AIR QUALITY ANALYSIS FOR BISHKEK

$PM_{2.5}$ Source Apportionment and Emission Reduction Measures

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Acronyms and Abbreviations

A2W	Air-to-Water
AQMS	Air Quality Management System
BC	Black Carbon
CAMx	Comprehensive Air Quality Model with extensions
CHP	Combined Heat and Power
CLRTAP	Convention on Long-Range Transboundary Air Pollution
DPF	Diesel Particulate Filter
EE	Energy Efficiency
EF	Emission Factor
EPA	Environmental Protection Agency
ESA	European Space Agency
ESP	Electrostatic Precipitator
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
CAPEX	Capital Expenditure
GBD-MAPS	Global Burden of Disease-Major Air Pollution Sources
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHS	Global Human Settlements
GIS	Geographic Information System
HGV	Heavy Goods Vehicle
HoB	Heat-only-Boiler
IOM	International Organization for Migration
KYRGYZ HYDROMET	Agency on Hydrometeorology under the Ministry of Emergency Situations of the Kyrgyz Republic
LCOH	Levelized Cost of Heating
LDV	Light Duty Vehicle
MNRETS	Ministry of Natural Resources, Ecology and Technical Supervision
MOZART/ WACCM	Model for Ozone and Related Chemical Tracers/ Whole Atmosphere Community Climate Model
OPEX	Operational Expenditure
OSM	Open Street Maps
PM	Particulate Matter
SFH	Single Family House
SLCP	Short-Lived Climate Pollutants
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
W2W	Water-to-Water
WHO	World Health Organization
WRF	Weather Research & Forecasting

Signs and Units

km^2	square kilometer
m/s	meters per second
MW	Megawatt
MWh	Megawatt hour
t	Ton
t/yr	ton per year
US$	United States dollar
$\mu g/m^3$	Microgram per cubic meter

Executive Summary

Objective of this study

This study aims to evaluate the air quality situation in Bishkek, focusing on $PM_{2.5}$[1] pollution, which has the largest impact on human health, and to provide support for the design of measures to improve air quality in the city. $PM_{2.5}$ concentrations in Bishkek substantially exceed international air quality standards—for instance, the annual average $PM_{2.5}$ concentrations in Bishkek exceed over 10 times the guideline of the World Health Organization (WHO) of 5 µg/m^3. The annual health damages of $PM_{2.5}$ pollution in Bishkek are estimated to be equivalent to 1.2 percent of the Kyrgyz gross domestic product (GDP).

Existing information and studies on air quality in Bishkek are limited and at times present contradictory information regarding the main sources of air pollution in the city. This study thus uses a scientific approach to identify the main sources of air pollution in Bishkek, estimate their relative contributions to $PM_{2.5}$ concentrations, model the dispersion of $PM_{2.5}$ pollution across the Bishkek airshed and assess the impact on $PM_{2.5}$ concentrations of a range of emission reduction measures. The study's results support the evidence base for the design of measures to improve air quality in Bishkek.

Air quality management is a complex and multi-sectoral agenda, which requires a systems approach and actions by many agencies and institutions in a country. A review of the air quality management system (AQMS) in the Kyrgyz Republic, with a focus on institutional arrangements, has been conducted separately. For comprehensiveness, this report summarizes the key findings of the institutional review and provides details on institutional responsibilities in Chapter 7.

Assessing the air quality situation in Bishkek

The study uses the latest methodologies and modeling approaches to assess air quality and determine the contribution of different emission sources to $PM_{2.5}$ pollution in Bishkek. To support the assessment of emission reduction measures, the various sources of $PM_{2.5}$ emissions and their contributions to ambient concentrations have been studied comprehensively. With the help of a detailed emission inventory, developed as part of the study, and pollution modeling, pollution maps have been produced, presenting spatial and temporal distributions of both emissions and ambient concentrations.

The $PM_{2.5}$ pollution modeling in Bishkek incorporates various inputs using both local data and data from global studies. $PM_{2.5}$ emission maps (spatial distribution of emissions) are used as key inputs in the pollutant transport model. The pollutant transport model uses many other inputs, including meteorological data, topographic data, land use data, and chemical reactions of specific pollutants of concern in the air to determine how the pollutants are spread across the city, leading to different ambient levels at different locations in the city. As local data on some sectors, for instance, residential heating, were limited, some assumptions had to be made in line with existing studies. Naturally, data and information limitations introduce some uncertainty

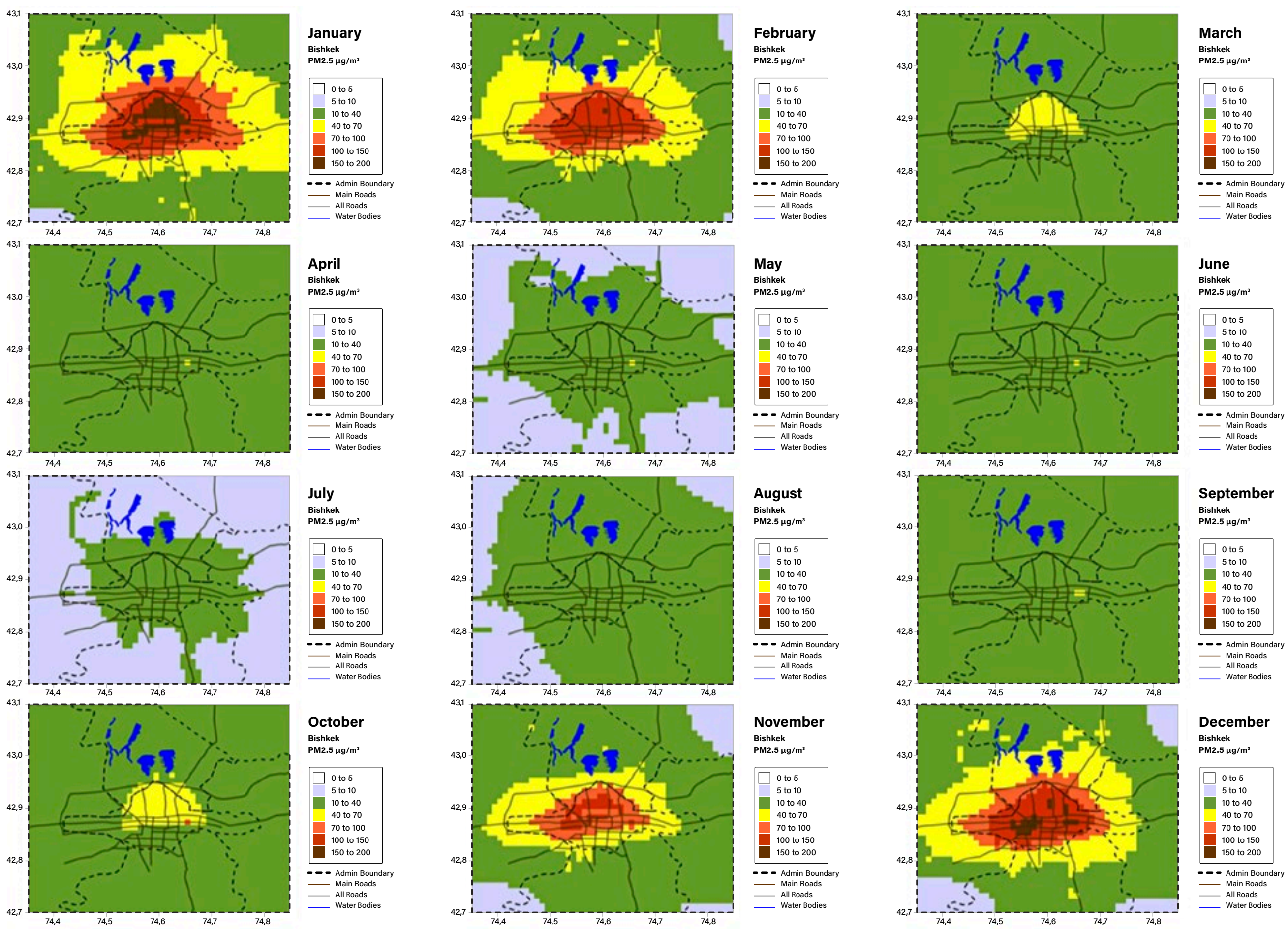
[1] $PM_{2.5}$ stands for fine particulate matter with a diameter less than or equal to 2.5 microns (µm).

in the modeling results, but they present a coherent picture of the current situation and the overall trend.

The modeled $PM_{2.5}$ concentrations match well with the monitored $PM_{2.5}$ concentrations, providing confidence in the robustness of the study's results despite some data limitations. To validate the performance of the model, monthly modeled concentrations were compared with the actual $PM_{2.5}$ concentrations from the analyzed air quality monitoring data. The modeled concentrations matched the monitored concentrations with a 94 percent confidence level. Hence, the model results are considered to adequately replicate the actual air pollution situation in Bishkek.

The modeled $PM_{2.5}$ dispersion in Bishkek's airshed demonstrates that $PM_{2.5}$ concentrations peak in the winter months with the highest concentrations occurring in the northern parts of the city where most of the single-family houses that use coal for heating are located. The modeling results demonstrate that concentrations in the city of Bishkek are over the WHO's annual average guideline (5 µg/m^3) and that even in the summer monthly average concentrations are above 10 µg/m^3 (see Figure ES 1). Therefore, to bring the annual $PM_{2.5}$ average concentration in Bishkek toward WHO guidelines, emissions reduction and mitigation measures should be implemented for a variety of sources to reduce $PM_{2.5}$ concentrations in each month of the year.

Figure ES 1: Modeled average $PM_{2.5}$ dispersion in Bishkek, by month

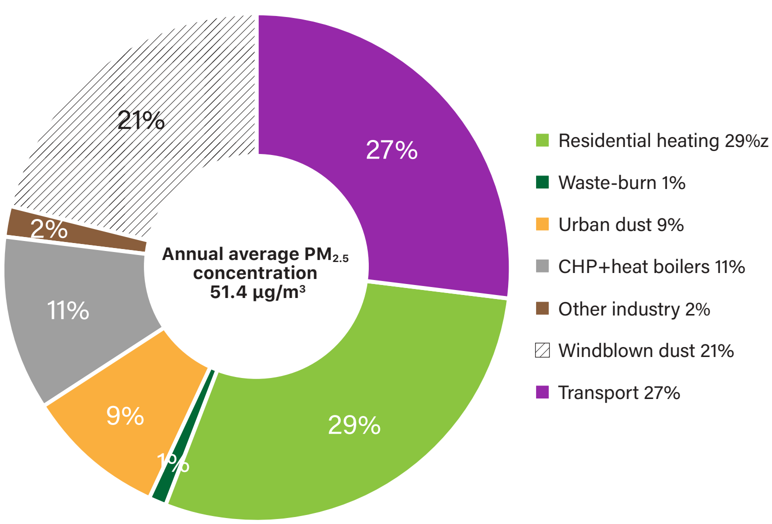


Source: Original elaboration for this publication.

Residential heating, transport, and windblown dust were estimated to contribute the most to average annual $PM_{2.5}$ concentrations, as depicted in Figure ES 2. The seasonal contributions of sources vary throughout the year due to, among others, differences in sectoral activity levels (e.g. residential heating is only used in the winter), meteorological and geographic features (e.g. dry periods in the summer, occurrence of dust storms in the summer). Residential heating has the highest contribution to $PM_{2.5}$ concentrations in the winter, reaching nearly 40 percent in some winter months (for example, January and November). On the other hand, windblown dust[2] has the highest contribution to $PM_{2.5}$ concentrations in the summer when $PM_{2.5}$ concentrations are generally lower than in the winter. Transport is the second most important contributor to $PM_{2.5}$ concentrations in all seasons—in the winter, it is second after residential heating, and in the summer, it is second after windblown dust.

The validated modeling system is used to make an initial assessment of the impacts of different air pollution reduction measures on $PM_{2.5}$ concentrations in Bishkek. This was done by first estimating the change in emissions associated with specific measures, which was reflected in the emissions inventory, followed by running the pollutant transport model to determine the reduction in $PM_{2.5}$ concentrations across the city. Several model runs were carried out to assess the impacts of a range of emission reduction measures and emission scenarios. The short list of measures and emission scenarios that were considered and included in the assessment were compiled by focusing on the largest emission sources and measures commonly used in other cities, complemented by local and international expert opinion. While the focus was on $PM_{2.5}$, the study also estimated the potential reduction of CO_2 emissions for the corresponding scenarios.

Figure ES 2: Source contributions to annual average $PM_{2.5}$ concentrations in Bishkek



Source: Original elaboration for this publication.

Key results

Various emission reduction measures in five key sectors were modeled, and impacts were provided for the individual measures and for combinations of measures within a sector. Table ES 1 shows the percentage reduction in the average annual $PM_{2.5}$ concentration in the Bishkek urban area that results from complete implementation of different air pollution reduction measures, as well as the co-benefit in terms of CO_2 emission reductions. The results are for 2018 but are expected to be indicative for the recent years, as the reductions are presented in percentage terms.

[2] Windblown dust represents particles carried by wind into Bishkek from the adjoining areas such as agricultural and open fields, for instance.

Table ES 1: The impact on $PM_{2.5}$ concentrations from the implementation of individual measures and the benefit of CO_2 emissions reduction

Sector	Measure	Reduction in annual $PM_{2.5}$ concentration (%)		Reduction in CO_2 emissions (%)	
CHP and heat boilers	Combined heat and power (CHP) plant switch from coal to gas	9		29	
	All heat-only-boilers (HoBs) switch from coal to gas	2		1	
	30% more renewables in CHP and HoBs	4		11	
Residential heating[a]	Home insulation - low and high	2	3	0.5	1
	Residential coal to gas - low and high	6	12	2	3
	Residential heat pumps - low and high	5	13	0.5	1
	Residential more electric heating - low and high	5	9	-2	-4
	Complete switch to clean heating	29		8	
Transport	Traffic management	3		5	
	Road dust suppression	1		–	
	Car emissions control - low and high	3	6	6	13
	Marshrutka emissions control	1		1	
	Buses emissions control	0.2		0.3	
	Light duty vehicle (LDV)/heavy goods vehicle (HGV) emissions control	3		4	
	Total of all transport measures combined	13		22	
	Complete switch to zero-emission vehicles	27		51	
Waste burning	Control waste open burning	0.6		–	
	No open waste burning, including dump	1		–	
Greening[b]	Natural dust controls - low	1		–	
	Natural dust controls - high	2		–	

Source: Original elaboration for this publication.

Note: a. Low and high scenarios refer to 20 percent and 40 percent, respectively, of houses using coal implementing energy efficiency (EE) measures or switching to cleaner heating. Additional electricity demand from the existing CHP was modeled for residential heating measures involving switching to electricity for heating (for example, heat pumps and heating with electric boilers/radiators). The CHP emissions depend on the fuel used to generate electricity. **b.** The greening measures are used as natural dust controls primarily affecting windblown dust.

With the large reductions of $PM_{2.5}$ concentrations that need to be achieved in Bishkek, implementing measures across sectors can deliver the required emission reductions. The modeled annual average concentration of $PM_{2.5}$ for Bishkek is 51.4 µg/m³, whereas the WHO guideline is 5 µg/m³. Furthermore, there is no one emissions source sector that could be targeted to deliver all of the $PM_{2.5}$ emission reductions that are required. While an air quality strategy for Bishkek might propose implementing the most impactful or easiest policies in a source sector, it appears evident that the strategy would need to achieve significant emission reductions across multiple source sectors. Therefore, a successful air quality strategy for Bishkek would need to be 'comprehensive' in its scope.

The conducted modeling shows that the largest improvements in air quality in Bishkek can be achieved by substituting coal used for heating

in individual homes and HoBs with cleaner alternatives. Complete switch to clean heating in households currently using coal would have the highest contribution to the reduction of $PM_{2.5}$ concentrations. This scenario is therefore considered as the high-impact scenario. Within the different cleaner heating options considered, the modeled measure showing the largest impact on $PM_{2.5}$ annual concentrations is replacing coal heating with heat pumps at the houses that currently use coal for heating.

Comprehensive road transport policies can have a significant impact on air quality, while waste and greening policies offer multiple benefits beyond air quality improvement. The impact of road transport policies appears to be relatively small if individual policies are considered separately. The transport measure with the highest impact on $PM_{2.5}$ concentrations in Bishkek is the increased adoption of newer vehicles (Euro 5 standard and higher) replacing old, pre-Euro standard vehicles. However, if the modeled transport emission reduction scenarios were considered together, then the resulting impact would be comparable to the high-impact scenario in the residential sector. The impacts of emission reduction scenarios and associated policies in the waste and greening sectors are relatively small. Nevertheless, the benefits from greening policies and measures and restrictions in open waste burning have multiple benefits beyond air quality improvement.

All modeled measures, except the switch to heating using electric boilers/radiators, show co-benefits of reducing CO_2 emissions. Electric radiators are less efficient than heat pumps and therefore use more electricity, which is currently produced by burning coal in Bishkek's CHP. If the source of fuel at the CHP is changed to less carbon-intensive fuels, then it is expected that even this measure will have co-benefits of greenhouse gas (GHG) emission reduction. In addition, $PM_{2.5}$ emission reduction measures typically lead to black carbon (BC) emissions reduction as BC is a major component of $PM_{2.5}$.

Review of the air quality management system in the Kyrgyz Republic

A separate study, titled 'The Air Quality Management System in the Kyrgyz Republic: A Review of Institutional Arrangements', was conducted in parallel to identify any gaps in the current air quality management system (AQMS) in the Kyrgyz Republic. The proper set-up of an AQMS is a key foundation for allowing efficient implementation of emission reduction measures with the ultimate goal to improve public health through reduced air pollution. While the detailed recommendations for strengthening the AQMS in the Kyrgyz Republic can be found in its report, the priority recommendations are as follows:

- Formation of an Inter-Ministerial Air Quality Co-ordination Committee and establishment of the appropriate governmental roles, responsibilities, and structures are the immediate actions needed to support an effective AQMS in the Kyrgyz Republic.
- The development of an air quality policy team, air quality standards and targets, an air quality communications strategy, and the capabilities relating to the air pollutant ambient monitoring network and the air pollutant emissions inventory are urgently needed.
- The development of an air quality master plan for the Kyrgyz Republic and Bishkek, in particular, is also a priority in order to direct the overall air quality work at national and local levels.

Air pollution is caused by activities in a number of sectors and therefore, formation of an inter-ministerial mechanism to efficiently coordinate actions across sectoral ministries will improve air quality governance. The Ministry of Natural Resources, Ecology and Technical Supervision (MNRETS) is the primary institution responsible for the overall AQMS in the Kyrgyz Republic. However, there are various institutions outside of MNRETS that are responsible for activities impacting air quality and for the implementation of the modeled emission reduction measures. Table ES 2 outlines the air quality-related responsibilities of key institutions and suggests the main institutions that might be involved in the implementation of the modeled emission reduction measures.

Table ES 2: Key institutions responsible for air quality management and for air quality improvement measures' implementation

Institution	Responsibilities related to air quality management	Suggested role in measures' implementation
Ministry of Natural Resources, Ecology and Technical Supervision	▪ Overall responsibility for air quality policies and legislation; ▪ Ensuring compliance with environmental legislation; ▪ Environmental and technical supervision; ▪ Establishing emission limit values for enterprises; ▪ Developing emission inventories and source apportionment; ▪ Environmental monitoring (air quality pollution source monitoring); ▪ Environmental assessment.	▪ Overall strengthening of the AQMS; ▪ Establishing and chairing an Inter-ministerial Air Quality Coordination Committee; ▪ Updating legislation related to setting emission limits and overall emission control in key sectors; ▪ Participating in the update of air quality standards; ▪ Establishing air quality policy and technical (emissions inventory) teams; ▪ Improving the technical infrastructure for air quality management (e.g. laboratories, emission monitoring, etc.)
Ministry of Health	▪ Development of air quality standards	▪ Participating in the update of air quality standards
Kyrgyz Hydromet under the Ministry of Emergency Situations	▪ Ambient Air quality monitoring, ▪ Air quality analysis; ▪ Air quality modeling and forecasts.	▪ Developing the ambient air quality monitoring network; ▪ Developing capacities for air quality modeling and forecasts; ▪ Improving the technical infrastructure for air quality monitoring (e.g. air quality monitoring stations, laboratory equipment).
Ministry of Energy	▪ Policies and regulations in the energy sector, including in heat and power generation.	▪ Updating legislation and strengthening enforcement of emission controls in the energy sector; ▪ Fuel switching at CHP Bishkek; ▪ Supporting residential energy efficiency and the adoption of cleaner heating alternatives.
Ministry of Transport and Communications	▪ Policies and regulations in the transport sector; ▪ Setting up technical standards and inspections of road vehicles.	▪ Updating legislation and strengthening enforcement of emission controls in the transport sector; ▪ Strengthening road vehicles' inspections; ▪ Supporting implementation of traffic management measures.

Table ES2

Institution	Responsibilities related to air quality management	Suggested role in measures' implementation
Bishkek Mayor's Office	Responsible for managing a variety of activities at local level such as: ▪ urban planning and development; ▪ management of heat-only boilers (HoBs) and heating networks in Bishkek; ▪ traffic management in Bishkek; ▪ public transport; ▪ inspection of smaller enterprises; ▪ waste management; ▪ greening.	▪ Developing air quality management capacities at Bishkek Mayor's Office; ▪ Conversion of remaining coal-fired HoBs to cleaner fuels; ▪ Supporting residential energy efficiency and the adoption of cleaner heating alternatives; ▪ Implementing traffic management measures to reduce traffic and road dust resuspension in the city; ▪ Improving emission controls for public transport vehicles and marshrutkas; ▪ Improving the greening infrastructure; ▪ Supporting urban planning that helps reduce air pollution; ▪ Strengthening control of open waste burning.

Source: Original elaboration for this publication.

In addition to the institutional stakeholders responsible for the implementation of emission reduction measures, there could be a variety of private sector actors who can be engaged in the implementation of such measures. For instance, governments usually engage commercial banks in funding energy efficiency and clean residential heating measures. Other private sector actors such as heat-pumps' distributors and installers and gas distributor companies could also facilitate the implementation of emission reduction measures. The civil society sector could be involved in communicating the need for emission reduction measures to improve air quality to the general public and to disseminate information about available funding for such measures.

Conclusions and way forward

The study's findings provide a strong analytical foundation for the development and update of strategic air quality documents such as the air quality plan of Bishkek. The purpose of this study is to determine the potential impact on ambient $PM_{2.5}$ concentrations in the Bishkek urban area from a wide range of emission reduction measures. The study provides valuable technical input to the decision-making tool in setting policy priorities to improve air quality in Bishkek. The air quality modeling conducted in the study can serve as a baseline for assessing the effectiveness of implementation of future emission reduction measures.

The results provide a very informative initial assessment of the extent to which $PM_{2.5}$ concentrations could be reduced, contextual information about the relative impact of different types of reduction measures, and the relative importance of reduction measures applied to different emissions sources. By identifying the major sources and comparing the effectiveness of various emission reduction measures, the study provides direction for further policy-related work in different areas. It may be noted that the study has been conducted based on data currently available. There is potential to further refine the data through additional efforts and some targeted investments in data collection both at the level of the emission sources and ambient concentrations. This analysis should be carried out at regular intervals to inform dynamic policy making.

It is recommended that the study and its findings are widely disseminated among the different stakeholders to develop a comprehensive air quality strategy for Bishkek. Recommended next steps include the following:

- Improve the understanding of different sources and their relative contributions to the growing air pollution issue in Bishkek.
- Based on feedback from local stakeholders, consider whether there is a need to revisit the emission reduction measures and scenarios that have been assessed in the study, including consideration of new measures in the modeling exercise.
- Plan the next steps that build on the outcomes of this work, to develop a comprehensive air quality strategy for Bishkek that, in particular, identifies the most effective investment opportunities for improving air quality. Such next steps might include: cost/benefit assessment of implementing emission reduction measures, distributional impacts of implementing air pollution interventions on economic growth and human capital, as well as implementation modalities, including legislation, resources, and capacities and implementation bottlenecks for the agreed policies and measures. Moreover, bottom-up analyses in key sectors relevant to air quality management will inform the need for strengthened sectoral policies and required investments.

Ultimately, to have a functioning AQMS, a comprehensive air quality management plan should be complemented by the capacity of air quality assessment and implementation. Several technical tools and relevant skills within several government ministries, government research organizations, academia, or private companies are needed to assess the existing status of air quality to determine whether air pollution levels have an unacceptably high impact on human health and help evidence-based policy making. Adequate institutional capacity and resources to set up and implement air quality policy and plan are needed, such as by preparing necessary legislative actions and enforcing legislation.

Overall, a comprehensive air quality plan for Bishkek and adequate institutional arrangements and capacity would prioritize policies and measures, monitor their implementation, and adapt as needed to improve air quality. A timeline for the implementation of the priority policies and measures would have to be drawn up, as well as responsible entities for implementation, financing, enforcement, and monitoring. Effective monitoring of policies and measures' implementation would then inform whether or not there is a need to redesign policies and measures, adopt different/additional policies and measures, alter implementation modalities, and/or procure additional funding. Such a process to air quality planning truly reflects the dynamic and complex nature of air quality management and provides flexibility to address issues in the implementation of policies and measures aiming to achieve an air quality target.

The findings from the studies on technical assessment of air quality in Bishkek and the institutional arrangements for AQMS in the Kyrgyz Republic informed designing the air quality improvement project supported by the World Bank. This report identifies the main sources of $PM_{2.5}$ pollution that must be tackled to improve air quality in Bishkek, whereas the assessment of institutional arrangements for AQMS identified gaps in infrastructure and capacity and recommendations to support policy development for air quality. Together, these reports highlight areas that the government of the Kyrgyz Republic can implement to improve air quality in the city of Bishkek and broadly in the Kyrgyz Republic.

1. Purpose of the Analysis

Bishkek made international headlines because of the poor air quality in the city at the end of 2020—beginning of 2021, especially after the IQAir platform announced Bishkek as the most polluted city in the world in 2020.[3] The ranking was mainly based on low-cost sensor data, generally inferior to reference-grade air quality monitoring, but encouraged a number of researchers and development partners to launch assessments about the air quality situation in Bishkek and the causes of air pollution in the city.

Existing information and studies on air quality in Bishkek before the launch of the current analysis were limited and at times contradictory. Some sources[4] claimed that transport was the main source of air pollution in Bishkek, others pointed at windblown dust as the primary reason for $PM_{2.5}$ pollution in the Kyrgyz Republic[5], while others claimed that Bishkek's combined heat and power (CHP) plant[6] or the city's dumpsite[7] are the main culprits for polluted air in the city. Similarly, the approaches that those existing studies took varied; some of the studies relied on emissions estimates, others on satellite observations and modeling, and some on limited monitoring data.

Therefore, there was a need for a comprehensive analysis of the air quality situation in Bishkek, utilizing all available data and resources and enhancing a local emissions inventory to be used as input to a state-of-the-art pollutant transport modeling. The comprehensive assessment that this study undertakes follows a scientific approach to air quality analysis and provides robust results to support the evidence based on the air quality situation in Bishkek.

This study has the following main objectives:

- To collect and consolidate all available data and information—both locally sourced data and data from global databases—about the key emission sources of particles with a diameter less than 2.5 µm ($PM_{2.5}$) in Bishkek
- To create the first spatially and temporally dynamic $PM_{2.5}$ emissions map of Bishkek
- To conduct the first state-of-the-art air pollution modeling over the entire Bishkek airshed to identify source contributions to $PM_{2.5}$ concentrations
- To model the impact on $PM_{2.5}$ concentrations of implementing key emission reduction measures.

While fulfilling the objectives, the study aims to inform the design of the evidence-based priority measures for air quality improvement in Bishkek. Hence, the study provides valuable technical input to decision-making in setting policy priorities to improve air quality in Bishkek. In addition, the air quality modeling conducted in the study can serve as a baseline for assessing the effectiveness of implementation of future emission reduction measures. The study's findings provide a strong

[3] https://www.iqair.com/kyrgyzstan.

[4] Center for Environment and Development. 2018. Air Pollution Sources in Cities in Kyrgyzstan. http://ced.auca.kg/wp-content/uploads/2019/10/Воздух-РС-для-сайта.pdf.

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[7] Moldogazieva, K. 2020. Влияние мусорных полигонов на здоровье населения. http://ekois.net/wp-content/uploads/2020/09/Vliyanie-na-zdorove-naseleniya-musornyh-poligonov.pdf.

analytical foundation for the development and update of strategic air quality documents such as the air quality plan of Bishkek.

As the study's main objectives are related to filling-in the existing knowledge gaps on sources of air pollution and establishing a common understanding of $PM_{2.5}$ emission sources and their contributions to concentrations in Bishkek, the study does not delve further into cost-benefit analysis of the considered emission reduction measures, distributional impacts of air pollution interventions on economic growth and human capital and on the specific arrangements for the measures' implementations. Such analyses are important in developing a comprehensive air quality assessment and will be taken up in the next steps, namely, while supporting the development of Bishkek's air quality plan.

The study's main focus is on $PM_{2.5}$ as the pollutant of the gravest health concern according to the World Health Organization (WHO). $PM_{2.5}$ is associated with causing cardiovascular (ischemic heart disease), cerebrovascular (stroke), and respiratory impacts due to the ability of particles to not only penetrate deep into the lungs but also enter the bloodstream. Moreover, morbidity and mortality from cardiovascular and respiratory diseases are linked to both long-term and short-term exposure to $PM_{2.5}$. Furthermore, long-term exposure to high $PM_{2.5}$ levels has been linked to adverse perinatal outcomes and lung cancer.[8] A World Bank report[9] on the global health cost of $PM_{2.5}$ pollution using results from the Global Burden of Disease (GBD) study estimated that 61 premature deaths per 100,000 people can be attributed to $PM_{2.5}$ pollution in the Kyrgyz Republic. Overall, $PM_{2.5}$ pollution was estimated to cause annual health damages in the country equivalent to 5.1 percent of gross domestic product (GDP). Using the same GBD methodology,[10] this study estimates that the annual health damages arising from the monitored $PM_{2.5}$ concentrations, and subsequently the calculated annual average population-weighted exposure, in Bishkek is equivalent to 1.2 percent of the Kyrgyz GDP.

In addition to $PM_{2.5}$, the study considers the impact of the $PM_{2.5}$ emission reduction measures on emissions of the main greenhouse gas (GHG)—carbon dioxide (CO2). The study also analyzes the key sources of black carbon (BC) in Bishkek—a key component in $PM_{2.5}$ and a short-lived climate pollutant (SLCP).

This report provides context for the air pollution situation in Bishkek (Chapter 2) and describes the methodology and data used (Chapter 3). It continues by summarizing the results from the $PM_{2.5}$ emission sources' analysis (Chapter 4), the conducted modeling (Chapter 5), and the emission reduction scenarios (Chapter 6). Chapter 7 provides key recommendations for improving the air quality management system (AQMS) in the Kyrgyz Republic. Chapter 8 recaps the study's main findings and concludes with suggestions for next steps and for how the study's results can be used and further developed.

8 WHO. Type of pollutants. https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/health-impacts/types-of-pollutants.

9 Awe, Yewande Aramide, Bjorn Klavdy Larsen, and Ernesto Sanchez-Triana. The Global Health Cost of $PM_{2.5}$ Air Pollution: A Case for Action Beyond 2021. International Development in Focus. World Bank, Washington, DC.

10 https://ghdx.healthdata.org/record/ihme-data/gbd-2019-relative-risks.

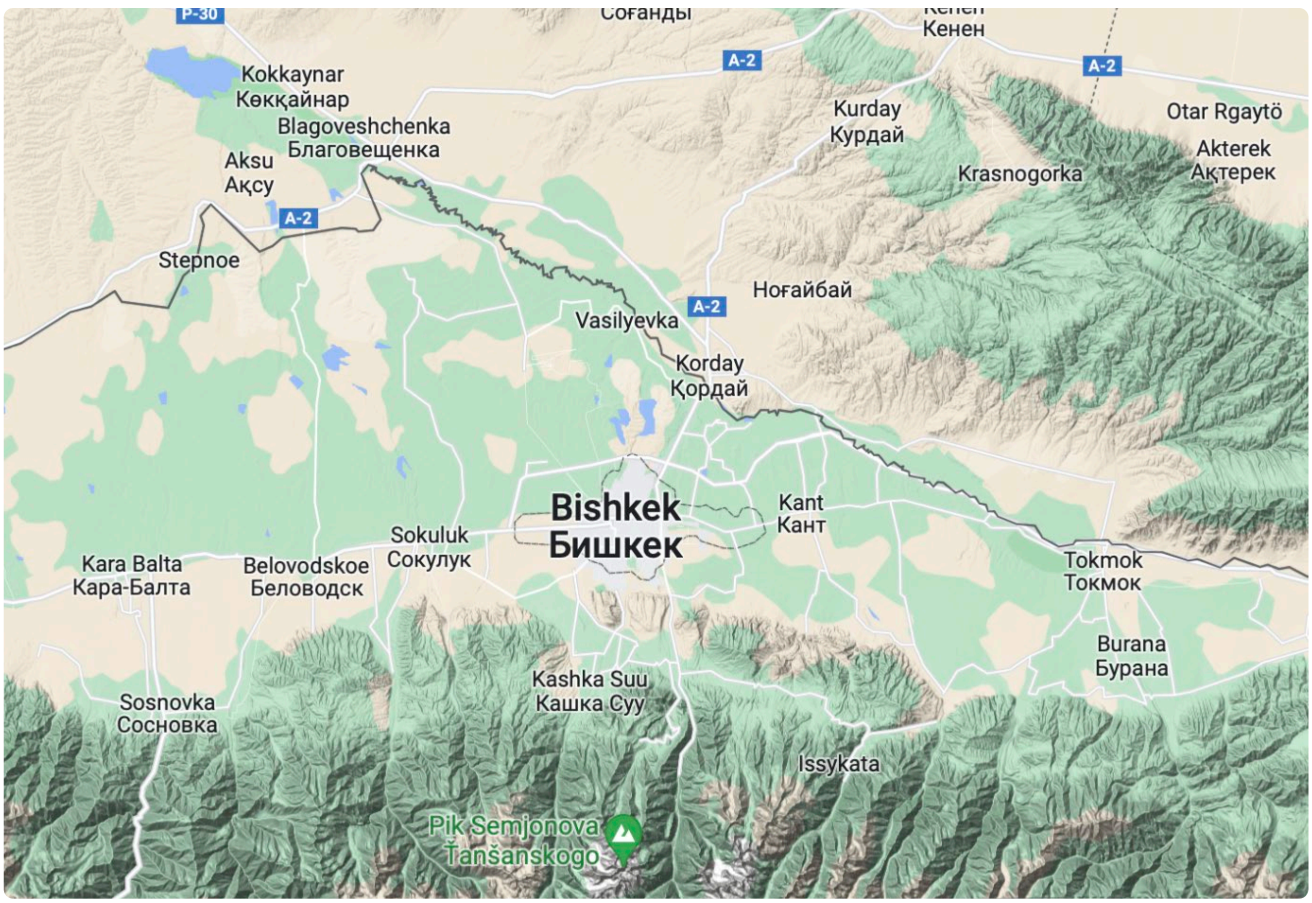
2. Background to Air Pollution in Bishkek

This chapter provides the context for the analytical work conducted in this study and includes three subsections. Section 2.1 describes the general characteristics of Bishkek such as location, population, and topography. Section 2.2 summarizes the key meteorological parameters that influence the dispersion of air pollutants in Bishkek. Section 2.3 provides a general overview of the air quality monitoring infrastructure in Bishkek and the conclusions of the $PM_{2.5}$ monitoring data analysis.

2.1. General context

Bishkek is the capital and the largest city in the Kyrgyz Republic with a population of just over 1 million in 2022.[11] Its urban area spans over 160 km^2, and the city is situated in the Chuy Valley at an altitude of about 800 m. It is located around 25–30 km north of the Kyrgyz Ala-Too mountain range's foothills. Some of the peaks in this mountain range rise over 4,000 m above sea level. A fertile steppe surrounds Bishkek on the city's north, east, and west sides (Figure 1).

Figure 1: Location and topography of Bishkek



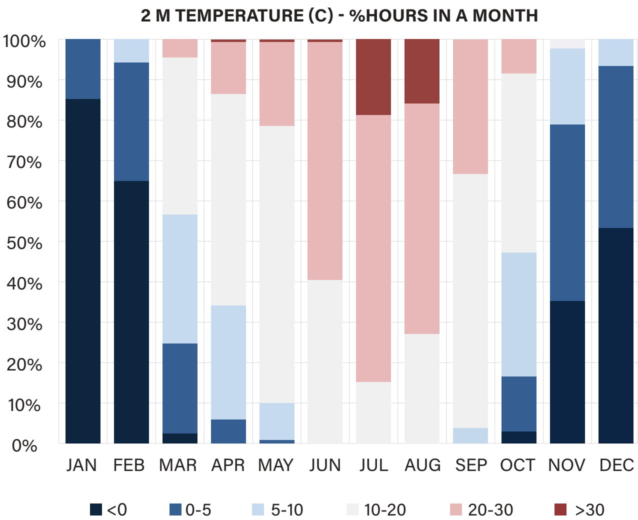
Source: Google Maps.

[11] National Statistical Committee of the Kyrgyz Republic. http://www.stat.kg/ru/statistics/naselenie/.

2.2. Meteorology

Bishkek's climate is characterized by cold winters and hot summers. Snowfall can occur as early as late September–early October and as late as April. The average monthly rainfall is the highest in the spring and the fall. Average daily temperature lows in the winter months are about -9°C, whereas average daily temperature highs in the summer reach 32°C. In addition, during the coldest winter months, temperatures are below 0°C for over 80 percent of the hours in a month and are generally below 10°C throughout the winter months which emphasizes the strong demand for heating in the winter (Figure 2).

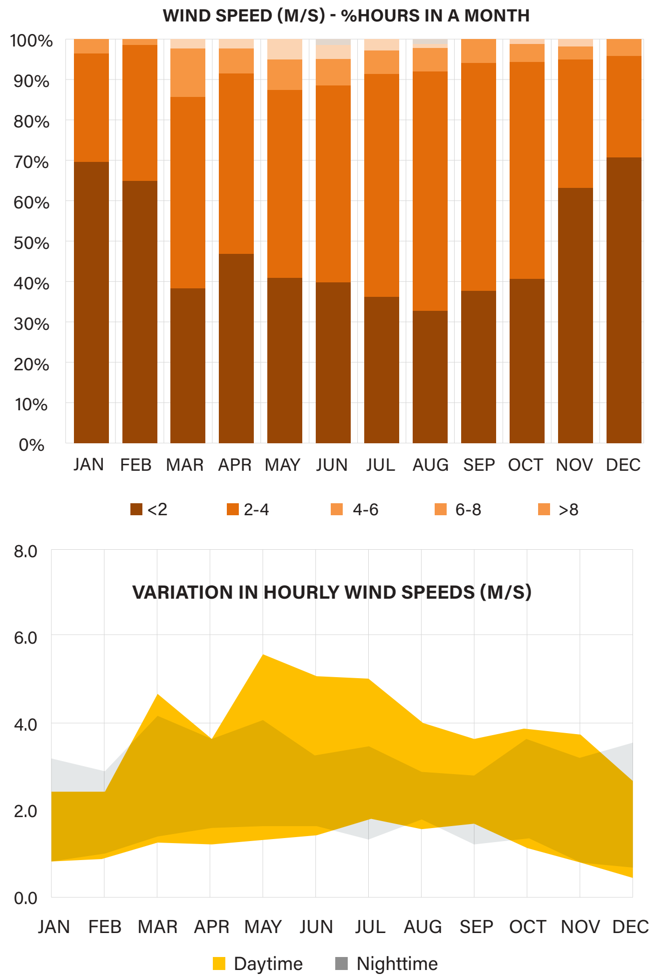
Figure 2: Modeled hourly temperatures in Bishkek at 2 m height by month, 2018, % of hours in a month



Source: WRF model.

Wind speeds in Bishkek are low in the winter months—under 2 m/s for over 60 percent of the time in winter (Figure 3, top). Moreover, there are minimal diurnal differences in wind speeds in the winter months (Figure 3, bottom). These factors are unfavorable for pollutant dispersion in the winter and assist in the trapping of air pollution over the city.

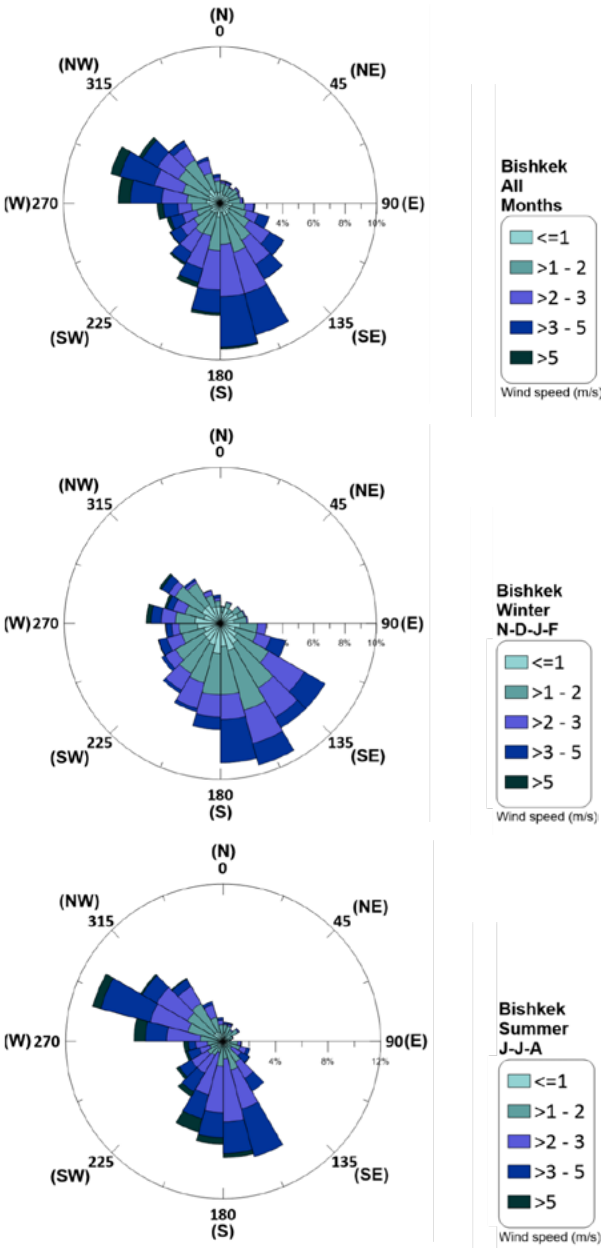
Figure 3: Wind speeds in Bishkek, 2018, by hour (top), diurnal (bottom)



Source: WRF model.

The dominant wind directions in Bishkek throughout the year are from the south and the west (Figure 4, top). Winds coming from the west have the highest wind speeds (the dark blue areas in Figure 4). The wind patterns change throughout the year with mainly Southerly, low-speed winds dominating in the winter months and Westerly, higher-speed winds in the spring and summer months (Figure 4, middle and bottom). Therefore, while low wind speeds trap pollution in the city during winter, higher wind speeds in the spring and summer have the potential to bring particles into Bishkek, especially from areas to the west and south of the city.

Figure 4: Wind directions in Bishkek, 2018, annual average (top), winter[a] (middle), summer[b] (bottom)

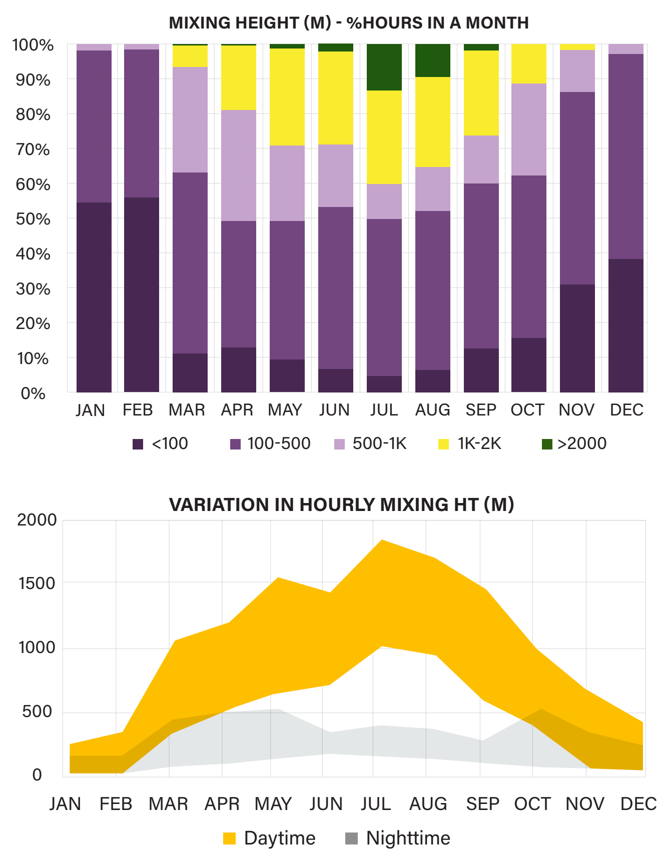


Source: WRF model.
Note: a. Winter months are November, December, January, and February; **b.** Summer months are June, July, and August.

Another key parameter for the dispersion of air pollutants is the mixing height. The mixing height indicates the height above ground of the vertical mixing of air, including suspended particles. A parcel of air will rise up in the atmosphere as long as it is warmer than the ambient temperature. However, once the parcel of air becomes colder than the temperature of the surrounding ambient environment, its rise will slow down and eventually stop. It is at this point that the parcel of air has reached the maximum mixing height beyond which there is no more possibility to disperse further up in the atmosphere. Temperature inversions, frequently observed in Bishkek, restrict vertical mixing and prevent the dispersion of pollution.

As shown in Figure 5, the mixing height in Bishkek can be under 100 m for over half of the hours in some winter months. Overall, winter months are characterized with low mixing heights and small diurnal differences in the mixing height as opposed to summer months when the mixing height is much higher. Low mixing height, combined with low wind speeds in the winter, is conducive to trapping pollution over Bishkek.

Figure 5: Mixing height in Bishkek, by hour (top), diurnal (bottom)



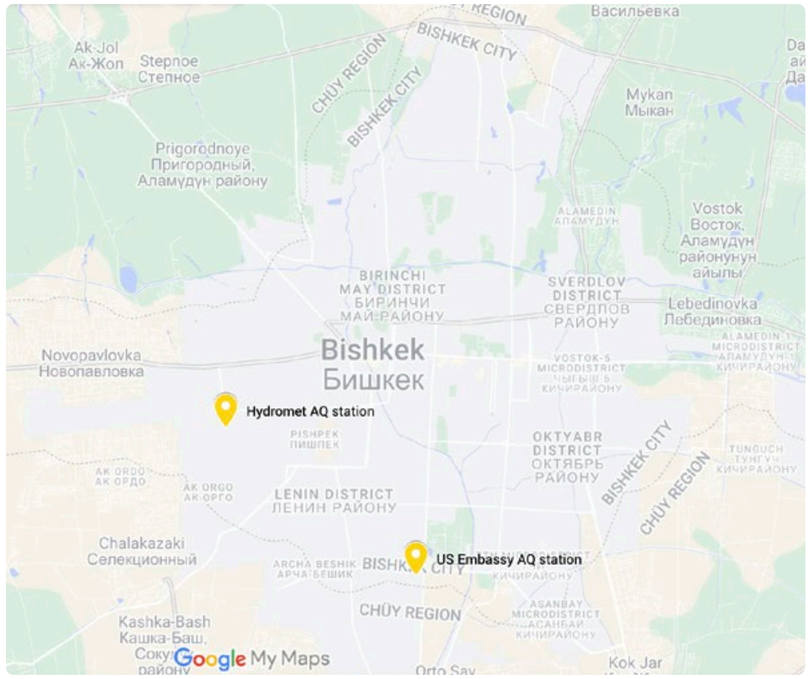
Source: WRF model.

2.3. Air quality data analysis

2.3.1. Air quality monitoring infrastructure in Bishkek

This study analyzed all available $PM_{2.5}$ monitoring data for Bishkek from both automatic reference-grade and sensor networks. There are two automatic air quality stations in Bishkek that meet international monitoring standards. One is managed by Kyrgyz Hydromet, and the other by the US Embassy in Bishkek using EPA reference equipment and methods. The Kyrgyz Hydromet station is located in a residential area in the western part of Bishkek, whereas the US Embassy's station is located in the southern part of the city (Figure 6).

Figure 6: Locations of reference-grade air quality monitoring stations in Bishkek



Source: Google Maps.

The automatic air quality monitoring station managed by Kyrgyz Hydromet was installed in the fall of 2015 and monitors most of the key air pollutants. Due to technical issues, no $PM_{2.5}$ data were reported from August 2018 to September 2020. On the other hand, the US Embassy's automatic air quality monitoring station became operational in February 2019 and has reported $PM_{2.5}$ data since.

The largest air quality sensor network in Bishkek is managed by Kyrgyz Hydromet and consists of 50 Clarity Node sensors. The Clarity Node sensors are calibrated according to the data reported by Kyrgyz Hydromet's automatic air quality monitoring station. The sensors are installed across Bishkek City, including a number of sensors placed just beyond the administrative boundaries of the city (Figure 7). In this respect, the Clarity Node sensor network provides good geographical coverage of Bishkek. Other sensor networks from which data were collected for this study are Purple Air and AirKaz. Data are available for around 15 sensors from each of the two networks.

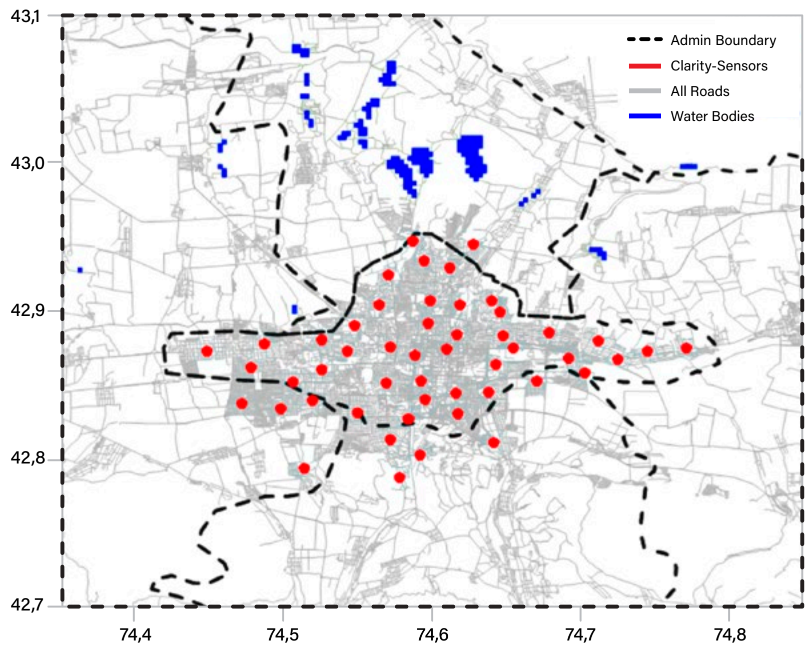
2.3.2. Air quality trends in Bishkek

All collected air quality monitoring data were used in the analysis of air quality trends in Bishkek. The automatic air quality monitoring stations provide the highest data reliability, but there are only two of them in Bishkek. In addition, Kyrgyz Hydromet's automatic air quality station did not report $PM_{2.5}$ data for a two-year period.

On the other hand, data from sensor networks are less reliable as the sensors do not have the precision of the equipment installed in the automatic air qualit2y stations. However, the sensor networks provide a better geographical coverage than the automatic stations and are indicative of air quality trends. Data from the sensor networks were carefully analyzed, and sensors reporting improbable data (for example, $PM_{2.5}$ concentrations higher than PM_{10} concentrations) were not included in the analysis.

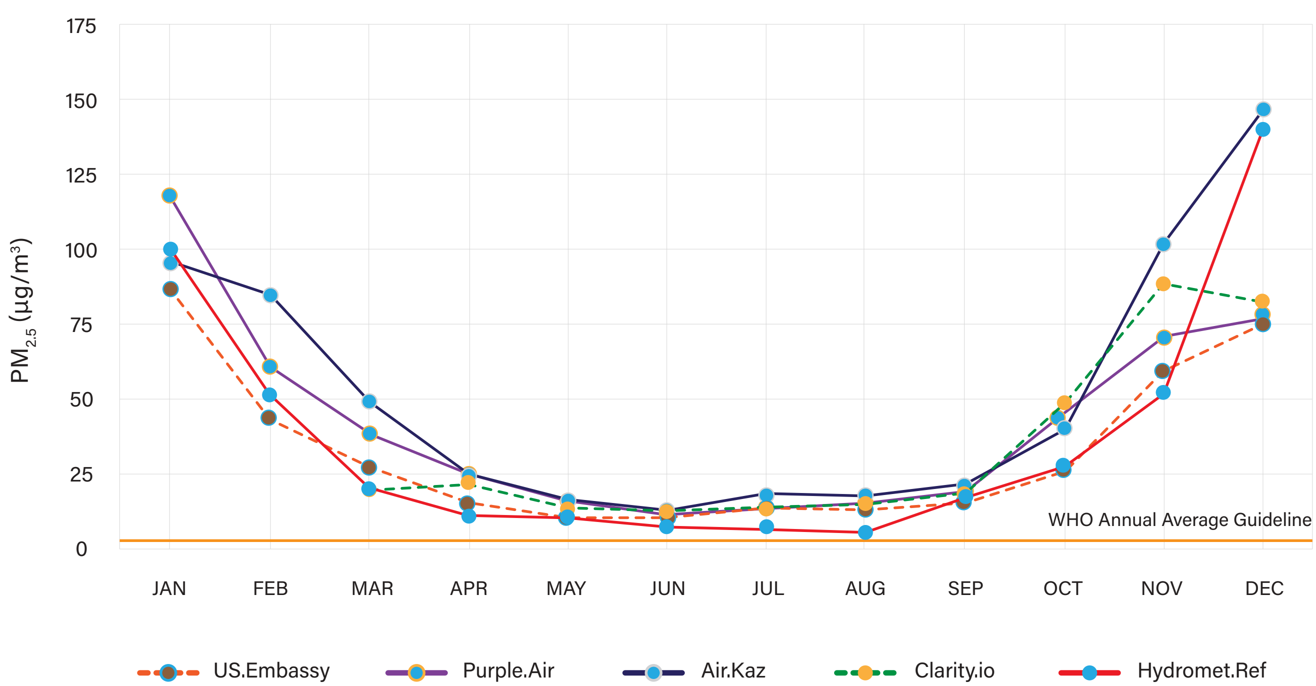
Moreover, due to the different times of installation and periods with no data reported of the various air quality monitoring networks, it was not possible to have a time series with data from all networks that spans over a number of years. Therefore, the available time series from each monitoring network were analyzed separately. Figure 8 shows a comparison between all analyzed monitoring networks over 2020–2021 when data were available from all of them.

Figure 7: Location of Clarity Node sensors in Bishkek



Source: Kyrgyz Hydromet.

Figure 8: $PM_{2.5}$ concentrations in Bishkek, average over 2020–2021, in µg/m³



Source: Kyrgyz Hydromet, US Embassy, Purple Air, and AirKaz.

Despite some differences in the absolute values reported by the different air quality monitoring networks, Figure 8 demonstrates that there is a clear trend in $PM_{2.5}$ concentrations. $PM_{2.5}$ concentrations peak in the winter months (January, February, November, and December) and are the lowest in the summer months (June, July, and August).

Because of the differences in absolute values in monitored concentrations, annual average $PM_{2.5}$ concentrations calculated from the different monitoring networks range from 30 µg/m^3 (Kyrgyz Hydromet station) to 64 µg/m^3 (AirKaz sensor network). Even the lowest calculated annual average $PM_{2.5}$ concentration is six times above the WHO guideline.

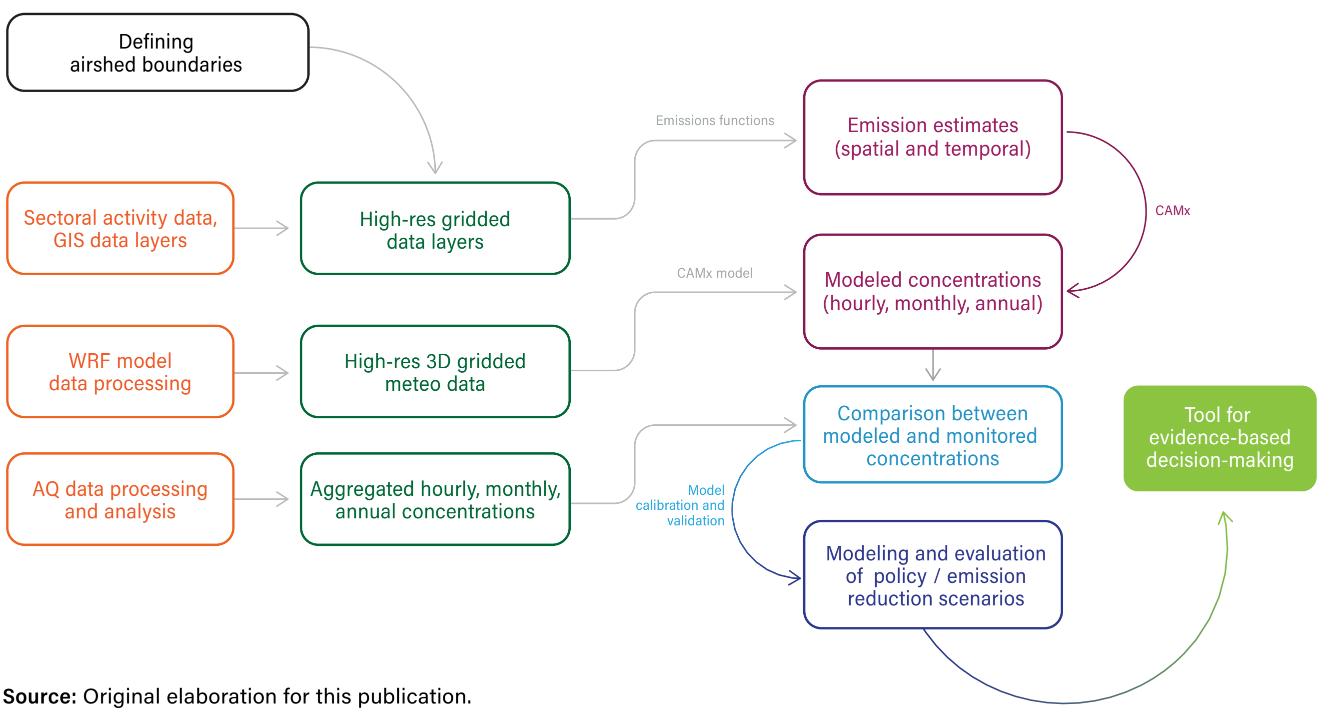
$PM_{2.5}$ concentrations in the winter are extremely high—breaching both Kyrgyz and international air quality standards[12] and potentially causing significant harm to human health. Even in the summer months when $PM_{2.5}$ concentrations are at their lowest levels, concentrations are above WHO guidelines.

[12] WHO annual and daily average $PM_{2.5}$ guideline values are 5 µg/m^3 and 15 µg/m^3, respectively. Kyrgyz annual and daily average maximum allowed $PM_{2.5}$ concentrations are 25 µg/m^3 and 35 µg/m^3, respectively.

3. Methodology and Data Used

The estimation of source contributions to $PM_{2.5}$ concentrations requires the compilation of a baseline high-resolution emissions inventory. For this study, emissions were spatially and temporally distributed over the defined Bishkek airshed, which as a result created the first dynamic emissions map for Bishkek. Emissions were estimated and distributed at a spatial resolution of 1 km^2 by using data from various sources, described in Section 3.2. The approaches to emissions calculations are described in Section 3.4. The high-resolution emissions inventory enables the use of sophisticated models to analyze air pollution dynamics. The photochemical Comprehensive Air Quality Model with extensions (CAMx), which incorporates meteorological inputs from the Weather Research & Forecasting (WRF) model, was used in this study, and the model is described in Section 3.6. The modeling results were compared with the available air quality monitoring data for Bishkek. After model calibration and validation with the monitoring data, the model was used for assessing the impact on air quality of various emission reduction scenarios (Chapter 6). Finally, preliminary results from the study were discussed with stakeholders from the government, Bishkek City administration, development partners, academia, and civil society before finalizing the study's results (Section 3.7).

Figure 9: Schematic illustration of the study's main components

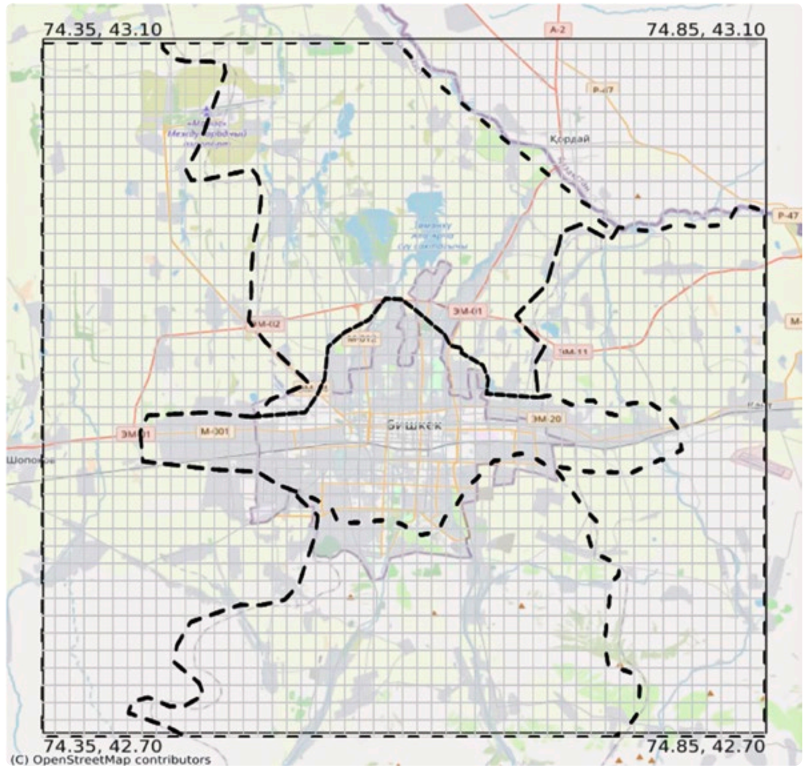


Source: Original elaboration for this publication.
Note: GIS = Geographic information system.

3.1. Definition of the airshed's boundaries

An initial task was to define the area to be studied, that is, the airshed, in such a way as to capture emissions dispersion from sources that possibly affect air quality in Bishkek. Geo-scanning of Bishkek and the surrounding area using Google Earth was performed to identify potential emissions sources. The selected airshed spans 50 × 40 grids with a total area of 1,800 km² (Figure 10). The area covers the main Bishkek City area and the neighboring regions with industrial estates, brick kilns, quarries, the airport, and the dumpsite—sources that might have an impact on air quality in Bishkek.

Figure 10: Bishkek's airshed



Source: Original elaboration for this publication overlaid on a Google Earth map.

Since the spatial grid resolution for this study is 0.01°, that is, each grid is equivalent to 1 km², all the collated information and analyzed results from the study are maintained in standard GIS-ready formats at this grid resolution. The GIS formats also allow the use of 3D modeling techniques. Hence, the following key data layers for air pollution analysis are available for each grid cell of the defined airshed:

Meteorological data layer

- Population layer
- Road network layer
- Level of urbanization layer
- Land use layer
- Topography layer
- Points of commercial activity layer (industries, hospitals, hotels, fuel stations, malls, markets, office complexes, banks, cafes, restaurants, convenience stores, and so on).

The high-resolution layers with key data allowed the estimation of emissions for each grid cell, thus enabling the creation of a spatially and temporally dynamic emissions map for the airshed (Chapter 4). The data from the resulting air pollution modeling are also available for each grid cell of the studied airshed (Chapter 5).

3.2. Data resources

To achieve high resolution of the data and allow for dynamic spatial and temporal emission estimates and pollution modeling, this study used various sources of data—a combination of locally obtained data, data from global databases, and published literature. Moreover, satellite data and data from globally recognized models were used to strengthen the foundations for the modeling conducted in this study.

Locally obtained data included the following:

- Air quality monitoring data from the Agency on Hydrometeorology under the Ministry of Emergency Situations of the Kyrgyz Republic (Kyrgyz Hydromet), including data from the reference automatic air quality station in Bishkek and the 50 Clarity Node sensors installed in Bishkek
- Data from the National Statistical Committee of the Kyrgyz Republic, including data on industrial emissions, energy consumption, fuel consumption, freight and passenger movement, number of registered vehicles in Bishkek, residential energy use, and waste composition.
- Data from the Bishkek Mayor's Office, including data on areas under construction; maps of the district heating infrastructure; location and consumption data of heat-only boilers (HoBs); map of the residential gas distribution network; and data on public transport and shuttles (marshrutki) such as fuel consumption, vehicle fleet, and average mileage of public transport.

The emissions reports that the Kyrgyz Republic had submitted to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) and to the United Nations Framework Convention on Climate Change (UNFCCC) were also analyzed.

Given that a number of development partners were conducting analytical work in the area of air quality in Bishkek, relevant data were obtained from the studies of

- United Nations Development Programme/United Nations Environment Programme (UNDP/UNEP),[13]
- United Nations Children's Fund (UNICEF),[14] and
- International Organization for Migration (IOM).[15]

In addition, the study utilized information from a number of global and local databases:

- **AirNow.** This is the US Department of State's web-based platform for publishing air quality data from US Environmental Protection Agency (EPA) reference grade monitoring stations deployed at US embassies around the world. Data were obtained from the US Embassy air quality monitoring station in Bishkek (https://www.airnow.gov/international/us-embassies-and-consulates/#Kyrgyzstan$Bishkek).
- **Purple Air.** This is a global network of air quality sensors. Data were obtained for the 13 sensors installed in Bishkek (https://www2.purpleair.com/).
- **AirKaz.** This is a regional network of air quality sensors. Data were obtained for the sensors installed in Bishkek (https://airkaz.org/bishkek.php).
- **STATISTA.** This is a commercial data service site, which provides information on vehicle sales, registration by vehicle type and year, population, and GDP (https://www.statista.com).
- **Open Street Maps (OSM) database.** This is used for information about the road network, covering highways and arterial and feeder roads as well as for information about commercial activity points such as hotels, hospitals, apartment complexes, industries, parking lots, fuel stations, malls, markets, office and commercial complexes, banks, cafes, restaurants, and convenience stores (https://www.openstreetmap.org).
- **Global Human Settlements (GHS) Program of the European Space Agency (ESA).** This is

[13] UNDP and UNEP. 2022. Air Quality in Bishkek: Assessment of Emission Sources and Roadmap for Supporting Air Quality Management. Bishkek and Nairobi. https://www.undp.org/kyrgyzstan/publications/air-quality-bishkek-assessment-emission-sources-and-roadmap-supporting-air-quality-management.

[14] UNICEF. 2022. Health and Social Impacts of Air Pollution on Women and Children in Bishkek, Kyrgyzstan.

[15] IOM. 2021. Air Pollution and Its Health Impacts on Internal Migrants in Bishkek, Kyrgyzstan - Assessment Report. Geneva: IOM. https://publications.iom.int/books/air-pollution-and-its-health-impacts-internal-migrants-bishkek-kyrgyzstan-assessment-report.

used for information on the built-up urban area in the airshed for 1975, 1990, 2000, and 2014 (https://ghsl.jrc.ec.europa.eu/datasets.php).

- **LANDSCAN program.** This database provided information on gridded population at a 30-second resolution for the entire city airshed (https://landscan.ornl.gov/). It uses official estimates from the respective governments at the district and ward levels, which are further segregated to finer grids using information on commercial, land use, and night light data fields.
- **FlightStats.** This is a commercial data service, which provides information on domestic and international flight schedules for airports in the airshed (https://www.flightstats.com).
- **Google Earth.** This is used for information on features of interest, identified while scanning the airshed, for which GIS fields are not readily available (https://earth.google.com/web/).
- **MOZART/WACCM[16] modeling system.** This is used for the analysis of the boundary conditions—determining the pollutant fluxes from surrounding areas into the defined airshed.
- **WRF modeling system.** All meteorological data were processed through the WRF modeling system at a spatial resolution of 0.01° and at a 1-hour temporal resolution (https://www.mmm.ucar.edu/models/wrf).
- **Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model.** An emission factors (EFs) database was extracted from the GAINS modeling system for the baseline emissions inventory (https://gains.iiasa.ac.at/models).
- **Washington University in St. Louis.** The university runs a program for long-term $PM_{2.5}$ concentration data based on a global chemical transport model coupled with satellite retrievals (https://sites.wustl.edu/acag/datasets/).

3.3. Data limitations

Despite best efforts to collect data from local and global sources, there are some important limitations of the data available for this study. The key data limitations and approaches to address those limitations are described in Table 1.

[16] Model for Ozone and Related Chemical Tracers/ Whole Atmosphere Community Climate Model.

Table 1: Main data limitations and ways to address them

Data limitation	Approaches to address data limitation
Missing or inconsistent air quality monitoring data: ▪ **$PM_{2.5}$ monitoring data from the reference automatic air quality station at Kyrgyz Hydromet were missing for the period August 2018 to September 2020.** ▪ **$PM_{2.5}$ data from sensors show inconsistencies and improbable values (for example, $PM_{2.5}$ concentrations higher than PM10 concentrations).**	To ensure adequate monitoring data coverage, all air quality monitoring data available for Bishkek were collected and analyzed. Sensor data were analyzed for inconsistencies and improbable values, and when certain sensors showed such, they were excluded from the analysis.

Data limitation	Approaches to address data limitation
No official data on consumption of fuels and on heating appliances used in the residential sector **No data on location of households using coal for heating**	Information from studies, including household surveys, was used and cross-checked to estimate average fuel consumption for residential heating and typical heating appliances used in households. The location of households using coal for heating was deduced from analyzing the existing heating infrastructure in Bishkek (CHP-fueled and HoB-fueled district heating), the buildings' type (multi-family versus single family), the population spread, and urbanization levels.
Lack of information on CHP abatement technologies	In the absence of availability of detailed data for the CHP plant in Bishkek, especially regarding the operation and performance of the pollution abatement equipment, it was assumed that electrostatic precipitator (ESPs) and bag filters at the CHP plant are working with an efficiency of over 98 percent.
Lack of mileage and traffic count data	Mileage data were estimated based on available data from the National Statistical Committee about fuel consumption and freight and passenger movement. Traffic flows were modeled using expert judgment and the data-rich GIS layers about population, urbanization levels, the road network, and points of interest.
Lack of detailed waste data	Estimates for emissions from the dumpsite were conducted based on the available waste composition information, as well as Google Earth imaging of the dumpsite's area on fire, complemented by a site visit to the dumpsite.
Lack of detailed data on smaller industries	Industrial emissions were estimated using energy balance data and other relevant industrial data from the National Statistical Committee.
No activity data for certain source categories (for example, brick kilns and quarries)	Emissions from those sources were estimated based on Google Earth imaging and experience from other countries regarding production levels and practices.
Lack of country-specific EFs	Relevant EFs were obtained from the global model GAINS.

Source: Original elaboration for this publication.

3.4. Emissions calculations

The emission calculations utilized data from the different sources, described in Section 3.2, as well as expert judgment for spatially and temporally distributing emissions across the airshed. Default emission factors from the GAINS database were used in the calculation of emissions. The GAINS model is a widely used model to assess strategies to reduce emissions of air pollutants and GHGs. The model is used for policy analyses under CLRTAP, by the EU and in numerous countries around the world. The GAINS database[17] contains emission factors for over 2,000 technologies that produce emissions and thus, is one of the largest emission factors' database globally. The emission calculations' methodology for the main emission sources is described in the sections below.

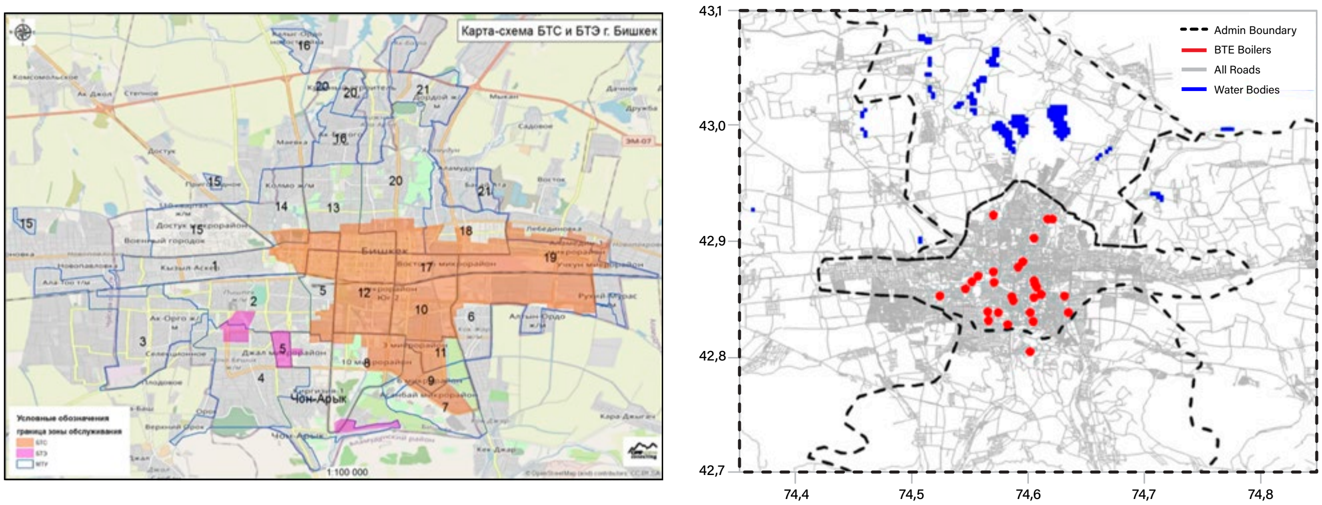
3.4.1. Residential heating

The main activity data needed for the estimation of residential heating emissions is the energy

[17] https://previous.iiasa.ac.at/web/home/research/researchPrograms/air/Global_emissions.html.

consumption for heating by fuels and the type of heating appliances used. Due to the lack of official data on those, the residential heating emissions estimates used a number of data sources to distribute emissions as accurately as possible spatially and temporally. Before the emissions calculations were performed, the availability of residential heating options in Bishkek was analyzed. Maps of the district heating infrastructure and information about the location and fuel consumption of the HoBs were obtained from Bishkek Mayor's Office (Figure 11).

Figure 11: District heating network (left) and HoBs in Bishkek (right)



Source: Bishkek Mayor's Office (left) and original mapping for this publication (right).

The available information indicated that about 50 percent of Bishkek's population is connected to the district heating network, and about 10 percent to the HoBs. Therefore, about 40 percent of Bishkek's population is not connected to any of the two and uses individual heating systems. The individual heating systems are predominantly used in single-family houses (SFHs) and rely on coal.[18]

Most SFHs (98 percent) rely on individual heating systems and 75 percent of those use coal as the primary fuel. Simple low-pressure boilers or traditional coal-fired stoves are the most common heating appliances used in households, sometimes using a combination of fuels for their heating needs, and are characterized by high pollutant emissions and low energy efficiency (EE).[19]

The information presented above aided the process of identifying the locations of SFHs using coal for heating. It was assumed that households in areas not covered by the district heating and/or HoBs used individual heating systems and that 75 percent of the SFHs in those areas used primarily coal for heating, whereas the multi-family buildings in those areas used other heating means (such as electricity and gas). In addition, scanning using Google Earth showed that there is a dominance of SFHs in the northern part of Bishkek.

A number of recent studies[20] have undertaken

[18] World Bank. 2021. Research and Assessment of Existing Heating Systems in Bishkek, Kyrgyz Republic.

[19] Ibid.

[20] Studies by the World Bank, UNICEF, and IOM.

household surveys and have collected coal consumption data. The coal consumption data vary depending on the specific conditions of the households. The data from the different studies indicate about 9 GJ/year/capita average coal consumption for heating, which was the coal consumption assumed in this study, in simple, inefficient appliances (that is, using the respective EFs for such appliances). The temporal distribution of residential heating emissions in the model is a function of ambient temperature—heating is assumed to be used when the temperature is below 15°C. As described in Section 3.2, meteorological data are available for every grid cell of the airshed at a 1-hour resolution, thus allowing for high-resolution and dynamic modeling of residential heating emissions.

Box 1: Calculation of residential heating emissions

Residential heating emissions calculations

Emissions from residential heating of SFHs were calculated using the following equation which is the default approach for residential heating emission calculations in the latest emission calculation methodologies (for example, European Monitoring and Evaluation Programme/ European Environment Agency air pollutant emission inventory guidebook 2019):

$$\mathbf{E_i = f(t)\Sigma_{j,k}EF_{i,j,k} \times A_{j,k}},$$

where

E_i = annual emission of pollutant *i*,

F(t) = a function of ambient air temperature *t*,

$EF_{i,j,k}$ = default emission factor of pollutant *i* for source type *j* and fuel *k*,

$A_{j,k}$ = annual consumption of fuel *k* in source type *j*.

For this study, the equation was solved for each SFH in the following way:

- The emissions equation was solved when hourly ambient air temperature was below 15°C and hence, the heating season is assumed to begin in October and last until end of March.
- The emissions equation was solved for the pollutant (*i*) $PM_{2.5}$.
- The source type *j*, that is, the type of heating appliances used in households, was assumed to be standard heating stoves with no emissions control.
- The fuel *k* was coal.
- The EF for the coal stoves with no emissions control was taken from the GAINS database and equaled 480 g/GJ.
- The annual coal consumption was estimated at 9 GJ/year/capita based on households' survey studies.
- The total emissions from residential heating from SFHs was then the sum of the emissions of each individual SFH.

Default functions from the latest international methodologies were used for the emissions calculations of the other emissions sources in this study.

3.4.2. Road transport

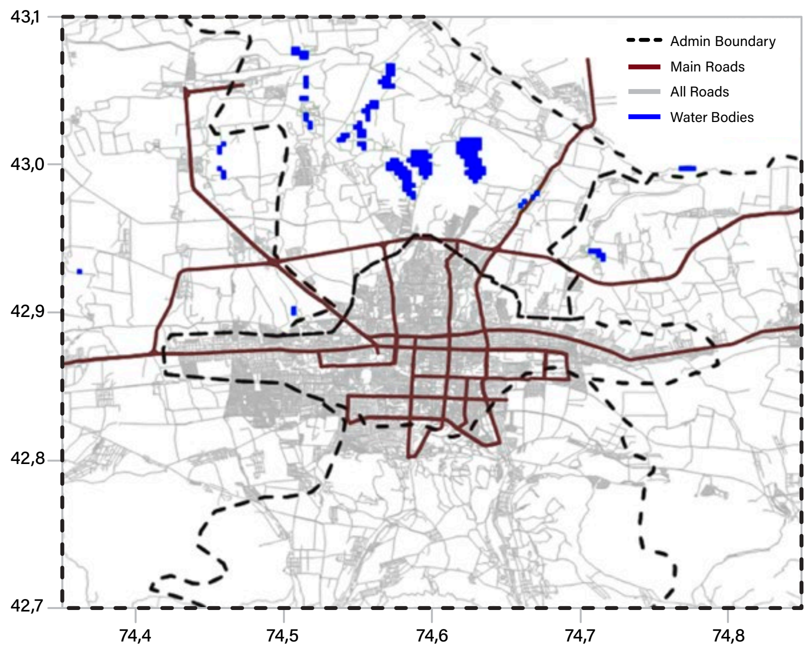
The main activity data needed to estimate emissions from road transport are the structure of the vehicle fleet, fuel consumption, and mileage. Data on the structure of the vehicle fleet were obtained from the National Statistical Committee of the Kyrgyz Republic, as well as from Bishkek Mayor's Office. The data indicated that about 95 percent of all vehicles registered in Bishkek are over 15 years old, and hence, EFs for older vehicle categories (Euro 4 and older) were used. Fuel consumption data from the national energy balance of the Kyrgyz Republic, as well as statistics on freight and passenger movement were used to estimate mileage and were obtained from the National Statistical Committee of the

Kyrgyz Republic. The amount of cargo transport and passengers moved on the national level was downscaled to Bishkek, based on population and economic activity. The obtained mileage was then compared to the calculated transport fuel consumption for Bishkek to verify the mileage assumptions for Bishkek used in the modeling.

To represent emissions spatially and temporally from road transport and in the absence of traffic count data at different locations in Bishkek, several assumptions of the traffic flows in the city had to be made. The detailed, high-resolution layers of the road network, population, urbanization levels, and points of commercial interest, described in Section 3.1, were used to simulate traffic flows in the Bishkek airshed by developing traffic flow calculations as functions of a combination of parameters. For instance, heavy-duty traffic was assumed to use the primary roads to and from the different industries in and around the city, and private vehicle traffic was primarily flowing to and from points of interest (office complexes, commercial areas, hospitals, and so on). In terms of temporal distribution of traffic flows, morning and afternoon rush hours were modeled using office complexes, industries, and different institutions as indication of where traffic is flowing to (for example, to and from work/school), as well as an increase in traffic was simulated to occur on the main roads connecting Bishkek with the airport around the times of flights' arrivals and departures.

In general, traffic flows were spatially and temporally distributed along 310 km of primary roads, 250 km of secondary roads, 4,500 km of tertiary roads, and 1,860 km of other roads across the defined airshed (Figure 12).

Figure 12: Road network in the Bishkek airshed



Source: Original elaboration for this publication.

Box 2: Road transport emissions calculations

Road transport emissions calculations

Emissions from road transport were estimated using the following equation:

$$E_{v,f,g,p} = NV_{v,g} \times S_f \times VKT_{v,g} \times EF_{v,f,g,p},$$

where

$E_{v,f,g,p}$ = total emissions (tons/year) of pollutant *p* by vehicle type *v*, fuel type *f*, and age *g*;

$NV_{v,g}$ = number of vehicles on the road of vehicle type *v* and age *g*;

S_f = the share of vehicles on the road for each fuel type *f*;

$VKT_{v,g}$ = the annual average vehicle kilometers traveled by vehicle type *v* and age *g*; and

$EF_{v,f,g,p}$ = the fleet average emission factor (g/km) for pollutant *p* by vehicle type *v*, fuel *f*, and age *g*.

3.4.3. CHP plant

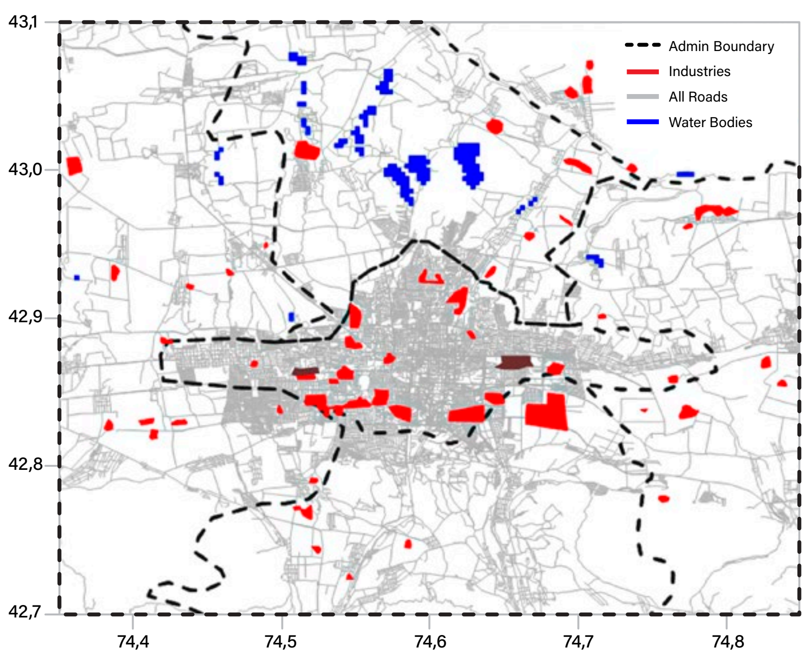
The main activity data about the CHP plant in Bishkek needed for emissions calculations is the installed capacity, the operating capacity, the annual fuel consumption, and stack parameters. In addition, the study estimated the $PM_{2.5}$ emissions originating from the coal storage outside the plant. Scanning of the CHP area, as well as a site visit, identified that coal is stored outside the plant and is not covered (Figure 13). Emissions from the outdoors coal storage at the CHP are a function of the storage area — the exact area was identified using Google Earth.

The CHP in Bishkek has 24 power generation units built in 1961 and the plant underwent modernization in 2017. Currently, 13 power generation units are operational and have a total installed capacity of 910 MW. The plant uses about 1 million tons of local coal and about 650,000 tons of coal from Kazakhstan annually. The coal consumption figures were confirmed by MNRETS. Information on the operation of abatement equipment at the CHP plant such as the efficiency of ESPs is not readily available, and hence, the study utilized information obtained from meetings with CHP staff confirming the operation of ESP filters. The study assumed that ESPs and bag filters are working with an efficiency of about 98 percent considering the recent partial modernization of the CHP in 2017 and information from CHP staff. The operation and efficiency of

Figure 13: CHP in Bishkek[a]

Source: Google Earth.
Note: a. The black area in the picture is coal stored outside the plant.

Figure 14: Locations of the industrial estates in the Bishkek airshed[a]



Source: Original map for this publication.
Note: a. CHP plant (the dark red area on the map) is also included in this map.

ESPs have a large impact on CHP emissions, and therefore represent important information which is suggested to be made publicly available and verified through independent periodic audits of the ESPs efficiency.

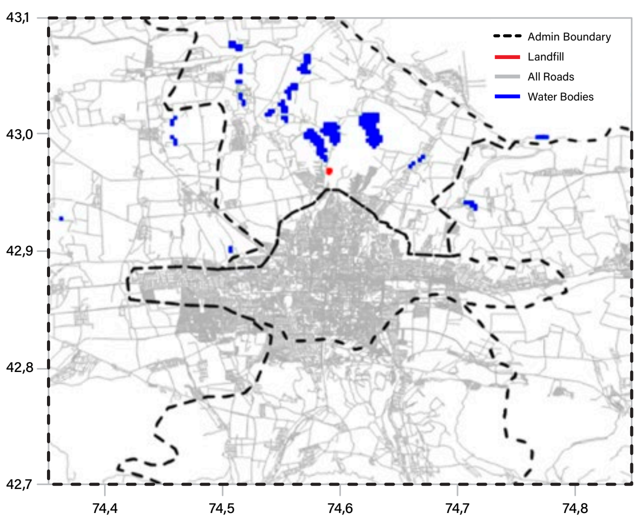
3.4.4. Industrial estates

Apart from the CHP plant, other industrial estates were also considered in the analysis (Figure 14). As mentioned in Section 3.3, industrial emissions were estimated by mainly using energy balance tables and information from the National Statistical Committee. Industrial estates are also important when simulating traffic flows as the traffic flows' functions assume heavy-duty vehicle traffic primarily going to and from industrial estates as well as some private vehicle traffic (for example, for work and commercial activities).

3.4.5. Dumpsite

The main parameters for emissions calculation from dumpsites are the composition of waste and the dumpsite's area that is on fire. Given the limited available data about the dumpsite, assumptions had to be made to model the impact that the dumpsite has on $PM_{2.5}$ concentrations in Bishkek. The assumptions were based on international studies, Google Earth imaging, and a site visit.

Figure 15: Bishkek dumpsite: location (left) and satellite imaging (right)

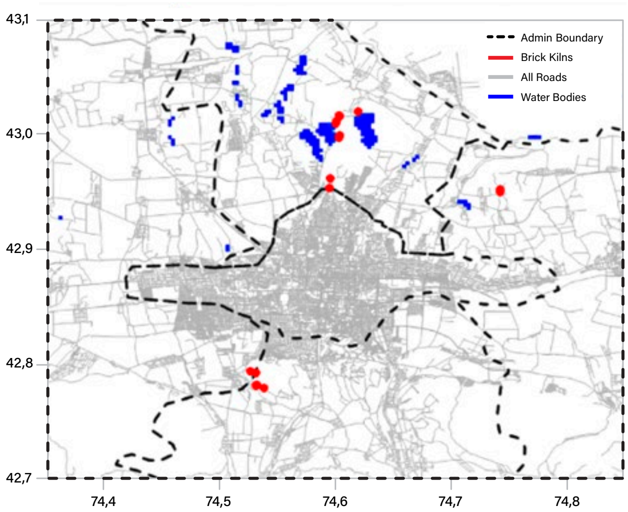


Source: Original map for this publication (left), Google Earth (right).

3.4.6. Brick kilns

The inclusion of brick kilns in the emission inventory is one of the unique features of this study, compared to existing ones. Emissions from brick production arise from the fuels used in the kiln and from the open-air drying of the bricks. There are 16 brick kilns in the defined airshed, mainly outside of Bishkek City (Figure 16). Google Earth imaging and a site visit to one of the brick kilns helped identify the scale of brick production. It was estimated that on average, the brick kilns produce about 20,000 bricks per operational day and the relevant EF for brick production of this scale was applied to estimate emissions.

Figure 16: Brick kilns' location (left) and imaging (right)

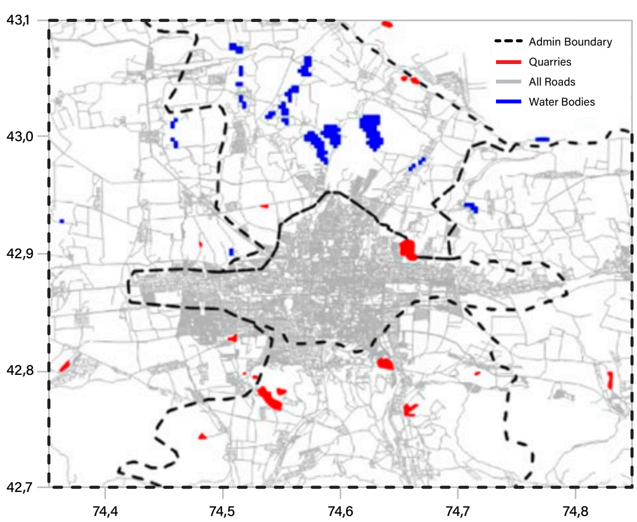


Source: Original map for this study (left), Google Earth (right).

3.4.7. Quarries

Other sources for which emissions were estimated for the first time for Bishkek were quarries. The total identified area with quarries in the defined airshed was 7.5 km^2 with most quarries located outside of the city (Figure 17). Emissions from quarries arise from the crushing equipment using fossil fuels (for example, predominantly diesel) and from the open quarry area. Google Earth imaging was used to identify the production practices at the quarries. Global databases and EFs specific for quarries were used to estimate emissions from this source.

Figure 17: Quarries' location (left) and imaging (right)

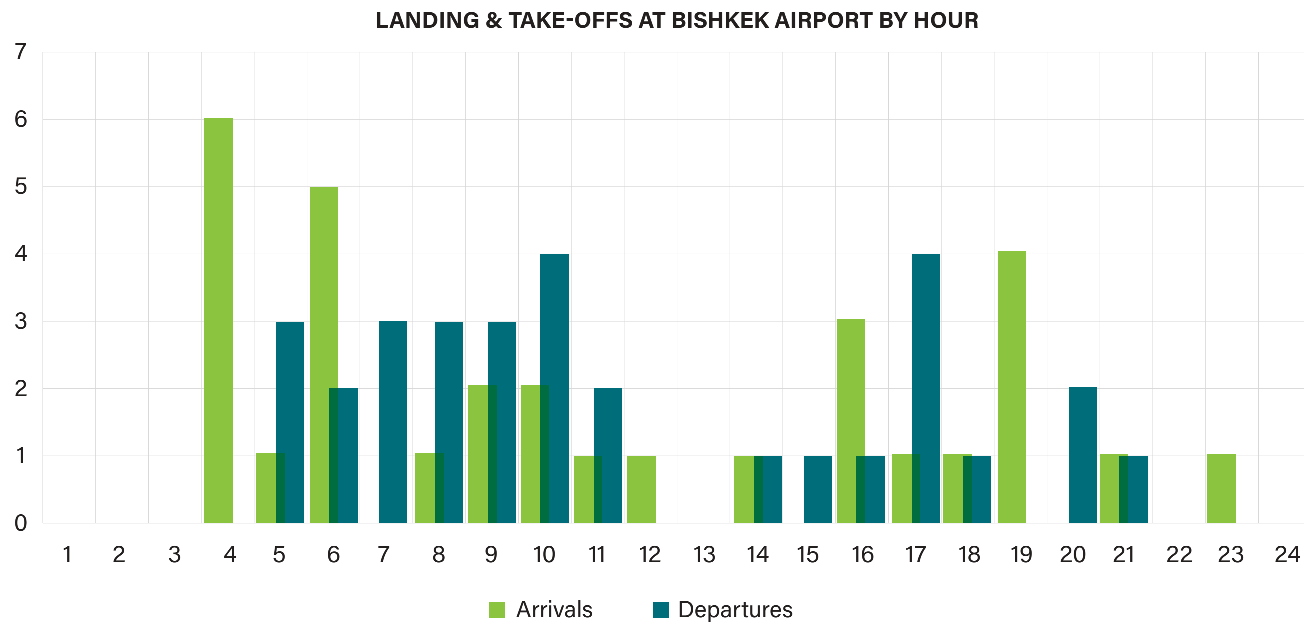


Source: Original map for this study (left), Google Earth (right).

3.4.8. Manas International Airport

Another source that was included for the first time in an emissions inventory for Bishkek was Manas International Airport. Based on information about landings and take-offs, standard EFs used for landings, take-offs, and passenger and freight shuttling were applied to estimate emissions from airport operations. The exact number of landings and take-offs per hour was obtained from the commercial flight database FlightStats[21] (Figure 18). The data on landings and take-offs were also incorporated into the traffic flows' functions—increase in traffic on the main roads connecting Bishkek City and the airport was modeled around the time of landings and take-offs.

Figure 18: Hourly landings and take-offs at Manas International Airport



Source: FlightStats.

3.5. Analysis of other sources of $PM_{2.5}$ pollution

$PM_{2.5}$ pollution can also occur due to natural dust events and dust transport, as well as from other urban-level activities such as construction and road dust resuspension. For this study, urban dust was defined as resuspension of dust on the roads and dust from construction activities occurring inside the defined airshed presented in Figure 10. On the other hand, boundary or windblown dust represents dust coming from outside the defined airshed (outside the red grid pictured on Figure 10) due to natural dust events, degraded pasture and forest lands around Bishkek, $PM_{2.5}$ transport from barren and agricultural land, and so on.

3.5.1. Urban dust

Urban dust consists of two main components—resuspension of dust on roads and dust from construction activities. Road dust resuspension is a function of silt loading on the roads, mix of vehicles on the roads (represented as fleet average vehicle weight), and vehicle-km travelled. Data on vehicle fleet and on vehicle-km travelled were obtained from the National Statistical Committee of the Kyrgyz Republic and from the Mayor's Office (number and type of vehicles registered in Bishkek).

Similarly, for construction dust, the calculation is a function of the amount of area under construction and a coefficient for the expected dust erosion. Data on the amount of area under construction were obtained from Bishkek Mayor's Office.

The study utilized the calculation method for urban dust standardized by US EPA in their US-AP42 protocol.[22] Dust resuspension following the US-AP42 protocol is a standard urban dust resuspension calculation method applied by institutions and academia around the world. In addition, the urban dust emissions are suppressed in the modeling whenever the grid experiences rain or some precipitation, and therefore, urban dust contribution to $PM_{2.5}$ concentrations is assessed dynamically considering the meteorological conditions.

3.5.2. Windblown dust

Natural dust events and dust transport from barren, agricultural land; degraded lands; and some commercial activities, such as quarries or borrow pits, giving rise to windblown dust, affect $PM_{2.5}$ concentrations across the globe. Global model data show that windblown dust is an important contributor to $PM_{2.5}$ concentrations in the Central Asia region. The GBD-MAPS database estimates that 44 percent of $PM_{2.5}$ concentrations in Central Asia are attributed to windblown dust.[23] Thus, any air quality analysis will be incomplete without considering the contribution of windblown dust to $PM_{2.5}$ concentrations. Traditional box models stop at the boundary of the airshed, and anything coming from outside the defined airshed is largely ignored. Therefore, the boundary conditions (that is, dust transport from outside the defined airshed) are essential for running the chemical transport model so that the contribution of sources outside the airshed are also included.

The boundary conditions for Bishkek modeling were taken from the MOZART/WACCM global model[24] which is one of the models and pre-processors included in the CAMx modeling system used in this study (Section 3.6). Given the absence of any major activity outside the designated airshed (identified through geo-scanning and reflected in the land-use layer in the modeling) and given the well-documented occurrence of dust events in the region, it is assumed that most of the boundary activity is windblown dust.

The analysis for Bishkek uses the calculations from the global model MOZART/WACCM, in which the windblown dust is calculated using two main factors—presence of dry and dusty land and the wind speeds above a certain threshold for the dust to uplift, entrain, and get transported. In this way, the model dynamically calculates for each grid of the defined airshed the $PM_{2.5}$ load that is attributable to windblown dust. The MOZART/WACCM is well established and has multiple applications globally, including in areas like the Sahara, the Gobi, and the Middle East.

21 https://www.flightstats.com.

22 https://www3.epa.gov/ttnchie1/ap42/ch13.

23 Washington University in St. Louis. Atmospheric Composition Analysis Group: GDB-MAPS – Global. https://costofairpollution.shinyapps.io/gbd_map_global_source_shinyapp/.

24 https://www2.acom.ucar.edu/gcm/waccm.

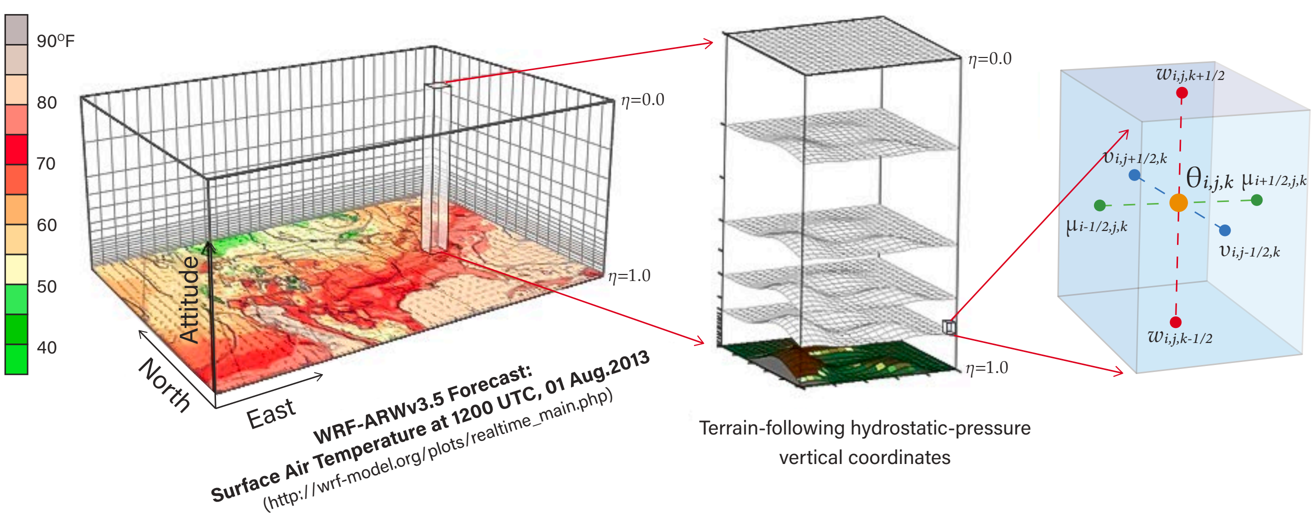
3.6. Approach to modeling

Modeling of air pollution utilizes meteorological data and emissions data to simulate the dispersion of air pollution over an airshed. Using the approaches for emissions calculations presented in Section 3.4, this study created a spatially and temporally dynamic emissions map for the defined airshed. The emission data were then coupled with spatially and temporally dynamic meteorological data layer to allow for high-resolution modeling at an hourly scale. This study used CAMx, which incorporates meteorological inputs from the WRF model.

There are several chemical transport models available with varying degrees of complexities in handling and processing the emissions and providing the final output in the form of concentrations. These range from simple box models to moderate physics and chemistry models using Lagrangian and Gaussian solvers to Eulerian models that are capable of processing the emissions in a 3-dimensional setting taking into consideration both advection and chemical transformations to the fullest extent possible. CAMx is an open-source, Eulerian state-of-the-art modeling system which aids in evaluating not only total concentrations, but also in apportioning sources and regions, at regional and urban scales and at multiple time scales and therefore, was deemed as the most appropriate model to fulfil the study's objectives. The CAMx modeling system has several applications as federal and state level case studies in the United States and multiple research applications worldwide.

WRF is a state-of-the-art mesoscale numerical model widely used for atmospheric research. It is used in a number of national meteorological centers across the world. With the help of the WRF model, 3D meteorological data were prepared for this study. The meteorological data are available at a spatial resolution of 0.01° and at a 1-hour temporal resolution. The 3D meteorological modeling that was conducted using WRF allows for the consideration of topography's impact on meteorological parameters and provides realistic simulations of the relevant meteorological conditions for air pollution modeling (Figure 19).

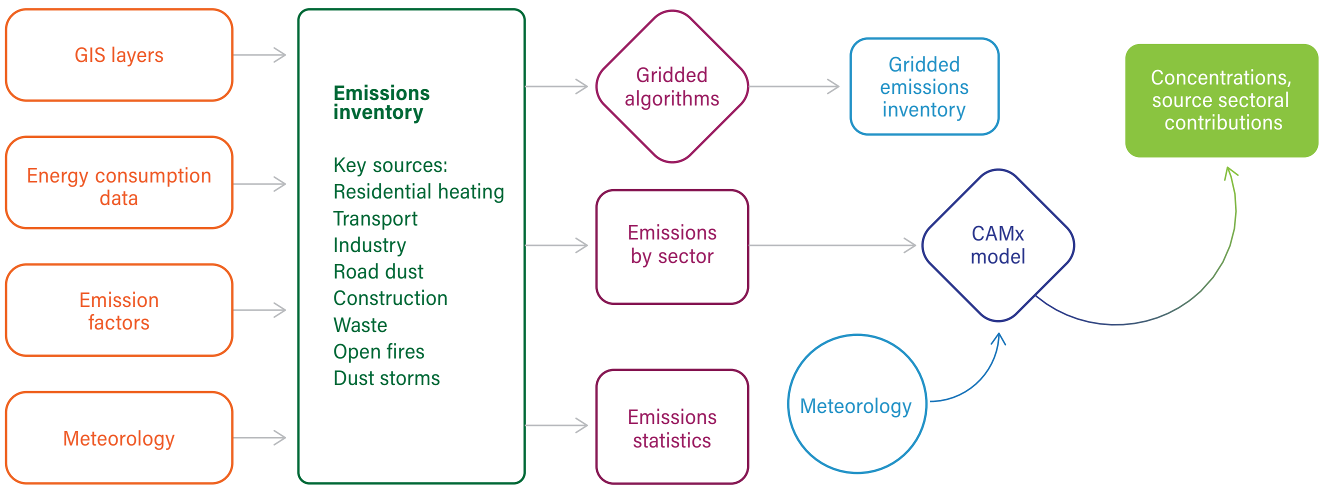
Figure 19: 3D meteorological modeling with the WRF model



Source: WRF model.

The CAMx model is a state-of-the-art photochemical model for simulating dispersion of air pollutants over varying scales—ranging from micro (neighborhood) to macro (continent) scale. CAMx is supported by a number of institutions, including the US EPA. The CAMx modeling system has a complex modular architecture that combines inputs from other modeling systems (such as WRF), as well as from user pre-processed data. The core components of CAMx include input data for emissions calculations (for example, energy consumption data and EFs), GIS layers, and meteorological data that are then processed by CAMx to result in modeled pollutant concentrations and source sectoral contributions to those concentrations (Figure 20).

Figure 20: Schematic diagram of the CAMx modeling system



Source: CAMx model.

As mentioned above, the WRF model was the source of meteorological input data to CAMx. With regard to emissions data, emissions are treated in two main ways in CAMx:

- Gridded emissions that are released in each 3D cell of the defined airshed
- Point emissions for which each emitting stack is associated with coordinates and a time-varying emission function.

Residential, commercial, mobile, nonindustrial, small industrial, and natural emission sources were defined as gridded emissions and are characterized by space- and time-varying emission rates. The emission rates are influenced by the additional layers included in CAMx for this study such as population distribution, housing density, road transport network, vegetative cover, and so on, described in Section 3.1.

Large stationary sources such as the CHP, for instance, were modeled as point emissions. In contrast to gridded emissions, the point emissions are associated with a specific location, but the emission rates are still time-varying. The plume rise from point emission sources is determined by CAMx and depends on stack-specific parameters such as height, diameter, velocity, and temperature of exiting gases. These parameters coupled with the ambient meteorological conditions provide the individual temporal emission rates of each point source.

Moreover, CAMx has a built-in module for particulate matter (PM) source apportionment to identify the sources of PM pollution. CAMx uses multiple tracer families to identify the sources of primary PM emissions and secondary formation of PM in the atmosphere. By including secondary formation of PM, CAMx simulates the actual atmospheric chemistry and provides a robust source apportionment analysis which is an essential tool for decision-making in air quality management.

This study created emission maps for each of the sources described in Section 3.4, and in this way, the model is flexible to 'switch on and off' certain sources to analyze the impact of individual sources on air pollution in Bishkek. In addition, having the various emission sources as different layers within the modeling system allows for assessing 'what-if' scenarios—the overall impact on air quality of emission reduction measures targeted at a specific source.

3.7. Consultation process

A significant amount of publicly available data from governmental institutions, development partners, civil society, and global databases were collected for the first run of the modeling. The approach used in this study as well as the preliminary findings of the modeling were then presented to a wide range of stakeholders in Bishkek.

On September 21, 2022, MNRETS invited the main institutions involved in air quality management to a presentation of the study's preliminary results. In addition to the various departments of MNRETS, other institutions such as Kyrgyz Hydromet, Ministry of Transport, National Statistical Committee, and different departments in Bishkek Mayor's Office were present and provided their feedback.

On September 22 and 23, 2022, the preliminary study's results were presented to the civil society, academia, and the main development partners involved in air quality work. Feedback was also collected from these sessions.

Following the stakeholder consultations, the study's team embarked on site visits of places of interest or for which data availability was limited. The team visited a brick kiln, the dumpsite, and the area around the CHP plant and made observations about natural and roadside dust sources outside of Bishkek City. As a result of the stakeholder consultations and the site visits in September 2022, additional data requests were sent to institutions. A second run of the modeling was performed after receiving the additional data requested.

The updated findings of the study were then presented again to a wide group of stakeholders before finalizing the study. For logistical reasons, two separate sessions took place at MNRETS on December 1, 2022—one with the civil society organizations, academia, and development partners and another one with governmental institutions. The December consultations attracted even broader stakeholder participation—for instance, the Ministry of Health and the Road Safety Agency were also present. The feedback received from those meetings was used to further fine-tune and finalize the modeling—the results of which are presented in the following sections.

4. $PM_{2.5}$ Emission Sources Analysis: Results

The $PM_{2.5}$ emissions source analysis builds on the emissions inventory compiled in an UNDP/UNEP report.[25] The emissions inventory in the UNDP/UNEP report serves as the initial base for the emissions analysis in this study. The emissions inventory in this study further developed the existing emissions inventory by

- Adding unstudied emissions sources such as construction, quarries, brick kilns, and Manas International airport;
- Mapping emissions sources by location, size, and geographical features using the latest satellite imagery; and
- Creating a spatially and temporally dynamic emissions map of Bishkek at a spatial resolution of 0.01° (~1 km^2), suitable for chemical transport modeling.

The resulting emissions estimates are presented in Table 2. Transport emissions account for nearly one-third of the total annual $PM_{2.5}$ emissions in Bishkek. The second largest emissions source annually, albeit mostly concentrated in the winter months, is the residential sector—26 percent of total annual $PM_{2.5}$ emissions. Urban dust (from construction activities and resuspension of dust from roads) and industries are the two other main emissions sources in Bishkek with 20 percent and 17 percent share in total annual $PM_{2.5}$ emissions, respectively.

Table 2: $PM_{2.5}$ emissions estimates for Bishkek, 2018

Emissions source	Description	$PM_{2.5}$ emissions, tons/year
Transport	Includes all road transport and emissions from the airport	1,737.6
Residential heating	Includes emissions from residential heating and cooking	1,424.0
Urban dust[a]	Includes emissions from construction activities and resuspended dust from roads	1,157.8
CHP and HoBs	Includes emissions from the CHP plant and HoBs	751.7
Industry	Includes emissions from other industrial estates, excluding the CHP plant, quarries, and brick kilns, as well as from diesel generators at commercial buildings	249.2
Open waste burning	Includes emissions from the dumpsite	168.3
Total		**5,488.6**

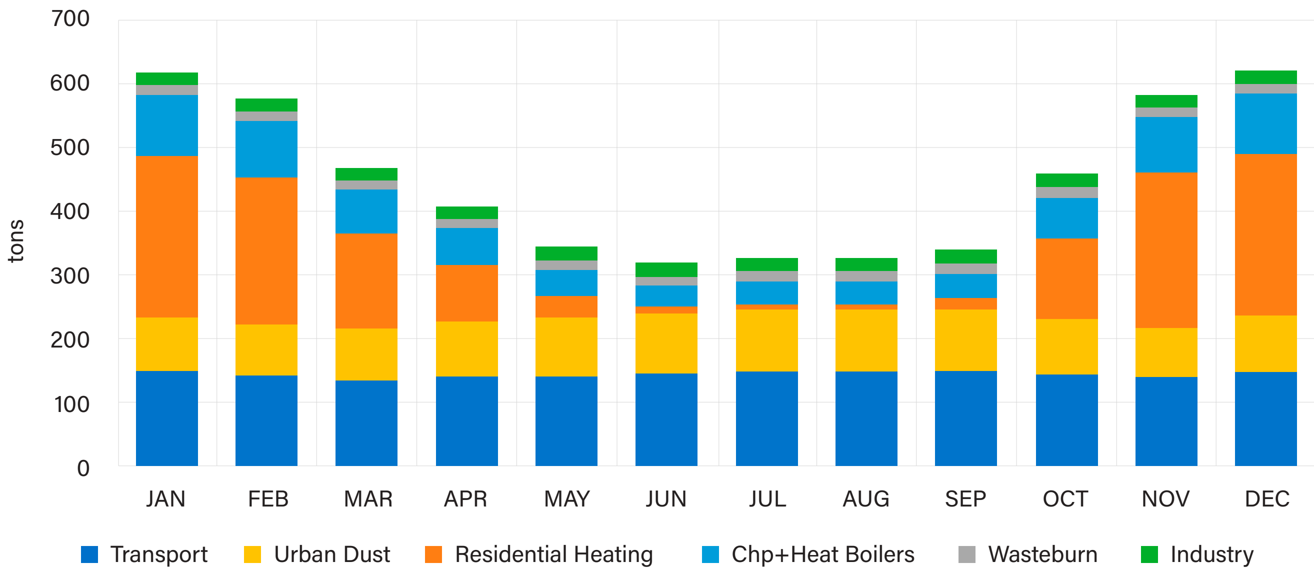
Source: Original calculations for this publication.

Note: a. Windblown dust is a source of direct $PM_{2.5}$ concentrations, and therefore, windblown dust is not included as an emissions source. Windblown dust is included in the modeling as $PM_{2.5}$ loads for each airshed's grid estimated from the global MOZART/WACCM.

[25] UNDP and UNEP. 2022. Air Quality in Bishkek: Assessment of Emission Sources and Roadmap for Supporting Air Quality Management. Bishkek and Nairobi. https://www.undp.org/kyrgyzstan/publications/air-quality-bishkek-assessment-emission-sources-and-roadmap-supporting-air-quality-management.

Emissions levels throughout the year are not constant—for instance, residential heating emissions occur only in winter months. Therefore, it is important to analyze the temporal distribution of emissions sources. Figure 21 shows that even though transport sector emissions have the highest annual total, residential sector emissions are dominant in the winter months. Similarly, urban dust emissions are higher in the summer months than in the winter months because of increased construction activity and higher dust resuspension from roads. Industrial emissions have a relatively stable share in total emissions in the different months of the year.

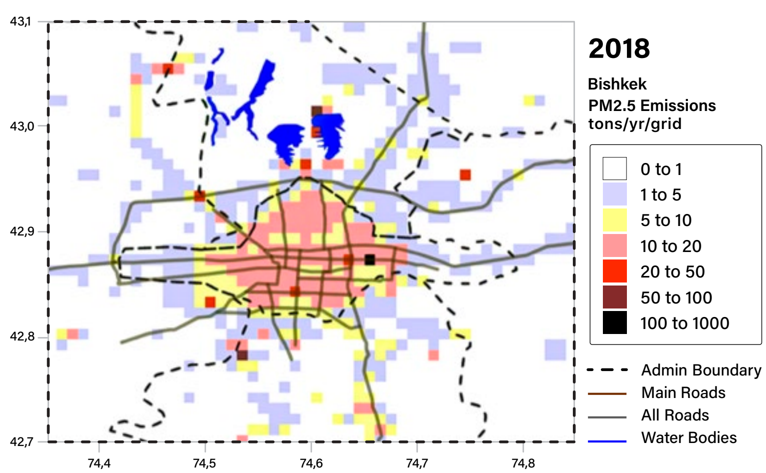
Figure 21: Monthly variations in $PM_{2.5}$ emissions in Bishkek by sector



Source: Original elaboration for this publication.

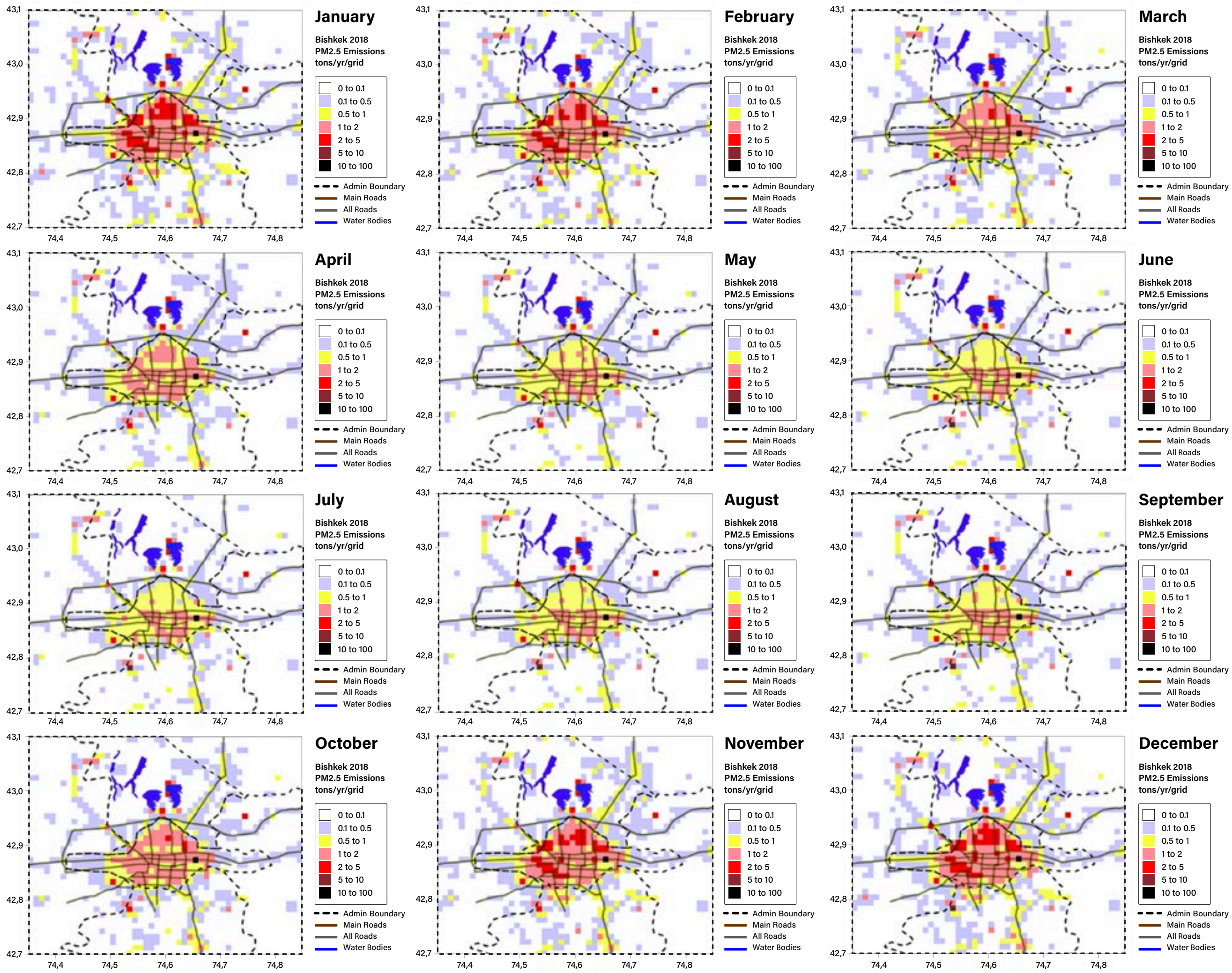
In addition to temporally distributing $PM_{2.5}$ emissions in Bishkek, this study mapped emissions from the different emissions sources at an approximately 1 km^2 resolution. The latest year with available data before the COVID-19 pandemic was used as a baseline year for the emissions mapping to avoid skewing the spatial distribution of emissions due to the impact of the pandemic—especially with respect to transport emissions during the lockdowns. Figure 22 shows the spatial distribution of $PM_{2.5}$ emissions in Bishkek for the entire 2018, whereas Figure 23 shows the monthly emissions maps.

Figure 22: $PM_{2.5}$ emissions map for Bishkek, 2018



Source: Original elaboration for this publication.

Figure 23: $PM_{2.5}$ emissions map for Bishkek, 2018, by month



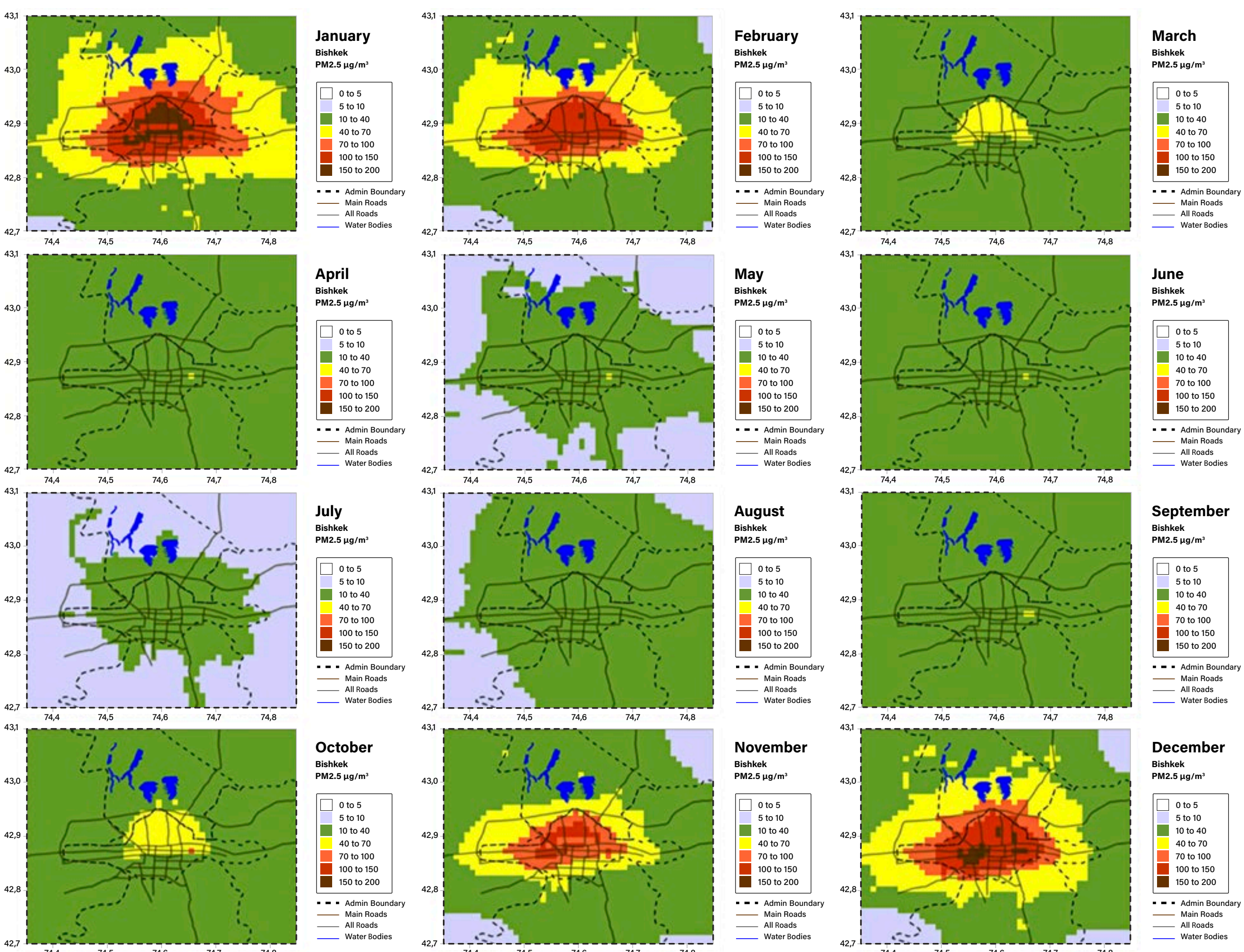
Source: Original elaboration for this publication.

As expected, the single largest source of $PM_{2.5}$ emissions in Bishkek is the CHP plant (the black grid on Figure 22). Other large single sources of $PM_{2.5}$ emissions include some quarries and brick kilns. Overall, the majority of emissions in Bishkek's airshed occur within the city boundaries and are along main roads and in residential areas, especially in the north of the city where there is a higher number of SFHs using coal for heating.

5. $PM_{2.5}$ Modeling Analysis

There is no linear correlation between $PM_{2.5}$ emissions and $PM_{2.5}$ concentrations. The translation of emissions into concentrations is affected by a number of factors among which are the location of the emissions source, characteristics of the source (height of emissions release, temperature and velocity of gases, and so on), meteorological conditions, and topography. Therefore, to determine how emissions translate into concentrations, modeling needs to be conducted considering all these. This chapter describes the results from the chemical transport modeling using the CAMx system, coupled with WRF meteorological data, conducted in this study. Information on the dispersion of $PM_{2.5}$ concentrations in Bishkek's airshed and the source contributions to $PM_{2.5}$ concentrations are presented in the sections below.

Figure 24: Modeled average $PM_{2.5}$ dispersion in Bishkek, by month



Source: Original elaboration for this publication.

5.1. $PM_{2.5}$ dispersion

The spatially and temporally dynamic emissions map was coupled with spatially and temporally dynamic meteorological data layer to allow for high-resolution modeling at an hourly scale. CAMx, which incorporates meteorological inputs from the WRF model, was used in this study. The approach to modeling was described in Section 3.6.

Figure 24 illustrates the average monthly $PM_{2.5}$ dispersion across Bishkek's airshed for 2020–2021. Average $PM_{2.5}$ concentrations were modeled and are available for each grid of the airshed (approximately 1 km² resolution).

The modeled $PM_{2.5}$ dispersion in Bishkek's airshed demonstrates that $PM_{2.5}$ concentrations peak in the winter months, in line with what has been reported by air quality monitoring networks. In addition, concentrations in most parts of the city during winter are well above international standards. In some months, such as January and December, $PM_{2.5}$ average monthly concentrations are over 150 µg/m³ (the dark red areas on Figure 24) in large areas of Bishkek City; such concentrations are more than 10 times over WHO's daily average guideline (15 µg/m³), for instance.

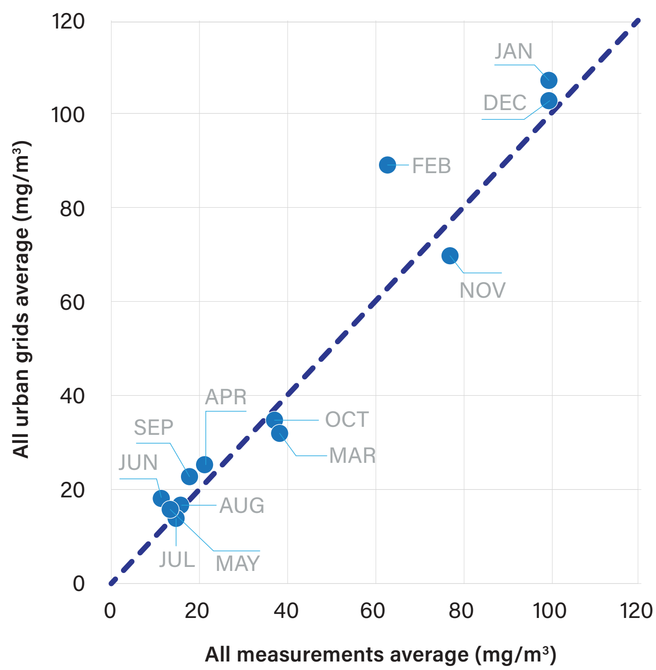
Moreover, modeling of pollution dispersion is useful for identifying pollution hot spots within an urban area. The modeling results shown on Figure 24 illustrate that the northern part of Bishkek and some areas in the western and eastern parts of the city are the locations with the highest monthly average $PM_{2.5}$ concentrations. These locations generally include areas with predominantly SFHs using mainly coal for heating.

The modeling results on Figure 24 also demonstrate that concentrations in the city of Bishkek are over the WHO's annual average guideline (5 µg/m³) for all months in the year, even in the summer. Therefore, to bring the annual $PM_{2.5}$ average concentration in Bishkek toward WHO guidelines, emissions reduction and mitigation measures should be implemented for a variety of sources to reduce $PM_{2.5}$ concentrations in each month of the year.

5.2. Comparison with air quality monitoring data

A general practice in modeling is to compare modeled concentrations of pollutants with the actual concentration measurements from air quality monitoring. The modeling results show a good fit ($R^2 = 0.94$) with the collected monitoring data which suggests that the simulation conducted in this study closely approximates the observed $PM_{2.5}$ levels and dynamics in Bishkek in 2020–2021 (Figure 25).

Figure 25: Modeled and monitored $PM_{2.5}$ concentrations in Bishkek



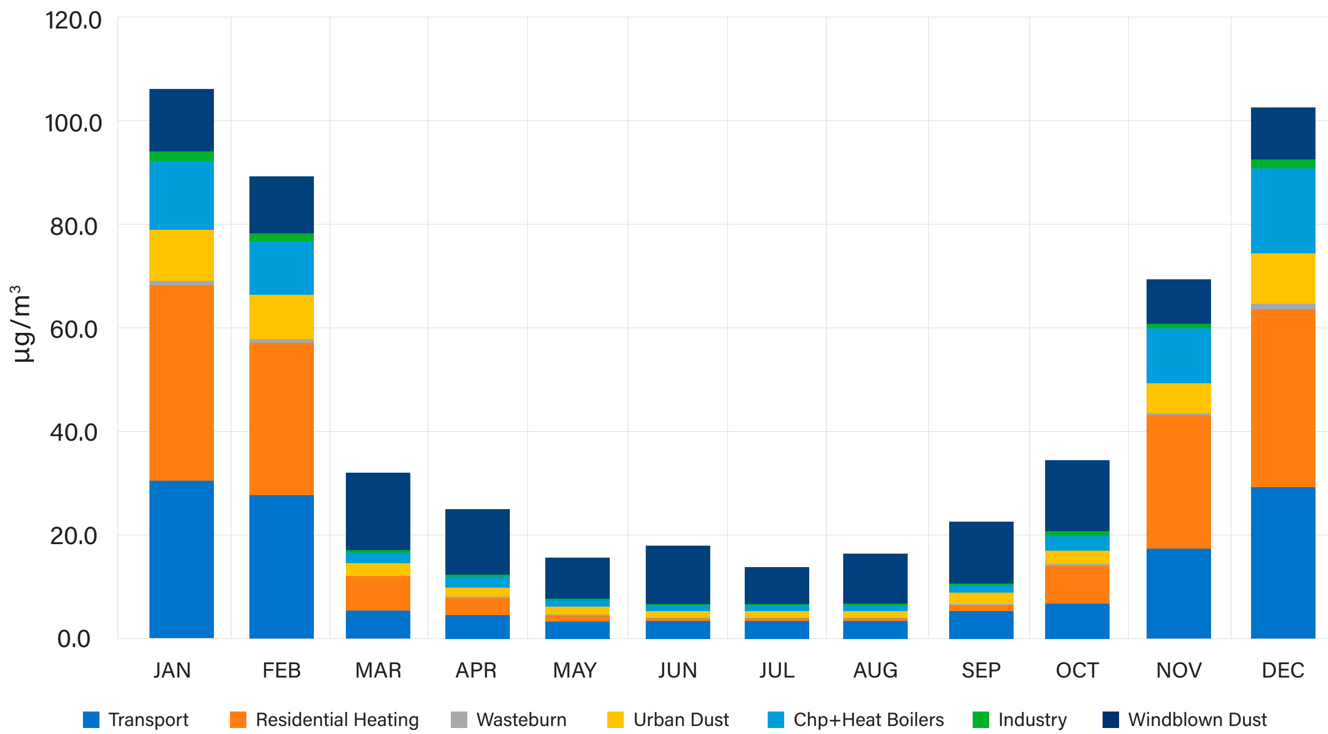
Source: Original elaboration for this publication.

Figure 25 shows that the modeled concentrations are a good representation of all the monitoring data collected for this study and also capture the seasonal dynamics of $PM_{2.5}$ pollution in Bishkek. The modeled monthly averages coincide closely with the monitored monthly average concentrations. There is a bigger difference in the modeled monthly average concentrations, compared to the average from the monitoring networks, only in the month of February, whereas for all other months, the modeled and monitored concentrations largely overlap.

5.3. Source contributions to $PM_{2.5}$ concentrations

The modeling conducted in this study allowed the identification of source contributions to $PM_{2.5}$ concentrations (Figure 26). As discussed in Chapter 4, emissions sources have varying temporal intensities throughout the year, and therefore, it is to be expected that the sources' contributions to $PM_{2.5}$ concentrations will also vary in the different months and seasons.

Figure 26: Modeled source contributions to $PM_{2.5}$ concentrations in Bishkek by month, in µg/m³



Source: Original elaboration for this publication.

Residential heating has the highest contribution to $PM_{2.5}$ concentrations in the winter, reaching nearly 40 percent in some winter months (for example, January and November). On the other hand, windblown dust[26] has the highest contribution to $PM_{2.5}$ concentrations in the summer when $PM_{2.5}$ concentrations are generally lower than in the winter. The contribution of transport to $PM_{2.5}$ concentrations varies from 17 percent in the spring to 30 percent in the winter. Transport is the second most important contributor to $PM_{2.5}$ concentrations in all seasons—in the winter, it is second after residential heating, and in the summer, it is second after windblown dust.

[26] Windblown dust represents particles carried by wind into Bishkek from the adjoining areas such as agricultural and open fields, for instance.

The contribution of the CHP plant and HoBs combined to $PM_{2.5}$ concentrations peaks in the winter due to larger loads at the CHP plant and the operation of the HoBs. The maximum modeled contribution to $PM_{2.5}$ concentrations of the CHP plant and HoBs combined is estimated at 15 percent.

Urban dust originating from construction activities and resuspended particles from roads have a fairly constant contribution to $PM_{2.5}$ concentrations throughout the year—varying between 7 percent and 10 percent. The contributions of industries, other than the CHP plant, and open waste burning are relatively constant throughout the year—estimated at 2 percent and 1 percent, respectively.

6. Emission Reduction Measures' Impact on $PM_{2.5}$ Concentrations in Bishkek

The modeling system explained in detail in Section 3.6 was used to explore some 'what if' emission reduction measures, that is, the improvement in the ambient $PM_{2.5}$ concentration in the Bishkek urban area that results from introducing one of several different policies and measures. The study focused on $PM_{2.5}$ as it is the most significant pollutant in Bishkek in terms of health impacts, by some margin. In addition, the study also estimated the potential reduction of CO_2 emissions for each of the modeled emission reduction measures.

6.1. Approach to assessing the impact of emission reduction measures

Building on the gridded emissions maps and GIS layers for Bishkek established in this study, the assessment of the impact of emission reduction measures on $PM_{2.5}$ concentrations involved several additional steps:

- **Targeting a source or source sector.** There are a wide range of options available to policy makers who wish to improve air quality. The most common approach is to reduce the emissions arising from a specific source or source sector, and this is the approach that has been investigated in this study. However, other approaches are possible. For example, increasing the height of chimneys or moving industrial sources away from city centers are options that would improve air quality in the city center without changing the level of emissions. For this study, we consider only policies and measures that reduce emissions, as these are expected to be the most widely used in improving air quality in the city. However, future studies might consider other approaches, for example, road traffic management schemes that relocate, rather than reduce, traffic activity and hence emissions.
- **Defining the detail of a policy or measure.** A policy or measure needs to be accompanied by quantified information on the impact that it has on emissions. For example, a policy aimed at improving insulation in houses needs to be accompanied by information on the resulting reduction in the fuel used for residential heating and hence the reduction in emissions. Furthermore, spatial distributions and variations in time need to be considered. In this example, the number of houses with improved insulation would need to be defined, and the type of fuel that they use for heating and the rollout of the scheme across several years would need to be considered. All of this is used to determine how the mapped emissions change with time, compared to the 'base case'. Seasonal variations in emissions would also need to be considered, because this is needed for input into the modeling of the resulting concentrations. It is also important to understand 'knock-on' effects. For example, a policy that encourages residential heating to change from coal to electricity would result in lower emissions from the residential sector, but the higher demand for electricity could be met by increased renewables or increased generation by the CHP plant—clearly giving very different outcomes.
- **Determining the impact on ambient concentrations.** The revised emissions maps are used as input into the model, which gives

revised concentration maps as an output. These can then be compared with the 'base case' concentration maps to show the improvement in ambient $PM_{2.5}$ concentrations in the Bishkek urban area. The impact of policies and measures on the annual average $PM_{2.5}$ concentration in Bishkek was used as the main metric for initial prioritization; cost-benefit and implementation modalities can be considered at the next stage.

In this study, we consider a range of policies and measures one by one. There are two reasons for this. First, the purpose of this study is to provide an indication of which policies and measures are the most effective at improving ambient $PM_{2.5}$ concentrations in the Bishkek urban area. This is only the first step in forming a strategy, which would also need to consider associated costs, the practicalities of implementation, co-benefits and disbenefits, political willingness, and so on.

Second, policies and measures are not simply additive, that is, the improvement in air quality from two or more policies and measures is not always the sum of the individual improvements, because there can be 'diminishing returns' or overlap of policies and measures. Therefore, while the effectiveness of different policies and measures can be shown here, more involved analysis will be needed on the combination of policies and measures after policy makers have given an indication of the types of policies and measures that they would be interested in including in an air quality management strategy.

6.2. Short list of selected policies and measures

A wide range of policies and measures could be investigated, and it was decided to short-list several across the largest emissions source sectors. The intention was to select a range of policies and measures which showed variation across the different sectors and also variation within an emission source sector by implementing a policy at different ambition levels. The short list of policies and measures is explained in the following sections.

6.2.1. Electricity and heat generation — fuel switching, modernization, and use of renewables

Bishkek CHP plant is a large emitter, and there have been extensive discussions about converting the CHP plant to gas, so it is sensible to include this change in the short list.

HoBs are also relatively large emitters, and in contrast to the CHP plant, they are spread throughout the city with emissions that are released much closer to the ground level. Hence, it is informative to include them in the short list. The policy that has been chosen is the conversion to gas from coal which is the policy that Bishkek Mayor's Office has been implementing.

In addition to fuel switching options, it is informative to understand the impacts that might arise if there was a general reduction in emissions from both the CHP plant and HoBs because more renewables were used for electricity generation, driven by the climate agenda. This assumes that some residential heating would change from being supplied by HoBs to the increased electricity supply from renewables.

6.2.2. Residential combustion — insulation, fuel switching, electric heating, and use of heat pumps

Emissions from residential fuel use are the largest source of $PM_{2.5}$ pollution in Bishkek, so several types of policies and measures are included in the short list. The modeling system assumes that coal is used in SFHs not on the district heating networks (mainly in the northern and western parts of the city), and this has implications for the distribution of the improvements in air quality that arise from policies and measures in the residential sector.

Home insulation. It is recognized that there is potential to significantly improve home insulation across a large number of SFHs in Bishkek, so low and high scenarios of improved EE in households using coal for heating are included in the short list.

Fuel switching. The most obvious fuel switching option is coal to gas, but others are also possible and have been included. The introduction of heat pumps may be seen as a relatively expensive option, but it delivers large emission reductions in the residential sector with only a small increase in the need for electricity supply. Switching from coal to electric heating is similar, albeit with a larger increase in the need for additional electricity supply than in the heat pumps scenario. For each of these three, low and high scenarios are included in the short list.

6.2.3. Road transport — traffic management, dust suppression, and emissions control

Road transport emissions are a major contributor to the $PM_{2.5}$ concentrations in the city center. There are many types of policies and measures which can be implemented in the road transport sector, and the intention of the emission reduction scenarios is to show the impact of a variety of policies, so that the relative benefits can be understood. More work would be needed to develop the details of policies, consider the practicalities of implementation, and so on.

Traffic management/reduction. Improvements in road traffic management and planning schemes could reduce the need for journeys. The impact is assumed to be a reduction in all road transport by 10 percent. This is a deliberately simple change, designed to be illustrative, which might be achieved by implementing more detailed policies and measures.

Road dust suppression. The suspension of road dust is a not an insignificant source, and there are ways of controlling this without impact on the volume of traffic using the roads. But in general, it is challenging to have a large impact on dust suspension, so the policy assumes only a 10 percent reduction in this source.

Car emissions control. The car fleet in Bishkek is relatively old and hence has outdated emissions control equipment. In addition, it is known that the illegal removal of catalytic convertors is commonplace. Therefore, reducing the emissions from cars by improving emissions controls is an obvious policy to consider. Low and high scenarios are included that assume old vehicles are converted to modern emissions standards. There are many ways in which this might be implemented (legislation and enforcement, incentivization and grants, and so on), but these are not considered in this study and would need to be investigated in more detail to inform actual implementation.

Shuttle buses (*marshrutkas*) emissions control. The extensive use of *marshrutkas* makes it appealing to consider emissions control for this mode of transport. Furthermore, implementation might be easier than measures targeted at cars because the smaller ownership base could have their licenses to operate dependent on the inclusion of emissions control equipment. The assumption is that a significant percentage of the *marshrutkas* are converted from no emissions control to modern standards.

Bus emissions control. This is similar to the *marshrutka* emissions control, except that it is assumed that all buses are converted to modern standards.

Light duty vehicles (LDVs) and heavy goods vehicles (HGVs). Similar to the car emissions control, low and high scenarios for conversion of old LDVs and HGVs to modern standards are assumed.

6.2.4. Waste — reduction in waste burning

The extent to which open burning of waste contributes to ambient $PM_{2.5}$ concentrations in the city center has been difficult to determine with any certainty due to the lack of detailed data. Two scenarios are included in the short list. The first assumes good control of open waste burning, which results in a 50 percent reduction in burning. The second assumes that there is no open burning of waste and that the fire at the dumpsite is put out. This latter policy may not be particularly realistic but gives informative results about the potential impact of banning the uncontrolled open burning of waste.

6.2.5. Greening — regional dust suppression

Dust from outside the city limits has a significant impact on $PM_{2.5}$ concentrations in the city center, especially in the summer months. It is typically very difficult to control this natural source, but there are environmental greening schemes, such as planting vegetation, which can reduce the extent to which dust becomes suspended and transported into a city. Low and high control scenarios are included in the short list.

6.3. Results of the emission reduction measures modeling

Table 3 shows the percentage reduction in the average annual $PM_{2.5}$ concentration in the Bishkek urban area that results from the complete implementation of each single policy or measure. It is recognized that the completion of most of the measures will require more than one year; however, the purpose of the modeling of emission reduction measures was to illustrate the relative impact of different policies and measures, independent of implementation timescales. Each of the policies and measures includes some descriptive text to provide information on some of the underlying assumptions that have been included in determining the change in the $PM_{2.5}$ emissions. A color scale is used to emphasize the size of the positive impact—the largest positive impacts are shown in green, and the smallest positive impacts are shown in red (note that these are still positive impacts on the $PM_{2.5}$ concentration levels; it is just that they are the smaller impacts of the range of policies and measures investigated).

When interpreting the results, it is important to keep in mind that the $PM_{2.5}$ reductions represent reductions in average annual concentration over the entire Bishkek urban area. Certain policies and measures might have a larger impact in a certain area of Bishkek than in others. For instance, due to the concentration of coal use for residential heating in the northern and western parts of the city, switching to cleaner heating options would have a larger impact in those areas, compared to the impact on average over the whole city. Similarly, some measures might have more pronounced impact in a given period of the year—for example, the largest impacts of cleaner residential heating measures are achieved in the winter months.

Table 3: Impact on $PM_{2.5}$ concentrations in Bishkek from the implementation of individual policies and measures

Sector	Measure	Description	Reduction in annual $PM_{2.5}$ concentration (%)
CHP and heat boilers	CHP coal to gas	Assume same power output, but CHP using modern gas turbine technology instead of current coal	8.8
	HoBs coal to gas	Assume same power output, but all HoBs using modern gas technology, not current coal	2.0
	More renewables	Assume 30% reduction in CHP and HoBs emissions because of adoption of renewables	3.9
Residential heating[a]	Home insulation - low	Assume 20% of houses using coal reduce heating needs by 33% through EE measures	1.8
	Home insulation - high	Assume 40% of houses using coal reduce heating needs by 33% through EE measures	3.3

Table 3

Sector	Measure	Description	Reduction in annual $PM_{2.5}$ concentration (%)
Residential heating[a]	Residential coal to gas - low	Assume 20% of houses using coal change from coal to modern gas heating system	5.8
	Residential coal to gas - high	Assume 40% of houses using coal change from coal to modern gas heating system	11.7
	Residential heat pumps - low	Assume 20% of houses using coal change to heat pumps, increase CHP emissions (3%)	5.4
	Residential heat pumps - high	Assume 40% of houses using coal change to heat pumps, increase CHP emissions (6%)	13.0
	Residential more electricity - low	Assume 20% of houses using coal change to electric boiler heating, increase CHP emissions (10%)	4.7
	Residential more electricity - high	Assume 40% of houses using coal change to electric boiler heating, increase CHP emissions (20%)	9.3
	Complete switch to clean heating	**Complete replacement of coal heating with zero-emission heating**	29.0
Transport	Traffic management	Reduce all traffic emissions in the city by 10%	2.7
	Road dust suppression	Reduce in-city dust emissions by 10%	0.8
	Car emissions control - low	Convert 20% of pre-Euro/non-cat petrol cars to Euro 5, and 20% pre-Euro/non-cat diesel cars to Euro 5	3.1
	Car emissions control - high	Convert 40% of pre-Euro/non-cat petrol cars to Euro 5, and 40% pre-Euro/non-cat diesel cars to Euro 5	6.0
	Marshrutka emissions control	Convert 40% of pre-Euro/non-DPF diesel LDVs from pre-Euro/non-cat to Euro VI	1.2
	Buses emissions control	Convert all buses to Euro VI	0.2
Transport	LDV/HGV emissions control	Convert 40% pre-Euro/non-DPF diesel LDVs and 40% HGVs to Euro VI	3.1
	Total of all transport measures combined	**Combined impacts of all the modeled transport measures (high scenarios)**	13.0
	Complete switch to zero-emission	**Complete switch to zero-emission vehicles for the entire vehicle fleet**	27.0
Waste burning	Control waste open burning	Assume 50% reduction of open waste burning	0.6
	No open waste burning, including dump	Assume zero emissions from dumpsite and open waste burning	1.0
Greening[b]	Natural dust controls - low	Assume 5% reduction in regional dust emissions	1.2
	Natural dust controls - high	Assume 10% reduction in regional dust emissions	2.1

Source: Original elaboration for this publication.

Note: DPF = Diesel particulate filter; **a.** Additional electricity demand from the existing CHP was modeled for residential heating measures involving switching to electricity for heating (for example, heat pumps and heating with electric radiators). The CHP emissions depend on the fuel used to generate electricity; **b.** The greening measures are used as natural dust controls primarily affecting windblown dust.

6.4. Emission reduction measures: Summary

Conclusions are given below for each of the emission reduction scenarios resulting from the policies and measures in the short list. The metric used in this study for the initial prioritization of policies and measures is their impact on the annual average $PM_{2.5}$ concentration in Bishkek. As seen in Table 3, the complete replacement of coal heating with zero-emission heating in SFHs would have the highest contribution to the reduction of $PM_{2.5}$ concentrations. This scenario is therefore considered the high-impact priority scenario. However, considering the large reductions of $PM_{2.5}$ concentrations that need to be achieved to bring $PM_{2.5}$ concentrations to the WHO guideline values, it is apparent that there is no one policy that can deliver the reductions required. In fact, there is no one emissions source sector that could be targeted to deliver the $PM_{2.5}$ emission reductions required. While an air quality strategy for Bishkek might propose implementing the most impactful or easiest policies in a source sector, it appears evident that the strategy would need to achieve significant emission reductions across multiple source sectors. Therefore, a successful air quality strategy for Bishkek would need to be 'comprehensive' in its scope.

6.4.1. Electricity and heat generation — fuel switching, modernization, and use of renewables

This study considers the impact of the CHP plant on the wider Bishkek urban area. The findings from the modeling (Table 3) show that measures to reduce the emissions of the CHP plant have an appreciable impact on the $PM_{2.5}$ concentrations in the city. Converting the remaining coal-fired HoBs would also have a positive impact on air quality in Bishkek.

Given the very large reductions in $PM_{2.5}$ concentrations that are required to bring concentrations down from the current annual average of about 51 $\mu g/m^3$ to anywhere near the recommended WHO $PM_{2.5}$ annual average value of 5 $\mu g/m^3$, it seems likely that implementing emissions controls on both the CHP plant and the HoBs will be required. They are also some of the easier sources to control, because emissions control technologies are already available, and they represent a limited number of individual sources. However, it is appreciated that the example measure given here, converting to gas, has political implications.

6.4.2. Residential combustion - insulation, fuel switching, electric heating, and use of heat pumps

Home insulation. Improving home insulation is usually a high-priority measure in most cities. It gives both improvements in air quality and a reduction in GHG emissions. However, in this study, the impact is relatively small compared to other options. This is partly because, unlike many other cities around the world, the largest EE interventions are still available as options because they have not yet been implemented. Improving home insulation is an example of a policy which could easily be implemented in addition to options such as fuel switching.

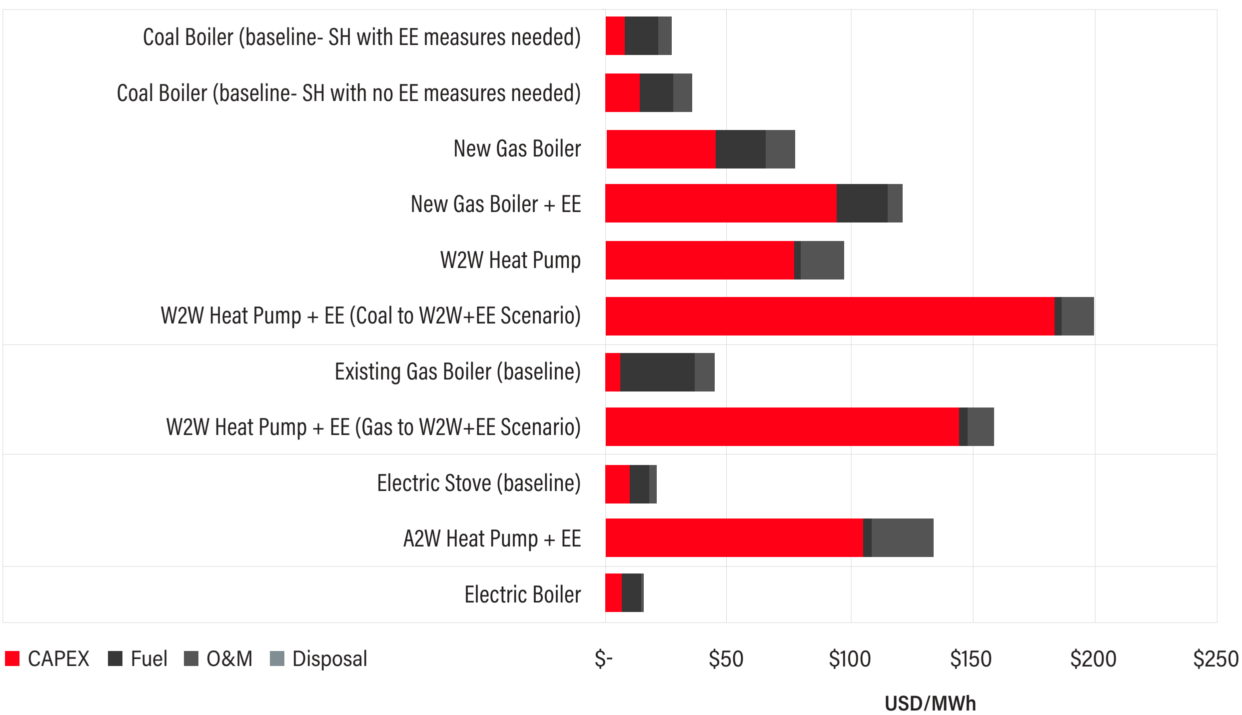
Fuel switching. As might be expected, fuel switching in the residential sector gives rise to policies which have some of the largest impacts, because the emissions from the residential sector make a very large contribution to the $PM_{2.5}$ emissions in the 'base case'. There is relatively little difference between the different fuel switching options investigated here, and each will have their pros and cons in terms of cost, ease of implementation, and so on. However, it is important to appreciate that the scale of the policies presented here is ambitious. Delivering fuel switching to, for example, 40 percent of households that use coal for heating would be a huge undertaking.

Box 3: Costs of heating options to replace coal in single-family buildings in Bishkek

The ongoing World Bank assessment 'Heating Options Study for Bishkek' estimated the financial and economic levelized cost of heating (LCOH) for different heating options. The assessment then ranked the alternatives to replacing coal heating in SFHs also considering factors such as operating expenses (OPEX) affordability, availability of the heating technology to replace coal, CO_2 reductions per US dollar invested, and $PM_{2.5}$ emissions reduction per US dollar invested.

The financial LCOH for all SFH heating options shows that only electric boilers compare favorably to the use of coal for heating in the baseline. This result is largely driven by high up-front capital expenditure (CAPEX) for alternative heating options, which are larger than the substantial fuel cost savings for some of those alternative options. While electric and gas boilers offer the lowest CAPEX solutions, heat pumps—both water-to-water (W2W) and air-to-water (A2W)—offer the greatest reduction in monthly fuel costs (Figure 27).

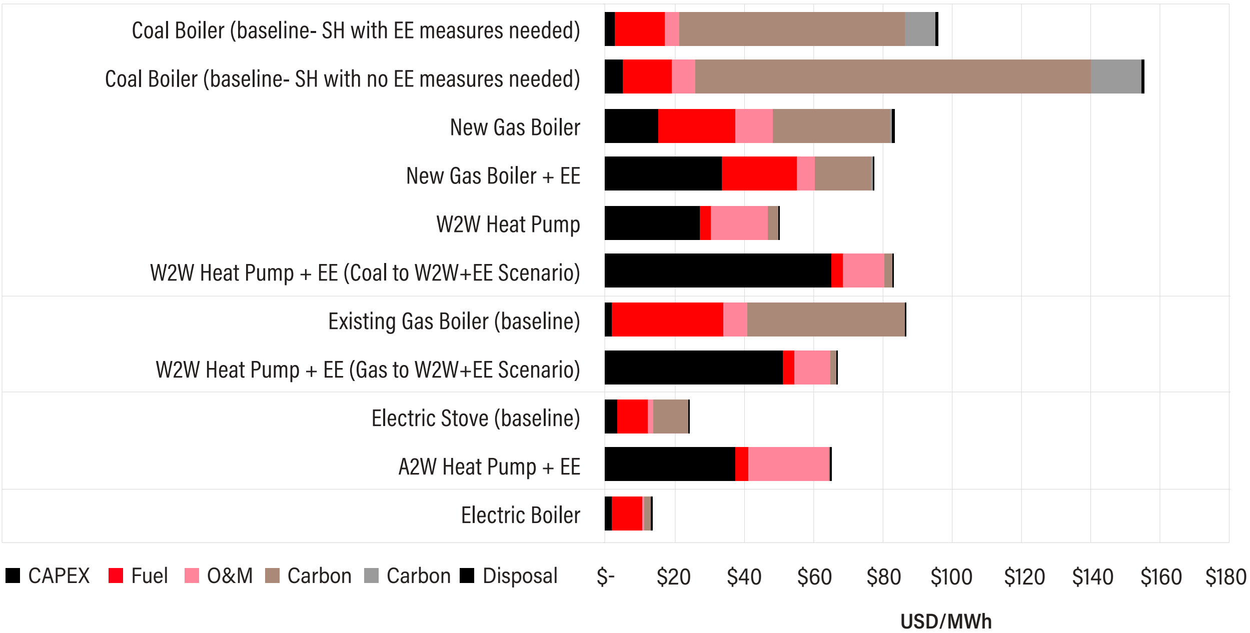
Figure 27: Financial LCOH in SFHs in Bishkek



Source: World Bank.

The economic LCOH for SFHs, in contrast, shows all options outperforming the baseline use of coal boilers. While gas options still show higher fuel costs and heat pump options still show higher CAPEX costs, these cost increases compared to the use of coal for heating are exceeded by the savings in carbon emissions and health impacts from $PM_{2.5}$. Electric stoves are the only baseline technology which do not have an economically viable alternative, as the potential for emissions reductions is not enough to offset higher CAPEX costs of alternatives. Likewise, new electric boilers outperform all baseline scenarios and could be used to replace coal or gas (Figure 28).

Figure 28: Economic LCOH in SFHs in Bishkek



Source: World Bank.

An alternative heating options ranking, compared to the baseline use of coal for heating in SFHs, was performed considering the results from the financial and economic LCOH analyses, as well as household affordability of OPEX (fuel and operation and maintenance), availability of the proposed technology, CO_2 emissions savings, and $PM_{2.5}$ savings (Figure 29). For SFHs, electric boilers rank as the top option to replace the use of coal for heating, followed by A2W heat pumps. New gas boilers and W2W heat pumps are the next most favorable, followed by all the other options with included EE measures, which rank lower due to the higher CAPEX costs. However, it should be noted that the higher-ranked options would not achieve the full potential of savings without a baseline level of building energy efficiency, which is not the case in all SFHs.

Figure 29: Ranking of heating options to replace coal in SFHs in Bishkek

	Financial LCOH	Economic LCOH	Household OPEX Affordability:	Availability of the Service/ Technology	CO_2 Emissions Savings Potential	$PM_{2.5}$ Savings Potential	Overall Rank
SFH Options	**USD/m²**	**USD/m²**	**USD/m²**	**Description**	**ton CO_2/year/ 1,000 USD**	**g $PM_{2.5}$/m²/USD**	**All ranks weighted equally**
New Gas Boiler	$4.15	$(7.20)	$3.23	Gazprom service area	3.69	0.20	3
New Gas Boiler + EE	$20.96	$(0.33)	55.51		0.82	0.04	7
W2W Heat Pump	$6.23	5(10.47)	$2.07	Limited by geothermal potential	2.98	0.12	4
W2W Heat Pump + EE	$22.77	$(5.21)	$2.18		0.91	0.04	6
A2W Heat Pump + EE	$5.10	$(11.86)	$2.18	Anywhere	3.07	0.12	2
Electric Boiler	$1.75	$(10.75)	53.06		10.01	0.41	1

Source: World Bank.

6.4.3. Road transport — traffic management, dust suppression, and emissions control

Given that transport emissions, including dust resuspension, of $PM_{2.5}$ are similar to $PM_{2.5}$ emissions from the residential sector, the impact of road transport policies appears to be smaller by comparison. However, to some extent, this is due to the way the data have been analyzed and presented. Individual policies have been explored for different types of road vehicles—cars, *marshrutkas*, buses, LDVs, and HGVs. If these were considered together, that is, reducing emissions from all road vehicles, then the resulting impact would be comparable to high-impact policies in the residential sector. However, given that the ownership of different types of road vehicles varies, it is convenient to consider the emissions control policies individually here.

Traffic management/reduction. The impact of this policy provides some useful context when considering the emission reduction policies. Traffic activity would need to be reduced by a substantial amount to give similar impacts to improving the emissions control technologies on vehicles—a clear reflection of how effective modern emissions control technologies are for road vehicles. This is why policies in other countries have focused on ensuring that new vehicles entering the fleet comply with the most up-to-date emissions standards, whereas existing vehicles comply as a minimum to their manufacturing standards, to ensure that emissions per km driven are low. Only after these are in place and enforced do countries typically consider restricting vehicle flows in cities with congestion charging or low-emission zones. Such policies require emission reductions beyond what is achievable from ensuring the fleet is dominated by vehicles equipped with modern emissions control equipment.

Road dust suppression. While this is a significant source, the policy assumes only a 10 percent reduction in emissions, because it is challenging to control. As a result, the overall impact on $PM_{2.5}$ concentrations is relatively small.

Car emissions control. The impact of these measures is relatively large, not only because road transport is one of the important $PM_{2.5}$ emission sources but also because converting a pre-Euro car to Euro 5 emissions standard reduces emissions per km by a very large amount. It is expected that some sort of policy focused on reducing emissions from cars would feature in a citywide air quality strategy.

***Marshrutka* and bus emissions control.** The smaller impact, compared to cars, reflects the difference in vehicle numbers and hence vehicle-kms. However, improvements in the emission standards of these vehicles would probably be relatively easy to implement, so emission control policies on public transport vehicles remain a sensible consideration for an air quality strategy.

LDVs and HGVs. Falling between the impact of similar policies on cars and *marshrutkas*/buses, controlling emissions of LDVs and HGVs also appears to be an effective way of having a significant impact on $PM_{2.5}$ concentrations in Bishkek. Again, it is expected that some sort of policy associated with reducing emissions from LDVs and HGVs would feature in a comprehensive air quality strategy.

6.4.4. Waste — reduction in waste burning

Emissions from open waste burning are relatively small when compared to most other sources. As a result, even reducing these emissions to zero has little impact on $PM_{2.5}$ concentrations compared to other policies. In addition, this type of policy would be particularly difficult to enforce.

6.4.5. Greening — regional dust suppression

The impact of these scenarios on $PM_{2.5}$ concentrations is modest, but this option does warrant further exploration. The next step could be to gather information that shows how practical it would be to implement planting and other dust control techniques in locations upwind of the city to deliver a 5 percent or 10 percent reduction in natural dust entering the city. Additional analysis is needed on the origins of the windblown dust coming into Bishkek. The dust might be transported from nearby areas such as degraded lands, quarries, borrow pits and agricultural fields, however, due to the possibility of fine particles travelling for hundreds of kilometers, sustainably tackling windblown dust transport into Bishkek might require additional studies to inform national and transnational measures.

6.4.6. Co-benefits and trade-offs with CO_2 emission reductions

Nearly all modeled $PM_{2.5}$ emission reduction measures show co-benefits in terms of CO_2 emission reductions (see Annex 1 for details). The notable exceptions are the measures that replace coal heating with heating with electric radiators. Electric heaters and radiators are not the most efficient electric heating devices and can use a significant amount of energy, especially compared to the more efficient electric heating options—using heat pumps. Since a switch to electric heaters and/or radiators will increase the demand for electricity supplied by Bishkek coal-fired CHP, there is a small negative impact on CO_2 emissions from implementing this measure. In addition, the small CO_2 penalty for this measure is because Bishkek CHP uses coal—if the CHP switches to less carbon-intensive fuels, then it is expected that even the switch to electric heaters will show CO_2 co-benefits.

The individual modeled $PM_{2.5}$ emission reduction measure that shows the largest CO_2 emission reduction co-benefits is the complete switch to zero-emission vehicles in Bishkek. The switch to gas of Bishkek coal-fired CHP is the measure that shows the second highest CO_2 emission reduction co-benefit. The combined impact of all transport measures, excluding the extreme case of a complete switch to zero-emission vehicles, represents the third largest CO_2 emission reduction co-benefit from the modeled measures in this study.

Overall, analyzing the impact of $PM_{2.5}$ emission reduction measures on CO_2 emissions demonstrates that priority sources and hence measures to reduce $PM_{2.5}$ pollution and CO_2 emissions differ. Therefore, when designing air quality policies, it is important to not only maximize synergies with climate change policies but also be aware of and manage the possible trade-offs.

7. Review of Air Quality Management System (AQMS) in the Kyrgyz Republic

7.1. Introduction

As suggested in Chapter 6, the modeling of emission reduction scenarios demonstrates that a balanced approach with measures covering multiple sectors is needed to substantially improve air quality in Bishkek. Hence, it is important to strengthen the overall AQMS on national and local levels to support efficient and effective implementation of emission reduction measures. Therefore, parallel to the technical work, a review and assessment was also carried out of the overall AQMS in the Kyrgyz Republic, in general, and in particular in Bishkek.[26]

For comprehensiveness, the key findings from the AQMS review are provided in this report to support discussions with stakeholders, particularly with relevant ministries and government agencies for strengthening the overall AQMS, including developing an Air Quality Master Plan.

7.2. Findings from the assessment of the current AQMS in the Kyrgyz Republic

The existing roles and responsibilities of different parts of government that are relevant for air quality management, and the corresponding linkages were reviewed. Particular focus was given to understanding the activities within the MNRETS as this is where most of the relevant activities are located, and this is outlined in Figure 30, but the review also included the roles and responsibilities of the: Ministry of Health, Ministry of Emergency Situations, Ministry of Energy, the Ministry of Transport, as well as considering responsibilities at the sub-national level.

The current scope and organizational structure of the existing AQ management functions was compared with an idealized model to identify gaps and areas for improvement. The most notable were:

- Significant improvements are needed in the technical tools that support AQ assessment, e.g. the emissions inventory, ambient monitoring, dispersion modeling, and health impact studies.
- Significant improvements are needed in planning a strategy that is evidence-based. Particular components included quantification of emissions under different scenarios to understand the potential impact of different policies and measures.
- There is a need to modernize some of the AQ standards, and the measurement techniques used for quantifying emissions.
- There is a need to improve the governance structure of AQ as a whole, by introducing a high-level inter-ministerial committee, so that AQ management activities across Ministries can be effectively coordinated and managed.

[27] World Bank. 2023. The Air Quality Management System in the Kyrgyz Republic: A Review of Institutional Arrangements, forthcoming.

Figure 30: AQ roles and responsibilities of the MNRETS

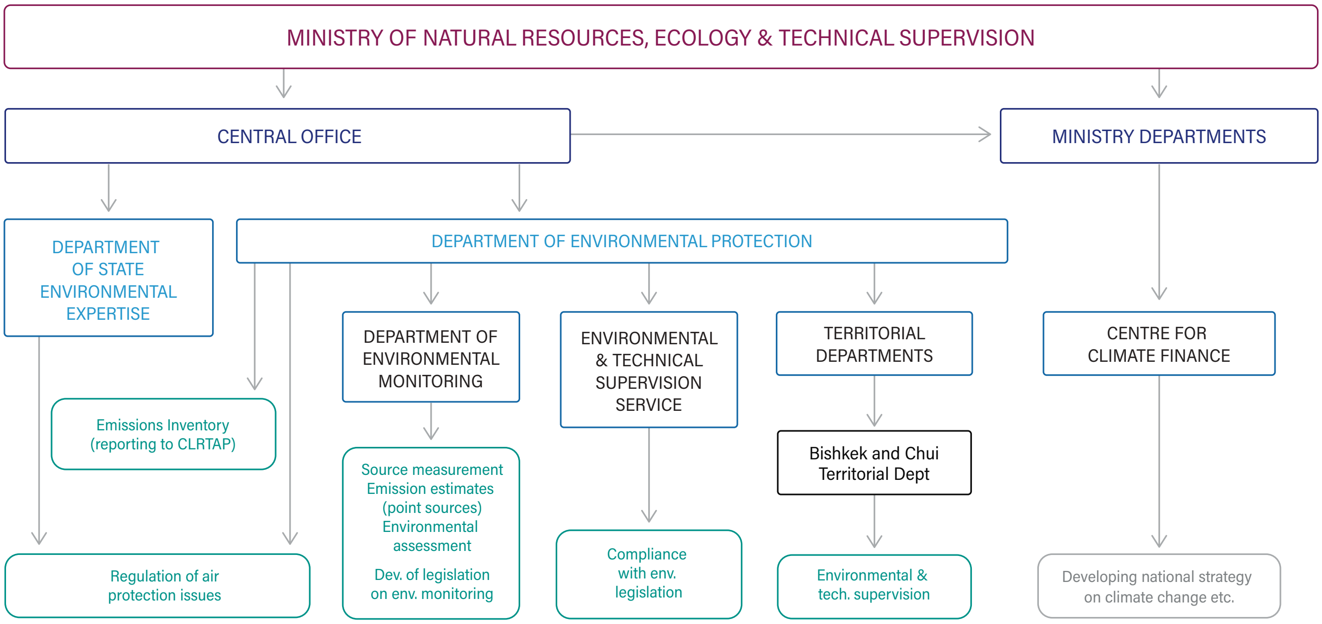


Table 4: Key institutions outside of MNRETS with responsibilities related to air quality management

Institution	Responsibilities related to air quality management
Ministry of Health	Responsible for developing air quality standards
Kyrgyz Hydromet under the Ministry of Emergency Situations	Responsible for air quality monitoring, technical capacities for air quality analysis, modeling and forecasts.
Ministry of Energy	Responsible for policies and regulations in the energy sector, including in heat and power generation.
Ministry of Transport and Communications	Responsible for policies and regulations in the transport sector, technical standards and inspections of road vehicles.
Bishkek Mayor's Office	Responsible for managing a variety of activities at local level such as: urban planning and development, management of HoBs and heating networks in Bishkek, traffic management in Bishkek, public transport, inspection of smaller enterprises, waste management, and greening.

Source: Original elaboration for this publication.

Prioritized improvement activities were then determined, that would improve the existing AQMS, in terms of technical capabilities, policy formation, management and coordination. These are presented in the following chapter. This provides a transition plan, that can be used to help attract external investment or funding, and also to direct currently available funds.

7.3. Recommended improvement activities and next steps

The review of AQMS has identified several measures and actions, which have been summarized in Table 4. The priority actions are mostly related to capacity building and technical training. While recommending actions and measures, indication of importance, expected timescales, and the size of the activity have been provided to enable prioritization and inclusion in Bishkek's Air Quality Master Plan.

Table 5: Recommended priority activities to develop the current AQMS

<table>
<tr><th colspan="2">FOR IMMEDIATE ACTION</th></tr>
<tr><td colspan="2">Policy reforms</td></tr>
<tr><td>Formation of an Inter-Ministerial Air Quality Co-ordination Committee</td><td>Critically important
For immediate action, but may take up to 6 months to complete
Need for high-level oversight
At the technical level, to be led by the deputy prime minister, or other similar high-level Kyrgyz Government representative, having mandate for air quality
No external resources required.</td></tr>
<tr><td>Establishment of the governmental roles, responsibilities, and structures that support an effective AQMS</td><td>Critically important. Setting up the Inter-Ministerial Air Quality Co-ordination Committee (stated above) is a prerequisite.
For immediate action, but may take more than 12 months to complete
Activity to be led by the coordination committee (above)
No external resources required.</td></tr>
<tr><th colspan="2">URGENT activities to be included in the Air Quality Master plan</th></tr>
<tr><td colspan="2">Policy reforms</td></tr>
<tr><td colspan="2">Development of an air quality policy team (target setting, policies and measures, air quality planning, and tracking progress)
Urgent - start immediately after finalizing the Air Quality Master Plan or earlier.
Critically important. This is a fundamental component of the AQMS which needs to be developed.
Training and development could be delivered across several months.
Medium-size investment.</td></tr>
<tr><td>Development of air quality standards and targets</td><td>Urgent - start immediately after finalizing the Air Quality Master Plan or earlier.
Critically important. This is a fundamental component of the AQMS which needs to be developed.
Training could be provided in less than a month.
Small investment.</td></tr>
<tr><td colspan="2">Interventions</td></tr>
<tr><td>Development of the ambient air quality monitoring network and data platform</td><td>Urgent - already started
Critically important. This is a fundamental component of the AQMS, and collecting reliable data with immediate effect is a priority.
Activity to be led by the Kyrgyz Hydromet (this activity has started)
Training and investment in monitoring equipment has already started. Training is likely to take several months.
Relatively large investment.</td></tr>
</table>

Table 5

Technical assistance	
Development of the **air quality emissions inventory team and data platforms**	▪ **Urgent** - some work has already been undertaken by World Bank consultants, but the main body of the capacity building to start after finalizing the Air Quality Master Plan (or earlier) ▪ Critically important as this is a fundamental component of the AQMS, and collecting reliable data with immediate effect is a priority. ▪ Training and development are best implemented across several annual cycles. ▪ Medium-size investment, building on the work already undertaken by the UNDP/UNEP and the World Bank.
Development of an **air quality communications strategy**	▪ **Urgent** - some work has already been undertaken, but the Air Quality Master Plan is an opportunity to compile a comprehensive air quality communications strategy. ▪ **Medium priority** - a hugely beneficial component of an AQMS, and essential for emergency measures ▪ A strategy could be prepared quickly, followed by relatively quick implementation across 1–2 months or longer. ▪ Relatively small investment.
MEDIUM-TERM activities to be included in the Air Quality Master Plan with investment needs identified in the investment plan	
Policy reforms	
Development of **source measurement legislation and capabilities:** ▪ **Industry and residential team** ▪ **Road transport team**	▪ **Medium term** - start within 12 months of finalizing the Air Quality Master Plan or earlier. ▪ **A high priority** ▪ A proposal to update legislation could be prepared quickly but could take a long time to implement. Equipment could be provided relatively quickly, with training to follow across several months. ▪ Relatively large investment.
Technical assistance	
Development of **air quality management capabilities within Bishkek City Hall**	▪ **Medium term** - start within 12 months of finalizing the Air Quality Master Plan or earlier. ▪ **Medium priority** - hugely beneficial for the effective management of air quality in Bishkek ▪ **Activity to be led by Bishkek City Hall** ▪ Training in compiling an air quality plan would take longer—probably several months. ▪ Relatively small investment.
Development of **emission dispersion/transport modeling capabilities**	▪ **Medium term -** start within 12 months of finalizing the Air Quality Master Plan or earlier. ▪ **A high priority** ▪ Would require training across several months ▪ Medium-size investment.

Source: Original elaboration for this publication.

MNRETS is the primary institution responsible for the overall AQMS in the Kyrgyz Republic. However, there are various institutions outside of MNRETS that are responsible for the implementation of the modeled emission reduction measures. Table 5 suggests the main institutions that might be involved in the implementation of the modeled emission reduction measures and highlights the need for cross-institutional coordination of air quality management.

In addition to the institutional stakeholders responsible for the implementation of emission reduction measures, there could be a variety of private sector actors who can be engaged in the implementation of such measures. For instance, governments usually engage commercial banks in funding energy efficiency and clean residential heating measures. Other private sector actors such as heat-pumps' distributors and installers and gas distributor companies could also facilitate the implementation of emission reduction measures. The civil society sector could be involved in communicating the need for emission reduction measures to improve air quality to the general public and to disseminate information about available funding for such measures.

Table 6: Key responsible institutions for the implementation of emission reduction measures

Sector	Measure	Relevance to air quality management	Key responsible institutions
CHP and heat boilers	Fuel switch at CHP Bishkek	Replacing the use of coal at CHP Bishkek with cleaner alternatives is among the modeled emission reduction measures with important contributions to reducing the annual average $PM_{2.5}$ concentrations in the city. In addition, replacing the use of coal at the CHP is one of the priority measures to reduce CO_2 emissions.	Electric Power Plants JSC (CHP owner) National Energy Holding Company Ministry of Energy
	Conversion of the remaining coal HoBs to gas	The conversion of the remaining coal-fired HoBs will allow for reducing $PM_{2.5}$ concentrations in the most polluted period of the year—the heating season.	Bishkek Mayor's Office Bishkekteploset Bishkekteploenergo
Residential heating	Home insulation	Home insulation is an underlying fundamental measure to reduce emissions of both air pollutants and CO_2 from the residential sector. Home insulation also maximizes emission reductions from implementing cleaner heating measures.	Bishkek Mayor's Office Ministry of Energy
	Switch to clean residential heating	The switch to clean residential heating, in particular to zero-emission heating as in the case of heat-pumps, is the priority measure to reduce $PM_{2.5}$ concentrations in Bishkek.	Bishkek Mayor's Office Ministry of Energy
Transport	Traffic management	Reducing traffic emissions in the city will contribute to decreased $PM_{2.5}$ pollution throughout the year.	Bishkek Mayor's Office Ministry of Interior Ministry of Transport and Communications

Table 6

Sector	Measure	Relevance to air quality management	Key responsible institutions
Transport	Road dust suppression	Road dust suppression can be achieved by either reduced traffic on roads or by reduced amount of dust on roads.	Bishkek Mayor's Office
	Vehicles' emissions control	Improving car emissions control is the key transport measure to reduce both $PM_{2.5}$ and CO_2 emissions in Bishkek.	Bishkek Mayor's Office Ministry of Transport and Communications
	Marshrutka emissions control	*Marshrutkas* operate a significant part of the public transport in Bishkek and hence, improved emissions control will reduce $PM_{2.5}$ concentrations.	Bishkek Mayor's Office
	Buses emissions control	Improving the emissions control of buses running the public transport network in Bishkek is a default emission reduction measure for air quality management.	Bishkek Mayor's Office
Waste burning	Control waste open burning	Despite the fact that open waste burning is not a major source of air pollution, controlling this source is a default emission reduction measure for air quality management.	Bishkek Mayor's Office
Greening	Natural dust controls	Greening measures do not directly reduce emissions, but could abate both $PM_{2.5}$ and CO_2 emissions.	Bishkek Mayor's Office

Source: Original elaboration for this publication.

8. Conclusion and the Way Forward

$PM_{2.5}$ concentrations in Bishkek peak in the winter months and are substantially exceeding international air quality standards—for instance, daily average $PM_{2.5}$ concentrations in Bishkek in the winter exceed over 10 times the WHO's daily average guideline of 15 μg/m^3 on most days. As much as there are adverse meteorological conditions limiting the dispersion of air pollutants in Bishkek, especially in the winter, such as low wind speeds and low mixing heights, anthropogenic sources have an important contribution to air pollution.

This study compiled all available data and information for the main $PM_{2.5}$ emissions sources in the Bishkek airshed and mapped those sources at a spatial resolution of approximately 1 km^2 and a temporal resolution of 1 hour. The mapped area covered a total of 1,800 km^2 and included Bishkek City and the surrounding areas where emissions sources that might affect air quality in the city are located. This dynamic emissions map, coupled with 3D meteorological gridded data from the WRF model, was used in the chemical transport modeling with the CAMx modeling system to simulate the dispersion of $PM_{2.5}$ pollution over the airshed and to identify the contributions of key emissions sources to $PM_{2.5}$ concentrations.[28]

Residential combustion of coal is the leading contributor to $PM_{2.5}$ concentrations in the winter in Bishkek—accounting for nearly 40 percent of $PM_{2.5}$ concentrations in the city in some winter months. Emissions from residential use of coal are characterized by low release heights and are exacerbated by low coal quality and low efficiency of the heating appliances in which coal is burned.

Transport is another important contributor to $PM_{2.5}$ concentrations in Bishkek and is the second most important source of $PM_{2.5}$ pollution throughout the year with contributions to $PM_{2.5}$ concentrations ranging between 17 percent in the spring to 30 percent in the winter. $PM_{2.5}$ concentrations in the spring, summer, and fall are mainly affected by windblown dust from outside the Bishkek area. The contribution to $PM_{2.5}$ concentrations of windblown dust in Bishkek peaks in the dry summer months at about 60 percent. Given the well-documented occurrence of natural dust storms in Central Asia and the large estimated contribution of windblown dust to $PM_{2.5}$ concentrations in the region from global studies, additional analyses are needed to identify the sources of windblown dust in the region and to discuss possible measures, including transnational, to limit the impact of windblown dust on $PM_{2.5}$ pollution.

Another source of $PM_{2.5}$ pollution in Bishkek is power and heat generation—the CHP plant and the HoBs in the city. The contribution of the power and heat generation sector to $PM_{2.5}$ concentrations in Bishkek is the highest in the winter due to the additional heating demand. The highest estimated contribution to $PM_{2.5}$ concentrations of the power and heat generation sector in Bishkek is 15 percent in the winter months. Urban dust from citywide construction activities and resuspended dust from roads has a relatively constant contribution to $PM_{2.5}$ concentrations in Bishkek of about 10 percent throughout the year. Other sources such as industries and waste burning have a contribution of about 2 percent and 1 percent, respectively, to $PM_{2.5}$ concentrations in Bishkek.

[28] As mentioned previously, emissions (the substances emitted directly from different sources) do not translate directly into concentrations (the pollution the population is exposed to). Therefore, a source with very high emissions might not have as large of an impact to concentrations compared to a source with lower emissions but having more unfavorable dispersion characteristics (for example, low height of emissions release).

Modeling the dispersion of $PM_{2.5}$ pollution over Bishkek's airshed identified some pollution hot spots in the city. The highest $PM_{2.5}$ concentrations in the winter months were estimated to occur mainly in the northern areas, as well as in some western and eastern parts, of the city. Those areas are where the majority of SFHs without access to the district heating network and using coal for heating are situated. Due to the low emissions release heights and low wind speeds in the winter, air pollution is contained in the areas where residential coal use is the highest.

Overall, comparing the modeled $PM_{2.5}$ concentrations with the monitored concentrations from both automatic air quality monitoring stations and sensor networks shows a good fit of the modeled and monitored data. The modeled concentrations capture both the seasonal and spatial variations of air pollution in Bishkek as reported by the different air quality monitoring networks. This underlines the robustness of the conducted modeling and hence the reliability of the study's findings.

The purpose of the emission reduction scenarios assessed in this study was to determine the potential impact on ambient $PM_{2.5}$ concentrations in the Bishkek urban area from a wide range of policies and measures. The results provide a very informative first look at the extent to which concentrations could be reduced, and contextual information about the relative impact of different types of reduction measures and the relative importance of reduction measures that could be applied to different emissions sources. By identifying the major sources and comparing the effectiveness of various emission reduction measures, the study provides direction for further policy-related work in different areas.

Modeling the impact on $PM_{2.5}$ concentrations in Bishkek from implementing short-listed policies and measures in different sectors demonstrated that there is no single policy and measure or emission reductions in a single sector that would deliver the necessary air quality improvements to meet the WHO guidelines. Therefore, a balanced approach to air quality improvement that includes policies and measures across different sectors is needed to substantially improve air quality in Bishkek.

Nevertheless, the analyzed emission reduction scenarios show that the largest improvements in air quality in Bishkek can be achieved by substituting coal used for heating in individual homes and HoBs with cleaner alternatives. The single emission reduction measure showing the largest impact on $PM_{2.5}$ annual concentrations is replacing coal heating with heat pumps in 40 percent of the houses that currently use coal for heating. The transport measure with the highest impact on $PM_{2.5}$ concentrations in Bishkek is the increased adoption of newer vehicles (Euro 5 standard and higher) replacing old, pre-Euro standard vehicles.

Although some individual policies and measures show only a small positive impact on $PM_{2.5}$ concentrations in Bishkek, this does not mean that those measures should be disregarded. For instance, policies and measures on stricter emission controls in industry and in public transport are easier to implement than policies and measures in the residential sector and therefore are a viable part of any air quality management strategy. On the other hand, the benefits from policies and measures such as greening and restriction in open waste burning have multiple benefits beyond air quality improvement alone.

All modeled measures, except the switch to heating using electric boilers/radiators, show co-benefits of reducing CO_2 emissions. Electric radiators are lesser efficient than heat pumps and therefore use more electricity, currently produced by burning coal in Bishkek's CHP. If the source of fuel at the CHP is changed to less carbon-intensive fuels, then it is expected that even this measure will show CO2 co-benefits.

The results from this study laid the technical foundations for the update/development of a comprehensive air quality plan for Bishkek. The study conducted analysis of air quality and meteorology trends, created a spatially and temporally dynamic emissions map, and modeled the contributions to $PM_{2.5}$ concentrations in Bishkek of different sources. In this way, the most important analytical work in preparing an air quality plan has been performed by this study.

Data limitations, described in Table 1, restrict the level of detail for some of the emissions sources. There is potential to further refine the data through additional efforts and some targeted investments in data collection both at the level of the emission sources and ambient concentrations. This analysis should be carried out at regular intervals to inform dynamic policy making. Therefore, collection of more granular data for the key emissions sources and subsequent analyses are important tasks for improving air quality management in Bishkek. Despite the data limitations, the models in this study and monitored $PM_{2.5}$ concentrations show a good fit, which indicates that the study's results can be reliably used as a technical baseline in air quality planning in Bishkek.

In addition, the assessment of the impact on $PM_{2.5}$ concentrations of selected policies and measures in different sectors provides the basis upon which an action plan including a set of policies and measures to improve air quality in Bishkek can be developed. The next steps for the development of an air quality plan for Bishkek are:

- Discussing the relevant policies and measures with stakeholders;
- Agreeing on the need for additional analyses and on a list of policies and measures to be further analyzed. An additional study on the chemical speciation of $PM_{2.5}$ can be undertaken to assess toxicity of $PM_{2.5}$ from different sources. Further analyses on policies and measures could focus on: cost/benefit assessment of implementing emission reduction measures, distributional impacts of air pollution interventions on economic growth and human capital, and scenario analysis of the combination of sectoral interventions. Moreover, bottom-up analyses in key sectors relevant to air quality management will inform the need for strengthened sectoral policies and required investments;
- Analyzing implementation modalities and potential improvements to the air quality management system, including legislation, resources, and capacities, as well as implementation bottlenecks for the agreed policies and measures; and
- Assessing the cost-effectiveness of the agreed policies and measures with regard to achieving set air quality targets (for example, a $PM_{2.5}$ annual average concentration).

All the steps outlined above will help define policies and measures to be implemented as a priority. A timeline for the implementation of the priority policies and measures would have to be drawn up, as well as responsible entities for implementation, financing, enforcement, and monitoring. Effective monitoring of implementation of policies and measures would then inform whether or not there is a need to redesign policies and measures, adopt different/additional policies and measures, alter implementation modalities, and/or procure additional funding.

Such a process to air quality planning truly reflects the dynamic and complex nature of air quality management and provides flexibility to address issues in the implementation of policies and measures aiming to achieve an air quality target. Dynamic air quality planning recognizes that there are a number of possible ways to achieving an air quality target. However, starting with a comprehensive action plan describing how to achieve air quality targets and effectively monitoring its implementation provides the tools for decision makers to better navigate the way forward to improved air quality in Bishkek.

Annex 1. CO_2 Co-Benefits from $PM_{2.5}$ Emission Reduction Measures

CO_2 emissions calculations

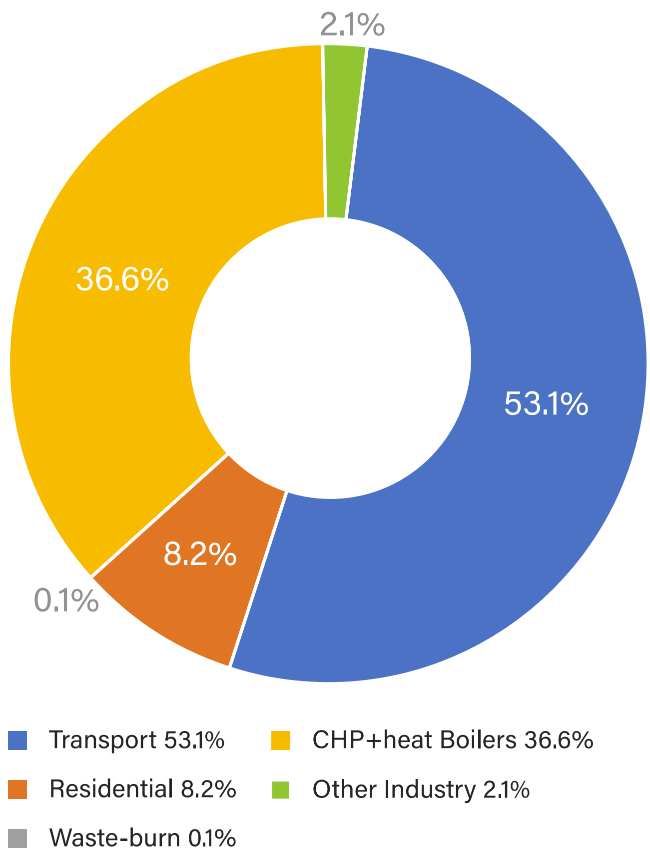
The baseline CO_2 emissions in Bishkek use the same activity data as the ones used for the $PM_{2.5}$ emissions calculations, presented in Chapter 3. CO_2 emissions are directly proportional to the carbon content of fuels, and therefore, CO_2 emissions in Bishkek were calculated from the compiled energy and fuel data.

The largest source of annual CO_2 emissions in Bishkek is transport, accounting for over half of the emissions in the city. Bishkek CHP and HoBs are another important source of CO_2 emissions responsible for over one-third of annual emissions. Burning coal in the residential sector is another important source of CO_2 emissions but, unlike the case with $PM_{2.5}$ emissions, is not the dominant source.

Impacts on CO_2 emissions of the modeled $PM_{2.5}$ emission reduction measures

As seen from Figure A 1, the priority sources of CO_2 and $PM_{2.5}$ emissions do not completely match. Therefore, the study analyzed the impact on CO_2 emissions of the modeled $PM_{2.5}$ emission reduction measures.

Figure A 1: Source contributions to CO_2 emissions in Bishkek



Source: Original elaboration for this publication.

Table A 1: Impact on CO_2 emissions of modeled $PM_{2.5}$ emission reduction measures

Sector	Measure	Description	Reduction in annual $PM_{2.5}$ concentration (%)	Reduction in CO_2 emissions (%)
CHP and heat boilers	CHP coal to gas	Assume same power output, but CHP using modern gas turbine technology instead of current coal	9.0	29.0
	HoBs coal to gas	Assume same power output, but all HoBs using modern gas technology, not current coal	2.0	1.0
	More renewables	Assume 30% reduction in CHP and HoBs emissions because of adoption of renewables	4.0	11.0
Residential heating[a]	Home insulation - low	Assume 20% of houses using coal reduce heating needs by 33% through EE measures	2.0	0.5
	Home insulation - high	Assume 40% of houses using coal reduce heating needs by 33% through EE measures	3.0	1.0
	Residential coal to gas - low	Assume 20% of houses using coal change from coal to modern gas heating system	6.0	2.0
	Residential coal to gas - high	Assume 40% of houses using coal change from coal to modern gas heating system	12.0	3.0
	Residential heat pumps - low	Assume 20% of houses using coal change to heat pumps, increase CHP emissions (3%)	5.0	0.5
	Residential heat pumps - high	Assume 40% of houses using coal change to heat pumps, increase CHP emissions (6%)	13.0	1.0
	Residential more electricity - low	Assume 20% of houses using coal change to electric boiler heating, increase CHP emissions (10%)	5.0	-2.0
	Residential more electricity - high	Assume 40% of houses using coal change to electric boiler heating, increase CHP emissions (20%)	9.0	-4.0
	Complete switch to clean heating	**Complete replacement of coal heating with zero-emission heating**	29.0	8.0
Transport	Traffic management	Reduce all traffic emissions in the city by 10%	3.0	5.0
	Road dust suppression	Reduce in-city dust emissions by 10%	1.0	–
	Car emissions control - low	Convert 20% of pre-Euro/non-cat petrol cars to Euro 5, and 20% pre-Euro/non-cat diesel cars to Euro 5	3.0	6.0
	Car emissions control - high	Convert 40% of pre-Euro/non-cat petrol cars to Euro 5, and 40% pre-Euro/non-cat diesel cars to Euro 5	6.0	13.0

Table A1

Sector	Measure	Description	Reduction in annual $PM_{2.5}$ concentration (%)	Reduction in CO_2 emissions (%)
Transport	*Marshrutka* emissions control	Convert 40% of pre-Euro/non-DPF diesel LDVs from pre-Euro/non-cat to Euro VI	1.0	1.0
	Buses emissions control	Convert all buses to Euro VI	0.2	0.3
	LDV/HGV emissions control	Convert 40% pre-Euro/non-DPF diesel LDVs and 40% HGVs to Euro VI	3.0	4.0
	Total of all measures combined	**Combined impacts of all the modeled transport measures (high scenarios)**	13.0	22.0
	Complete switch to zero-emission	**Complete switch to zero-emission vehicles for the entire vehicle fleet**	27.0	51.0
Waste burning	Control waste open burning	Assume 50% reduction of waste open burning	1.0	–
	No open waste burning, including dump	Assume zero emissions from dumpsite and open waste burning	1.0	–
Greening[b]	Natural dust controls - low	Assume 5% reduction in regional dust emissions	1.0	–
	Natural dust controls - high	Assume 10% reduction in regional dust emissions	2.0	–

Source: Original elaboration for this publication.

Note: a. Additional electricity demand from the existing CHP was modeled for residential heating measures involving switching to electricity for heating (for example, heat pumps and heating with electric radiators). The CHP emissions depend on the fuel used to generate electricity; **b.** The greening measures are used as natural dust controls primarily affecting windblown dust.

Nearly all modeled $PM_{2.5}$ emission reduction measures show co-benefits in terms of CO_2 emission reductions. The notable exceptions are the measures that replace coal heating with heating with electric radiators. Electric heaters and radiators are not the most efficient electric heating devices and can use a significant amount of energy, especially compared to the more efficient electric heating options—using heat pumps. Since a switch to electric heaters and/or radiators will increase the demand for electricity supplied by Bishkek coal-fired CHP, there is a small negative impact on CO_2 emissions from implementing this measure. In addition, the small CO_2 penalty for this measure is because Bishkek CHP uses coal—if the CHP switches to less carbon-intensive fuels, then it is expected that even the switch to electric heaters will show CO_2 co-benefits.

The individual modeled $PM_{2.5}$ emission reduction measure that shows the largest CO_2 emission reduction co-benefits is the complete switch to zero-emission vehicles in Bishkek. The switch to gas of Bishkek coal-fired CHP is the measure that shows the second highest CO_2 emission reduction co-benefit. The combined impact of all transport measures, excluding the extreme case of a complete switch to zero-emission vehicles, represents the third largest CO_2 emission reduction co-benefit from the modeled measures in this study.

Overall, analyzing the impact of $PM_{2.5}$ emission reduction measures on CO_2 emissions demonstrates that priority sources and hence measures to reduce $PM_{2.5}$ pollution and CO_2 emissions differ. Therefore, when designing air quality policies, it is important to not only maximize synergies with climate change policies but also be aware of and manage the possible trade-offs.

Annex 2. Black Carbon Emissions

Black Carbon (BC) is an integral part of the composition of $PM_{2.5}$ and at the same time is an SLCP. It absorbs solar radiation, influences cloud processes, and alters the melting of snow and ice cover. It can thus affect glaciers in the Kyrgyz Republic. However, the impact on glacial melting attributable to BC is uncertain due to studies not sufficiently accounting for natural impurities such as soil dust and due to difficulties in modeling in mountainous regions. Nevertheless, some studies estimate that BC might be responsible for 6 percent to 16 percent of glacial melting in Central Asia.

BC emissions calculations

The baseline BC emissions in Bishkek were calculated from the compiled energy and fuel data presented in Chapter 3. The main sources of BC emissions are fuels used in road transport and solid fuels used in industries and the residential sector.

Table A 2: BC emissions estimates for Bishkek, 2018

Emissions source	Description	BC emissions, tons/year
Transport	Includes all road transport and emissions from the airport	850
Residential heating	Includes emissions from residential heating and cooking	350
Industry	Includes emissions from other industrial estates, including the CHP plant, quarries, and brick kilns, as well as from diesel generators at commercial buildings	250
Total		**1,450**

Source: Original elaboration for this publication.

Impacts on BC emissions of the modeled $PM_{2.5}$ emission reduction measures[29]

$PM_{2.5}$ emission reduction measures typically reduce BC emissions as BC is one of the components of $PM_{2.5}$. Nevertheless, it should be noted that the estimated BC emissions for Bishkek are 0.03 percent of the global BC emissions.[30] Hence, BC deposition on glaciers in the Kyrgyz Republic is in general dependent on the global BC circulation, and therefore, additional regional and global BC emission reduction measures are needed to reduce glacial melting potentially affected by BC in the Kyrgyz Republic.

[29] Bond, T. C., et al. 2013. "Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment." J. Geophys. Res. Atmos. 118 : 5380–5552. doi:10.1002/jgrd.50171; Schmale, J., M. Flanner, S. Kang, et al. 2017. "Modulation of Snow Reflectance and Snowmelt from Central Asian Glaciers by Anthropogenic Black Carbon." Sci Rep 7: 40501; Zhang, Y., et al. 2020. "Effects of Black Carbon and Mineral Dust on Glacial Melting on the Muz Taw Glacier, Central Asia." Science of the Total Environment 740.

[30] European Commission. EDGAR – Emissions Database for Global Atmospheric Research: Air and Toxic Pollutants. https://edgar.jrc.ec.europa.eu/air_pollutants.

Air Quality Analysis for Bishkek: $PM_{2.5}$ Source Apportionment and Emission Reduction Measures

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