirational angle binds people to the cause because BC mitigation typically results in a higher standard of living and/or greater profitability for commercial enterprises.

To achieve greater BC mitigation, there must be sufficient political will to act, plus the institutional, economic and regulatory capacity to follow through. Ultimately, it comes down to unlocking enough capital to make the switch from solid fuels and low-temperature combustion engines to better technology. In many cases, leapfrogging is possible – by side-stepping disadvantageous "lock in" carbon-based technologies. In some cases, such as brick kilns, there is an opportunity to rethink the entire enterprise (i.e. what buildings could be made of other than baked clay).

But first things first. What lessons can be drawn from the starting positions of Brazil, China, India, Nigeria and the US? How cognizant are they about BC as a climate and public health threat? How much relative capacity do they have? Where have they acted? On what basis? What have they not done? And what does that suggest about the logical next steps or their applicability to other parts of the world? The following sections will examine and answer these questions.



1 Benefits of black carbon mitigation

The implementation of BC controls should be highly compelling given the significant benefits they offer. There is substantial evidence that mitigating BC reduces near-term climate change impacts while simultaneously improving air quality.[1] Black carbon and other short-lived climate pollutants also contribute to one-third of current global warming, adding to visible, worldwide warming and widening exposure to extreme heat.[2]

BC controls should practically sell themselves given the enormous return. A regional study in the Himalayan glaciers found that fully implementing existing policies on BC emissions in South Asia could cut BC deposition by 23%, while implementing economically and technically feasible measures could reduce up to 50% of BC deposits.[3]

A study on international shipping shows that if the European Union (EU) requires ships calling at EU ports and operating in Arctic waters to switch from heavy fuel oil (HFO) to distillate oil or less-brominated carbon fuels, it would reduce their BC emissions by 50-80%.[4]

Regarding health benefits, a 2020 study found that targeting BC emissions could prevent an estimated 4-12 million premature deaths between 2015 and 2030, the majority in Asia.[5]

This section lists key mitigation measures for BC emissions (Table 1) and the multiple benefits of those measures based on recent studies (Table 2).

TABLE 1: **Key mitigation actions for black carbon**

Source	Key mitigation actions
Residential	– Use cleaner fuels for cooking and heating in developing countries. – Stop wood combustion for heating in industrialized countries. – Replace kerosene lamps with solar or electric alternatives.
Transport	– Implement stringent emission standards for new diesel engines and fuels. – Phase out older, high-emitting diesel vehicles. – Use cleaner shipping fuels, particularly in Arctic regions.
Industry	– Upgrade brick kiln technologies. – Upgrade coke ovens. – Eliminate open flaring except where necessary for safety.
Open burning	– Ban open burning of agriculture and forest waste.

Source: United Nations Environment Programme/World Meteorological Organization (2011);[6] Sims, R., V. Gorsevski and S. Anenberg (2015).[7]

TABLE 2: **Mitigation solutions with multiple benefits**

Source	Actions	Health benefits	Climate benefits	Social benefits
Residential	Use cleaner fuels for cooking and heating.	770,000 deaths could be avoided by eliminating solid biofuel combustion for residential heating and cooking.[8]	Highly efficient stoves can reduce fuel use by 30-60%, cutting both carbon dioxide (CO_2) and BC emissions.[9]	Gender equality and women's empowerment.
	Replace kerosene lamps with cleaner lighting.	Cleaner lighting prevents an individual's exposure to kerosene fumes equivalent to smoking 20 cigarettes per day.[10]	Eliminating annual BC emissions from kerosene lamps is equivalent to 5 gigatons of carbon reduction over the next 20 years.[11]	Better quality of life and reduced risk of poisoning and burns.
	Reduce wood burning in saunas, fireplaces and stoves.	In Finland, reduction of small-scale wood combustion can prevent about 200 premature deaths each year.[12]	Maximum feasible controls for wood-burning boilers could cut emissions 63% by 2030.[13]	Less air pollution and better forest protection for all.
Transport	Implement stringent emission standards for new diesel engines and fuels.	Global adoption of world-class standards could reduce PM-related premature deaths annually by 75% in 2030.[14]	Doing so would also reduce short-lived climate pollutants, including BC, by the equivalent of 710 million metric tonnes of carbon dioxide equivalent (MMT CO_2e) annually.[15]	Better ecosystem health.
	Bring in new diesel vehicles, engines and diesel fuel.	A modelled scenario for replacing 300 diesel buses in the Philippines identified economic benefits of $9.5 million in avoided premature deaths.[16]	The same analysis calculated climate benefits worth $4-12 million depending on the assumed discount rate and social price of carbon.	Less soiling of buildings and the environment.
	Use cleaner marine fuels.	Cleaner marine fuel would reduce premature mortality due to ship emissions by 34%, which is equal to a 2.6% global reduction in PM2.5-related cardiovascular and lung cancer deaths.[17]	If the European Union required its ships in the Arctic to use cleaner distillate fuels, it would reduce their BC emissions in Arctic waters by 50-80%.[18]	Better quality of life and natural ecosystem for the Arctic communities.
Industry	Upgrade brick kiln technologies.	In Nepal, converting fixed chimneys to zig-zag kilns (ZZK) could cut PM2.5 by 20% per kilogram (kg) of fuel used, equal to a 40% reduction for PM2.5 per kg of fired brick.[19] In Pakistan, converting to ZZK technology can reduce particulate matter by 40%.[20]	Zig-zag kilns would cut BC emissions in Nepal and Pakistan by 30%[21] and 60%,[22] respectively, while also reducing overall full consumption.	Improved tourism value in rural areas previously plagued with black smoke.
	Upgrade coke ovens.	China's ban on beehive coke ovens reduced the estimated frequency of lung cancer cases.[23]	In China, its PM2.5 control measures cut baseline emissions of the coking industry in Beijing-Tianjin-Hebei by 68% from 2015 to 2019.[24]	Improved tourism value in rural areas previously plagued with black smoke.
	Eliminate gas flaring except where necessary for safety.	Eliminating flaring in the US would yield health benefits by avoiding up to 360 premature deaths annually, depending on which emission factors are used.[25]	Eliminating non-emergency flaring by 2030 would cut overall flaring by 95% and avoid 365 million tons of CO_2e emissions.[26]	Greater fuel security for all, less demand for new gas projects could support the energy transition.
Open burning	Ban open burning of agricultural and forest waste.	Banning agricultural burning in India could prevent 44,000 to 98,000 premature deaths per year.[27]	Improved air quality, slowdown of the rate of snow and glacier melt.[28]	Improved home safety, food security, public health and climate change mitigation.

BOX 1. What is black carbon and why does it matter?

Characteristics

Black carbon (BC, commonly known as soot) is an ultrafine particle produced by the incomplete combustion of fossil fuels, wood and biomass. It is the strongest light-absorbing component of particulate matter under 2.5 microns in diameter (PM2.5) and among the smallest components at 15-50 nanometres in diameter.

Climate impact

BC has a warming effect 1,500 times greater than that of CO_2. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) estimates the effective "radiative forcing"[29] of BC at the top of the atmosphere to be between -0.28 and 0.41 watts per meter squared (W/m^2) – it has thereby contributed to a temperature rise of 0.1°C from 1750 to 2019.[30]

Regional climate effects

BC impacts regional weather and rainfall patterns. It can alter precipitation by absorbing solar radiation and heating the surrounding air. Studies have found that regional BC emissions can lead to less precipitation in West Africa,[31] and decrease low-intensity rainfall in the pre-monsoon season in northeast India.[32]

Health risks

BC poses significant health risks, contributing to respiratory and cardiovascular diseases. Globally, an estimated 3.2 million lives are lost prematurely due to illnesses attributed to household air pollution arising from the incomplete burning of solid fuels and kerosene during cooking.[33] In rural India, household BC pollution is associated with high cancer risk and reduced lifespan.[34] In China, a total of 74,500 and 538,400 all-cause premature mortality cases are linked with short- and long-term BC exposure.[35]

Impact on snow and ice

BC deposition reduces the reflectivity (albedo) of snow and ice, thereby accelerating melting. The Arctic is warming four times faster than the global average,[36] with BC deposition identified as a major driver.[37] Glaciers in the Hindu Kush region of the Himalayas are melting at an unprecedented rate, due to the impact of BC on summer precipitation over the southern Tibetan plateau.[38]

Food security

BC deposits on plants reduce their photosynthetic ability, decreasing crop yields. A study reveals that in India, the combined effects of climate change and the direct impacts of tropospheric ozone and BC led to a decrease of up to 36% in wheat yields by 2010 compared to expected levels.[39] One analysis shows that air pollution and heat stress have significantly reduced maize and soybean yields in the US from 1980 to 2019, with soybean yields being more sensitive to aerosol pollution, such as BC and sulphates.[40]

2 Common barriers and implementation gaps

Given the multiple and multifaceted benefits of BC reduction, why are the necessary steps not being taken? The key reasons are:

Diplomacy gap

BC is not typically included in climate action plans because it is not one of the six GHGs designated by the United Nations Framework Convention on Climate Change (UNFCCC).[41] Only a handful of countries address BC in their Nationally Determined Contributions (NDCs) (Figure 1), with widely varying content.[42]

Currently, two multilateral agreements address BC. The first is the Gothenburg Protocol under the Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE). The other is the Fairbanks Declaration, developed and adopted by the Arctic Council, which sets a collective target for reducing BC emissions by 25% to 33% below 2013 levels by 2025.[43] Unfortunately, both multilateral agreements are geographically limited in scope and, by default, exclude the countries that emit the lion's share of BC (Figures 2 and 3).

FIGURE 1. **Climate and air quality frameworks to address black carbon**

Climate change

The integration of black carbon into NDCs

- 17 countries have integrated black carbon into their NDCs.
- 13 countries have set separate targets or mitigation potentials.

Air pollution

Europe

- Gothenburg Protocol under the Convention on Long-Range Transboundary Air Pollution

The Arctic

- Fairbanks Declaration
- The World Meteorological Organization's heavy fuel oil ban

Source: CAF, 2024.[44]

FIGURE 2. **Parties to the United Nations Economic Commission for Europe and the Convention on Long-Range Transboundary Air Pollution**

Source: UNECE, 1970.[45]

FIGURE 3. | **Arctic Council member states and observer countries**

Source: WWF, 2024.[46]

Regulatory gap

A robust policy and regulatory framework is needed to support BC mitigation. This includes emission control regulations, enforcement mechanisms, standards and measurements, as well as enabling policies such as technical assistance, capacity building and financing.

Financing gap

BC mitigation actions face significant challenges in securing adequate financing. For instance, upfront and operational costs are major barriers to the adoption of clean cookstoves in Sub-Saharan Africa.[47] Similarly, the lack of access to financing also hampers brick operators from upgrading brick kiln technologies in South Asia. Local financial institutions have limited experience in lending to these brick entrepreneurs, who often operate on leased land and lack the necessary collateral to access commercial loans.[48]

Technological gap

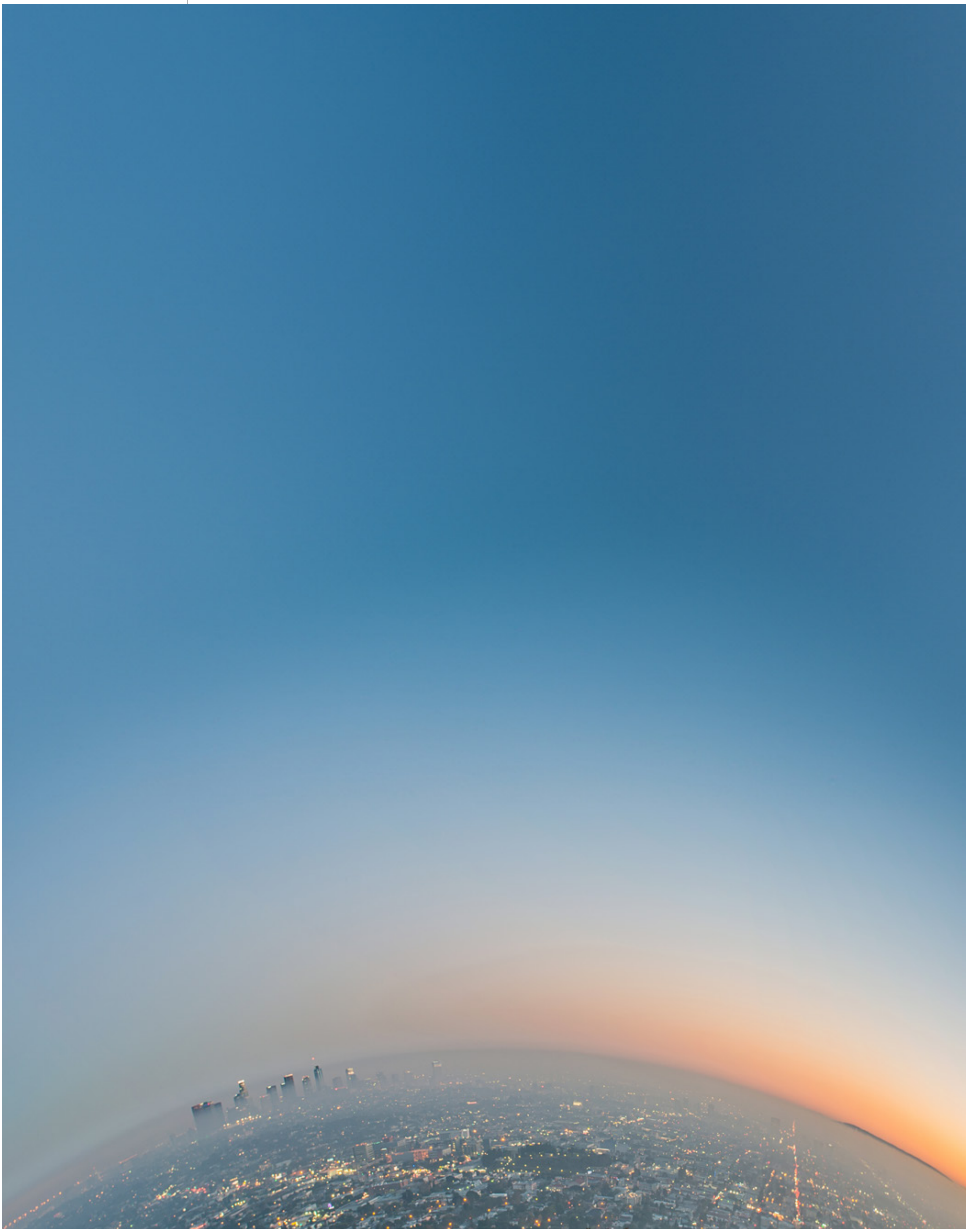
A lack of cost-effective, locally appropriate technologies is a barrier to implementation. While cleaner diesel fuel and particulate filters are widely used in the on-road transport sector, their uptake in off-road categories is more complex and time consuming. In maritime shipping, there are challenges regarding fuel switching and engine adaptation,[49] though cleaner distillate fuel is now used routinely in special emission-control areas.

Similarly, in aviation, alternative fuels to reduce BC and other emissions have produced mixed results regarding their feasibility for large-scale use.[50] Technical barriers also arise when new technologies fail to accommodate local conditions. For instance, when Chinese technologies for brick kiln operation were applied directly in Bangladesh without regionally specific customizations, the efficiency of brick production declined notably.[51]

Knowledge and awareness gap

Accurate, clear, timely and widely available information is needed to support many BC mitigation measures. For example, if consumers do not fully appreciate the health benefits of sootless cooking, they may be less amenable to purchasing new stoves. For wildfire management officials, inadequate monitoring data and lack of early warning signals makes fast responses difficult.

3 Regional responses to black carbon



The effectiveness of BC mitigation measures and the obstacles to their implementation vary across regions. Important factors include the relative size of BC emission sources, the prevailing policy environment, local knowledge, government capacity, social context and of course, technical and economic feasibility. For this paper, five of the top 10 anthropogenic BC emitting countries have been assessed to gauge their relative response to available BC information.[52] These emitters are Brazil, China, India, Nigeria and the US. The objective was to understand where BC appears in their respective national dialogues and/or policy frameworks, and to understand if the top priority BC controls measures are being implemented in each region. If these measures are not being implemented, this paper examines why.

China

China has been closely tracking global developments in BC science for the last 15-20 years and has invested heavily in its own research. Leading Chinese universities are doing cutting-edge work on national BC emissions, their air-quality and climate impacts, the abatement potential of various interventions, the behaviour of aerosols in the atmosphere and many other related topics.

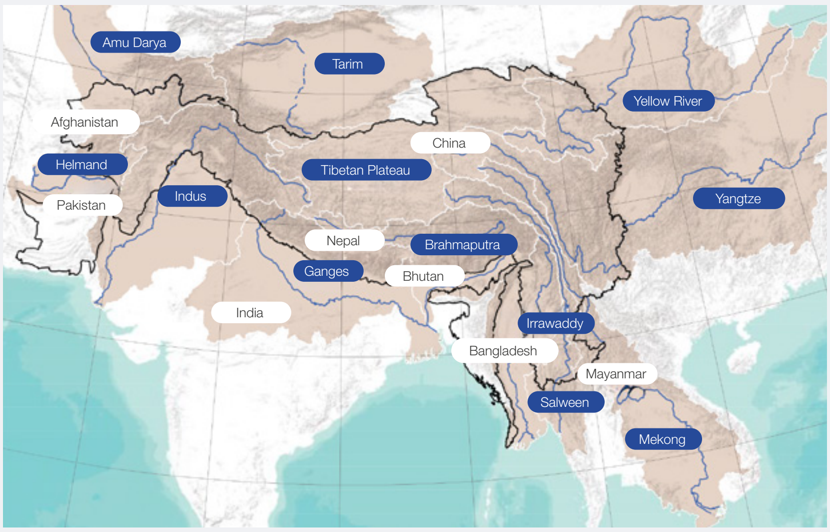
That said, the primary driver in China is air quality management; specifically, reducing PM2.5 emissions to protect public health. In pursuit of cleaner air, China has converted millions of solid-fuel heating systems to natural gas, banned fireworks, banned agricultural burning and switched residential and commercial cookstoves to cleaner fuels (briquettes and propane, respectively).[53] China is also steadily de-sulphurizing its on-road, off-road and marine diesel fuels, and has recently imposed filter-based standards for on-road diesel trucks.[54] The biggest remaining gap is extending all these emission control measures nationwide, since many apply to the capital region of Beijing-Tianjin-Hebei only.

BOX 2.

How BC affects glaciers in the Hindu Kush Himalayas, regional water supply and food security

The Hindu Kush Himalayas (HKH), often referred as the "water tower of Asia", are undergoing accelerated glacier melting due to climate change and heavy BC deposition.[55] An assessment from the International Centre for Integrated Mountain Development (ICIMOD) shows the HKH glaciers disappeared 65% faster in the 2010s than in the previous decade, and are expected to lose 30%-50% of their volume by 2100 if global warming extends to 2°C and 55%-80% of their volume by 2100 if global warming reaches higher levels.[56]

The retreat of these glaciers threatens water supplies and food security downstream. An estimated 129 million farmers in the Indus, Ganges and Brahmaputra basins currently depend on glacier melt to irrigate their crops,[57] and 1.9 billion people in Asia rely on the Himalayas for freshwater.[58] The regions surrounding the Himalayas are also home to highly populous cities and economic activities, such as the Indo-Gangetic and Yangtze river plains.[59] The availability of water is expected to peak in the mid-century and then decrease through the end of the century.



River basins
The HKH boundary
River networks

Source:
ICIMOD, 2023.[60]

India

Like China, India has tracked international research on BC for decades, the country itself being the focus of multiple studies about aerosol pollution in the Himalayas and the Hindu Kush region. India's progress in controlling BC emissions has been indirect, spurred by public health concerns over residential cookstoves and kerosene lamps, and by air quality-related lawsuits and public protests in the case of high-emitting diesel vehicles and seasonal agricultural burning.[61]

To address the former, India initiated the Pradhan Mantri Ujjwala Yojana (PMUY) to encourage the use of cleaner household cooking fuels and discontinued kerosene subsidies for household lighting and cooking.[62] India has also committed to the global Zero Emission Vehicles (ZEV) declaration,[63] aiming for a complete transition to zero vehicular emissions by 2030-2040.[64] To address the latter, the central government has been working with several local and international organizations to identify feasible alternatives to agricultural waste burning.

BOX 3.

Barriers to brick kiln modernization in South Asia

Brick kilns are major contributors to air pollution in South Asia. The brick kiln industry is also a key contributor to anthropogenic BC deposition in the Himalayan glaciers.[65]

The 2023 World Air Quality Report ranked Bangladesh as the most polluted country in the world, with Pakistan and India following closely.[66] Enhancing the energy efficiency of brick kilns is essential for managing BC in this region. While clean technologies such as zig-zag kilns (ZZK) and vertical shaft brick kilns (VSBK) are encouraged in brick manufacture, they encounter challenges for scaling up. For instance, in Bangladesh, around 30% of brick kilns use the fixed chimney kiln (FCK) technology, characterized by low construction costs but high levels of air pollution.[67]

The primary challenges are the financial burden and the knowledge gap for switching kiln technologies. A survey conducted among kiln owners in Punjab in Pakistan revealed that the main barriers to adopting cleaner ZZK technology included the high retrofitting costs, expensive skilled labour and maintenance challenges.[68] Similarly, in India, brick kiln operators have limited access to financial resources for retrofitting, the financial knowledge for making loan applications, and the skilled labour required for large-scale utilization of the technology.[69]

In addition, the lack of effective monitoring and enforcement of brick kiln regulations impedes the adoption of cleaner technologies. Widespread violations of the national regulations on brick manufacturing persist in Bangladesh, for instance, where 60% of brick kilns operated illegally without environmental clearance in 2023.[70]

Nigeria

Nigeria joined the Climate and Clean Air Coalition in 2012 and, shortly thereafter, began examining ways to reduce emissions from all short-lived climate pollutants (SLCPs), including BC. Nigeria's top priorities were cookstoves, agriculture, transport, brick kilns, and oil and gas. In 2019, Nigeria adopted a National Plan to Reduce SLCPs, which could reduce BC emissions by 83% if fully funded and implemented.[71] Three core elements of the plan were to eliminate gas flaring by 2020, cut waste burning in half by 2030 and convert 25% of diesel buses to natural gas by 2030.

Nigeria also pledged to eliminate kerosene lamps and to upgrade cookstoves to cleaner, more efficient technology. However, action on the ground has been slow. Flaring intensity has remained constant. Kerosene lamps have been phased out in a few public schools but remain widespread in villages. High-emitting cookstoves and three-stone fires are still prevalent. The primary barrier across the board is financing. In 2019-20, public and private climate finance flows in Nigeria were only 11% of the amount required to meet its carbon commitments.[72]

Poor environmental infrastructure is also a major problem in Nigeria.[73] In its search for innovative solutions, the Nigerian government in 2023 endorsed a carbon credit project that seeks to distribute 80 million cleaner burning stoves, free of charge, by 2035.[74]

BOX 4.

Implementation barriers to clean cooking in Sub-Saharan Africa

Solid-fuel cookstoves are a major source of human-caused BC emissions. While access to clean cooking is improving in Asia and Latin America, it is still very poor in Sub-Saharan Africa. According to the International Energy Agency (IEA), 29 countries in Sub-Saharan Africa have clean cooking access rates below 20%; and half of the nearly 1 billion people lacking access are in five countries (the Democratic Republic of Congo, Ethiopia, Nigeria, Tanzania and Uganda).[75]

The primary obstacle to clean cooking is the high upfront cost. Half the households in sub-Saharan Africa cannot afford clean cookstoves without additional support.[76] The lack of clean fuel infrastructure, such as distribution networks for liquified petroleum gas (LPG) canisters and/or electricity connections exacerbates this challenge.[77] Lack of funding for programme design and infrastructure further compounds the issue. Finally, there is a significant institutional challenge, because residential cooking doesn't "belong" to any ministry.[78]

Brazil

Brazil only recently joined the international BC dialogue, becoming a member of the CCAC in 2023. However, it has undertaken various initiatives for air quality control that can reduce BC emissions and is developing a national plan for short-lived climate pollutants, including BC.

However, challenges persist. In the residential sector, Brazil's gas-aid programme subsidizes LPG for low-income households, but high cooking-gas costs remain a barrier. In transport, Brazil promotes biodiesel and has launched a voluntary truck renewal programme to phase out old diesel vehicles, but infrastructure and affordability issues hinder broader adoption.[79]

Additionally, the government's response to forest fires has been more reactive than preventive – its integrated fire management strategy has seen limited implementation, and training in fire-free land management techniques has remained insufficient.[80]

These efforts reflect Brazil's commitment but also highlight the need for enhanced regulatory frameworks, infrastructure development and educational programmes. Meanwhile, open burning has been a significant issue in Brazil since the beginning of climate negotiations, as the Amazon rainforest, a crucial global carbon sink, continues to experience frequent fire outbreaks.[81]

BOX 5.

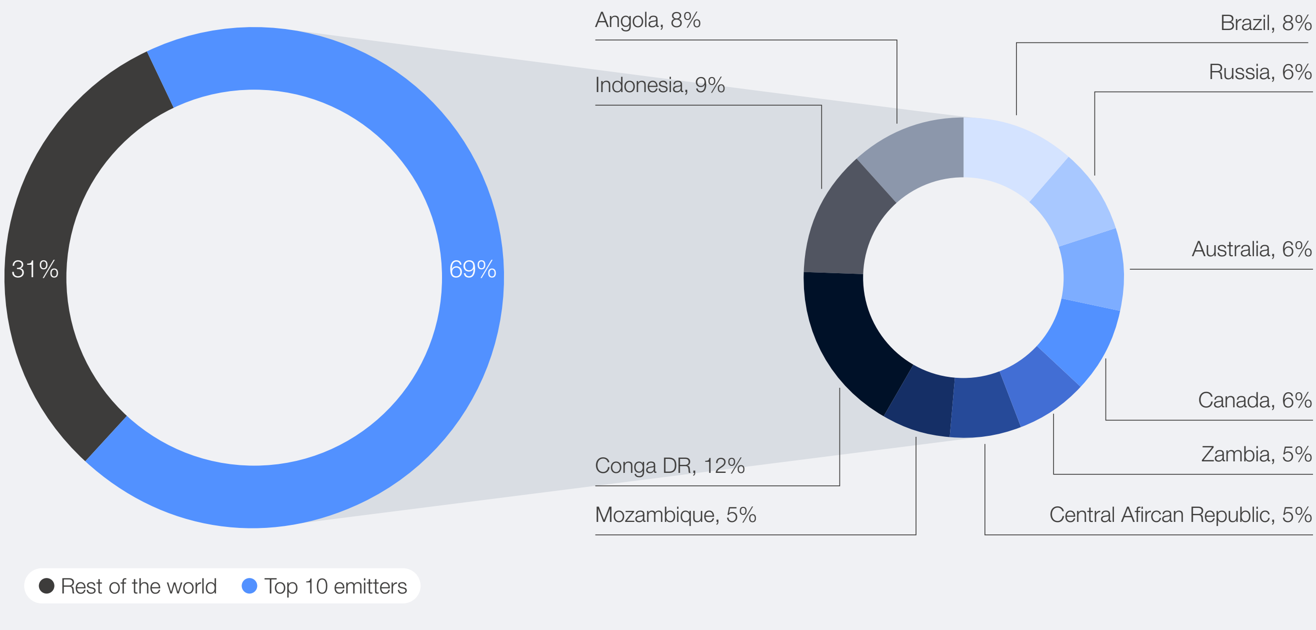
Black carbon and wildfire

Wildfire is key source of BC. As climate change increases the frequency, intensity and spread of wildfires, avoiding and mitigating wildfires will play a key role in managing BC emissions.

The 10 highest-emitting countries contribute to 69% of wildfire-related BC, and half are in Sub-Saharan Africa (Figure 5). Other key emitters include Indonesia, Brazil, Russia, Australia and Canada, which have large boreal forests and rainforest zones. As climate change is expected to increase the frequency and spread of wildfires, avoiding and mitigating wildfires will play a key role in managing BC emissions.

FIGURE 5:

Global wildfire-related BC emissions by country



Source: Xu et al., 2021.[82]

The United States

The US is a founding member of the CCAC and places a high value on abating short-lived climate pollutants as a climate mitigation strategy. That said, BC is not a high-profile issue at top political levels, nor is it the primary driver of domestic regulatory interventions. Instead, air quality management is the main motivation and BC reductions are a co-benefit.

Low-sulphur diesel fuel and particulate filters are the primary emission control methods used in the US, across all sizes and applications of diesel engines.[83] The state of California leads its 50 states in BC control, due to its aggressive regulation of new and existing diesel engines and substantial subsidy programmes.[84] California also banned agricultural burning several years ago, except where necessary to prevent disease.

Prescribed burning and wildfires are common in the western US and are becoming more severe, raising questions about land use (forest encroachment) and power line maintenance. Finally, several states control wood stove and fireplace emissions during the winter via a combination of voluntary programmes, rebates, tax exemptions and regulations (with limits on total fireplaces per ski lodge, labelling, fireplace inserts, etc.).[85]

BOX 6.

Black carbon and the Arctic

The Arctic is warming three times faster than the global average, leading to rapid changes in sea ice, land ice and snow cover.[86] Approximately 20% of Arctic and global snow/ice loss was due to the black carbon-albedo effect.[87] Arctic-bordering states are responsible for a third of BC's warming impact on the Arctic.[88] Gas flaring is the largest in-Arctic emission source, comprising more than 60% of BC emissions. Wood stoves and diesel vehicles make up most of the remaining emissions. The fastest growing emissions are from shipping, which accounts for 5% of Arctic BC emissions now but is expected to double by 2030 and quadruple by 2050.[89]

Many local and international groups are working to reduce BC emissions in the Arctic. The Arctic Council adopted the Fairbanks Declaration in 2017, setting a target for reducing BC emissions.[90] In addition, the International Maritime Organization (IMO) announced a ban on the use and transportation of heavy fuel oils in 2021.

4 Potential next steps for BC-emitting countries

Countries are at very different starting points for BC mitigation. Some have made tremendous strides; others are just beginning. Some sources are very well-controlled, others are not controlled at all.

For each BC emission source, there is a natural progression of interventions, from low-cost to more capital intensive and from incremental to transformative. The following BC mitigation "ladders" and actions can serve as a self-assessment guide for countries interested in abating BC and for the bilateral donors, development banks and other parties who wish to support them.

BC mitigation ladders and actions

Residential cooking

A natural progression up the cooking-related energy ladder takes place as incomes rise. Households expand and diversify their cooking methods, adding more appliances and ultimately switching to the cleanest fuel available. However, many people remain in poverty, unable to make even incremental progress on their own.

Clean cookstove distribution programmes have had decidedly mixed results. A more powerful remedy is to subsidize gas canisters, as India did under its Ujjwala programme, though affordability is still an issue.[91] Over the longer term, infrastructure investments are needed for widespread electrification. Pulling that off requires clear policy objectives, profit incentives for public and private utility companies, and a step-by-step buildout plan to achieve full connectivity.

Fuel	From raw coal to briquettes, from raw wood to uniform pellets, from solid fuel to gas, from gas to grid electricity to clean grid with 100% renewable power.
Cookstove	From three-stone fires to biomass stoves, from enclosed chamber to fan-equipped stoves, from solid fuels to gas stoves, from gas to electric stoves, from combustion to conduction burners drawing from a clean, renewable grid.

Residential heating

There are both poverty and luxury dimensions to solid-fuel heating. Some people need it to survive. For others, it is a source of pleasure, a crackling fire to lend ambiance to the family living room. Regulations work reasonably well for the latter, such as banning open fireplaces in new construction (such as allowing gas inserts and fake logs only). However, when low incomes prevent access to adequate heating, government intervention is crucial to ensure everyone can meet this fundamental need.

For district heating systems, BC mitigation may be as simple as installing conventional air pollution controls. For stand-alone houses and other dwelling units, the next logical step is to upgrade fireplaces to enclosed stoves and to use more uniform fuels (e.g. pellets). Work is also underway to develop retrofit particulate filters for exhaust flues at an affordable price. The ultimate solution is the same as for cookstoves: connectivity to gas pipelines and/or the electrical grid.

Fuel	From wood, trash or coal to more uniform pellets, from solid fuel to gas, from gas to renewable electricity.
Heating device	From an open fireplace to an enclosed stove, from uncontrolled to filter-equipped, from solid fuel to piped-in gas (or district heating with emission controls), from radiant electric heaters to ultra-efficient heat pumps.

New on-road diesel vehicles

There are not many incremental steps to reducing BC from diesel engines, though every reduction in the sulphur content of diesel fuel helps. Rather, there is a step change to filter-equipped diesel vehicles, which requires a guaranteed supply of ultra-low sulphur fuel everywhere those vehicles travel (to prevent poisoning of the catalysed filter).

Fuel quality	From regular to reduced sulphur content, to ultra-low sulphur (10 parts per million) or, for centrally fuelled fleets, switching from diesel to natural gas, renewable hydrogen or battery power.
Engine controls	From particle controls to filter-based exhaust standards, to zero-emitting cars and trucks.

New off-road diesel engines

The energy ladder for off-road diesels is basically the same as for on-road, but more expensive given the larger size of most off-road engines and smaller fleets to spread those costs across. “Offroad” includes back-up diesel generators, road paving equipment, construction equipment, cranes, locomotives, ferries, harbour boats and marine vessels. For these sources, it’s very important to get a head start on electrification, or the equivalent, because their lifetimes are so long.

It is also important to combine regulations with non-regulatory approaches, such as procurement standards and contract incentives to create stronger market pull for the greenest technologies.

Legacy (in-use) diesel vehicles and engines

In-use diesel vehicles and engines eventually wear out, but not fast enough to meet climate and air quality objectives. Hence, some countries accelerate those retirements via scrappage programmes, or, alternatively, retrofit in-use vehicles and engines to a higher standard. Both approaches require aggressive rules and generous subsidies to help owners/operators upgrade to cleaner technology.

Preventing the transfer of dirty older diesel vehicles to developing countries is also crucial, since outdated vehicles contribute disproportionately to air pollution in these regions.[92] Likewise, lower-quality diesel fuels are exported to lower-income countries, exacerbating pollution[93] and hindering global efforts to reduce BC emissions.

Brick kilns

In traditional kilns, anything that burns will be used: tyres, motor oil, plastic, garbage, dung, agricultural waste, plus multiple forms of wood and coal. The first order of business is to improve and standardize the fuel, while simultaneously reconfiguring the firing chamber to achieve more complete (and hence less polluting) combustion. Those steps alone can cut BC emissions by half, according to measurement studies conducted in the state of Bihar in India.[94]

Next is a major step change to mechanization, which implies vertical integration of cottage industries into more formal enterprises, relying on cleaner fuels. The final step is to replace energy-intensive bricks with entirely different, non-combustion-based building materials.

Fuel	From low-grade miscellaneous fuels to uniform fuel (e.g. pulverized coal), then to natural gas or electricity.	Transition to non-combustion-based building materials
Kiln type	From traditional beehive or vertical shaft to zig-zag configuration, then to fully mechanized with well-controlled exhaust stream.	

Coke ovens

Coke is a hard, grey, porous solid fuel, made by heating coal in the absence of oxygen. It is essential to steel production – it provides the tremendous heat needed to melt iron ore and pulls oxygen out of the ore, leaving pure iron behind.

The BC emissions from “coking”[95] depend on the oven type, the management of various processes (e.g. “quenching”)[96] and the presence of air pollution controls on the exhaust stack, where applicable. BC emissions from coking can be substantially reduced by upgrading oven types, following good practices and applying post-treatment technologies.[97] The ultimate solution to reducing BC from coke ovens is to maximize steel recycling and produce less virgin steel, thereby reducing the need for coke in the first instance.

Coke oven type	From primitive ovens (“beehive”, “kiln”, “pile” or “indigenous”) to slot oven (also called “machine” or “recovery” ovens), to “heat-recovery” ovens, while simultaneously maximizing steel recycling and minimizing virgin steel production.

Natural-gas flaring

When natural gas comes to the surface during oil drilling and there is no obvious, economically attractive place to put it, it is simply burnt off (i.e. “flared”). Flaring is also used in emergency situations, to keep large quantities of vented gases from exploding.

In remote oil-drilling locations, flaring is routine. It also occurs in populated areas where there is insufficient investment in gas recovery technology.

The flaring problem cannot be solved by pledges and flaring bans alone.[98] It requires thoughtful development of micro-processing plants to purify and then compress or liquefy the gas, distribution networks including local pipelines and/or export facilities, and economical end-uses such as small-scale gas-fired powerplants or fleet fuelling centres. These interventions make the most sense in gas-rich oil fields and in places where the soot from gas flaring is particularly harmful, such as in or near the Arctic.

Agricultural burning

Like flaring, agricultural burning is a convenient but highly polluting solution. It is the fastest, cheapest way to clear away stubble, kill weeds and eliminate massive piles of agricultural debris. It also helps warm the ground in northern climates, enabling earlier spring sowing.

To stop agricultural burning, there has to be someplace else for the waste materials to go and more mechanization of the planting process (e.g. the use of “happy seeders”).[99] Those interventions, in turn, require alternative waste management schemes, well-organized farmer cooperatives to share expensive machines and an array of supporting institutions and financiers.

Thus far, the best results have been at the urban-rural interface, where persistent smoke episodes have led to a huge public outcry, generating enough political will to act. Because it is such a heavy lift, the proponents of BC mitigation have focused on agricultural burning that is proximate to vulnerable snow and ice – such as in Siberia and the Himalayan region.

Forestry burning

Forest management has always been difficult given the sheer scale of the world’s forested areas. The combined threat of urban encroachment, agricultural expansion, pest infestations and hotter, drier temperatures has made the task nearly impossible.

Going forward, it is essential to acknowledge the need to co-exist with fire, while taking proactive steps to protect people, structures and valuable natural resources when the inevitable happens. That brings up tough, unpopular policy choices, such as limiting housing developments in fire-prone regions. Or the use of prescribed burning (plus pre-thinning of the forest undergrowth, which, however, environmentalists fear can encourage logging) to reduce the risk of catastrophes. BC mitigation is not central to these policy debates but should benefit from evolving forest protection schemes.

5 Potential next steps for the global community

Give each climate pollutant its due

As discussed above, the international climate change framework does not recognize black carbon. That omission has resulted in a lack of technical guidelines, reporting norms and a framework for crediting BC reductions. While the CCAC has tried to close the gap, its guidance alone cannot fill the vacuum.

The IPCC recently approved an outline for the 2027 Methodology Report on Inventories for Short-lived Climate Forcers (SLCFs),[100] which is a good start, but more action is needed. The world has changed since the 100-year CO_2-equivalent (CO_2e) metric was established in 1996 for reporting purposes. The 100-year GWP metric was itself a political compromise, intended to enable emissions trading across a range of GHGs with fundamentally different properties. Many scientists have pointed out that it would be more logical and effective to compare apples to apples.[101]

Identify, demonstrate and share best BC mitigation practices

The CCAC plays an important role in monitoring, funding and publicizing advancements in technologies to abate short-lived climate pollutants. However, its influence is limited in a crowded environment. Yet, while an internet-based platform can serve as a valuable starting point and resource library, it cannot build the same degree of trust and enthusiasm as is generated by on-the-ground projects.

Experience suggests that "kicking the tyres" – to see what works and what doesn't – is also extremely important. This would need enough demonstration projects in different places for stakeholders to see what's available and to talk to real-world practitioners.

Foster South-South regional cooperation on common source types

For countries facing similar challenges in BC mitigation, regional collaborative efforts can be effective in addressing these issues by pooling resources, expertise and technologies. Such collaborative actions could include sharing best practices, conducting joint scientific and technical research and working together to secure funding and technical assistance.

For instance, China is making great strides on coke oven modernization. India successfully converted an entire state's brick kiln industry to ZZK technology. Those are just two recent examples of the kinds of experience and knowledge that could be shared with other developing countries that are interested in making the same transitions.

Make grid connectivity a core objective of rural development

The end goal of many BC interventions is to replace combustion with widespread electrification, powered by a clean, renewable grid. However, for rural communities to benefit from these technologies as much as urban areas, it is essential to ensure sufficient charging capability. Otherwise, these communities will risk being left behind. Some countries have started aligning their power initiatives with rural development goals. India, for example, launched the Saubhagya Scheme[102] and PM-Surya Ghar,[103] which aims to provide electricity connections in rural areas and promote access to clean and green energy. China has also implemented programmes such as Wind Control Action for Thousands of Villages[104] to accelerate renewable energy development in rural areas.

Prioritize financing to BC mitigation in vulnerable communities

BC emissions are concentrated in lower-income regions, where households and small businesses rely on inefficient technologies such as traditional cookstoves and outdated diesel engines. Although BC mitigation technologies like clean cookstoves, modern brick kilns and clean lighting are widely available, their high cost is a barrier for these communities.

By directing climate finance towards these areas, these communities can adopt sustainable practices to reduce BC emissions. Such investment would not only address immediate health and environmental risks but also contribute to broader development goals by enhancing energy efficiency and fostering economic resilience in some of the world's most vulnerable regions.

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- Countries significantly affected by black carbon, e.g. the Arctic states of Canada, Denmark, Finland, Iceland, Norway, Sweden, Russia and the US; or the Himalayan states of India, Pakistan, Nepal, China, Afghanistan, Bhutan and Myanmar.
- Significant open burning: the Democratic Republic of Congo, Indonesia, Angola, Brazil, Russia, Australia, Canada, Zambia, Central African Republic and Mozambique.

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