air

MDPI

Article

Mapping $PM_{2.5}$ Sources and Emission Management Options for Bishkek, Kyrgyzstan

Sarath K. Guttikunda [1,2,*], Vasil B. Zlatev [3], Sai Krishna Dammalapati [2] and Kirtan C. Sahoo [3]

1. Transportation Research and Injury Prevention Centre, Indian Institute of Technology, New Delhi 110016, India
2. Urban Emissions Information, New Delhi 110001, India
3. The World Bank Group, Washington, DC 20433, USA

* Correspondence: sguttikunda@urbanemissions.info

Abstract: Harsh winters, aging infrastructure, and the demand for modern amenities are major factors contributing to the deteriorating air quality in Bishkek. The city meets its winter heating energy needs through coal combustion at the central heating plant, heat-only boilers, and in situ heating equipment, while diesel and petrol fuel its transportation. Additional pollution sources include 30 km^2 of industrial area, 16 large open combustion brick kilns, a vehicle fleet with an average age of more than 10 years, 7.5 km^2 of quarries, and a landfill. The annual $PM_{2.5}$ emission load for the airshed is approximately 5500 tons, resulting in an annual average concentration of 48 $\mu g/m^3$. Wintertime daily averages range from 200 to 300 $\mu g/m^3$. The meteorological and pollution modeling was conducted using a WRF–CAMx system to evaluate $PM_{2.5}$ source contributions and to support scenario analysis. Proposed emissions management policies include shifting to clean fuels like gas and electricity for heating, restricting secondhand vehicle imports while promoting newer standard vehicles, enhancing public transport with newer buses, doubling waste collection efficiency, improving landfill management, encouraging greening, and maintaining road infrastructure to control dust emissions. Implementing these measures is expected to reduce $PM_{2.5}$ levels by 50–70% in the mid- to long-term. A comprehensive plan for Bishkek should expand the ambient monitoring network with reference-grade and low-cost sensors to track air quality management progress and enhance public awareness.

Keywords: Bishkek; urban air quality; emissions inventory; $PM_{2.5}$ pollution; winter heating; emissions management

Citation: Guttikunda, S.K.; Zlatev, V.B.; Dammalapati, S.K.; Sahoo, K.C. Mapping $PM_{2.5}$ Sources and Emission Management Options for Bishkek, Kyrgyzstan. *Air* **2024**, *2*, 362–379. https://doi.org/10.3390/air2040021

Academic Editor: Joseph Pinto

Received: 22 July 2024
Revised: 15 September 2024
Accepted: 23 September 2024
Published: 1 October 2024

1. Introduction

Air pollution and related health impacts are a growing problem in Asia [1–4]. Most of the cities in the top 100 most polluted list are from Asia (https://iqair.com—accessed on 1 July 2024). This ranking is based on the annual average $PM_{2.5}$ (particulate matter with aerodynamic diameter < 2.5 μm) concentrations only. The six distinct blocks of nations with unique geographical, economic, and environmental models in Asia are East Asia, South Asia, Southeast Asia, Central Asia, the Middle East, and Russia. Of these, air pollution in Central Asian cities is the least discussed in the published literature and South Asia and East Asia are the most published with some positive news of improving air quality trends in East Asia [5,6]. While Bangladesh, Pakistan, and India from South Asia take top three spots as the most polluted countries, Tajikistan from Central Asia is ranked the fourth, followed by Burkina Faso from Africa. According to the 2024 State of the Global Air report, the overall mortality rate due to air pollution from outdoor $PM_{2.5}$, ozone, and nitrogen dioxide (NO_2), and indoor household energy use remained relatively constant at 84,000 and 83,000 in 1990 and 2021, respectively [3]. Improvements in household energy use interventions, like a shift to cleaner liquified petroleum gas (LPG) and electricity, resulted in lesser indoor air pollution-related deaths [7,8], but the outdoor mortality rate rose more than 50% from 41,000 and 66,000 in 1990 and 2021, respectively.

These changes are also evident in the annual average observations from the TROPOMI Sentinel-5P satellite, summarized in Table 1, for the period of 2019–2023 [9]. This columnar density (mol/m^2) represents the national average for each of the pollutants representing everything in the atmosphere from stratosphere and below, and it is a good proxy to understand the changes in the local and regional emission signatures. In general, regarding NO_2 and SO_2, primary emissions from fossil fuel combustion increased between 2019 and 2023. In Kyrgyzstan (KGZ), an increase was observed for all the gases. Formaldehyde (HCHO), which is a proxy for the volatile organic compounds (VOCs), increased only in KGZ and Tajikistan. The ultraviolet aerosol index (UVAI) is a useful residual index calculated as a difference in the aerosol index between absorbing (dust and carbonaceous particles) and non-absorbing aerosols (sulfates, nitrates, and ammonium). A shift in the values from strongly negative to less negative or positive numbers indicate the presence of more dust and carbon. This dust can come from wind erosion in the neighboring arid regions or from resuspension on the city roads, and carbon as black and brown carbon (part of organic aerosols) can come from combustion of fossil and biomass fuels. The increase in the column density numbers and the ambient pollution levels are linked to the growing number of vehicles and their usage; increasing demand for residential, commercial, and industrial electricity; increase in open waste burning from lack of comprehensive waste management plans; increasing dust resuspension from vehicle movement, construction activities, and wind erosion; and more residential and commercial space heating during the winters [10–12].

Table 1. Annual average columnar density (mol/m^2) of NO_2, SO_2, and HCHO and columnar UVAI for the area covering the national boundaries, as observed by the TROPOMI Sentinel-5P satellite and extracted from the Google Earth Engine platform. For NO_2, SO_2, and HCHO, the last column is calculated as (2023–2019)/2019 and for UVAI, the last column is calculated as (2019–2023)/2019 because of the residual nature of this metric to show the direction of change.

Pollutant	Country	2019	2020	2021	2022	2023	% 2023–2019
NO_2	Kazakhstan	7.0	6.4	7.0	6.7	7.1	2.2%
*10^{-5} mol/m^2	Kyrgyzstan	6.3	5.9	6.2	6.2	6.9	8.8%
	Tajikistan	6.5	6.1	6.4	6.3	6.8	4.2%
	Turkmenistan	6.9	6.5	7.1	6.8	7.3	5.5%
	Uzbekistan	7.2	6.7	7.5	7.1	7.7	6.6%
SO_2	Kazakhstan	6.0	6.6	4.1	6.0	5.8	−3.5%
*10^{-5} mol/m^2	Kyrgyzstan	1.4	3.7	5.0	2.7	2.3	58.7%
	Tajikistan	3.3	4.8	6.6	3.3	3.6	10.1%
	Turkmenistan	5.6	7.4	7.1	4.8	5.7	0.3%
	Uzbekistan	5.3	8.4	6.4	4.6	5.8	8.8%
HCHO	Kazakhstan	8.4	7.8	8.5	7.9	7.5	−11.5%
*10^{-5} mol/m^2	Kyrgyzstan	7.7	6.9	8.3	8.2	7.9	3.0%
	Tajikistan	7.3	6.4	8.2	8.2	8.4	15.7%
	Turkmenistan	10.8	9.7	9.7	9.6	9.7	−10.6%
	Uzbekistan	10.3	9.1	9.3	8.9	8.9	−13.2%
UVAI	Kazakhstan	−0.8	−1.0	−0.5	0.0	0.1	109.6%
No-units	Kyrgyzstan	−0.9	−1.2	−0.9	−0.4	−0.3	64.7%
	Tajikistan	−0.7	−0.9	−0.6	−0.1	−0.1	88.6%
	Turkmenistan	−0.5	−0.7	−0.2	0.7	0.8	247.2%
	Uzbekistan	−0.6	−0.7	−0.3	0.5	0.6	205.4%

In Central Asia, based on Table 1, the business-as-usual scenario suggests an increasing consumption trend for coal, biomass, petrol, diesel, and gas and limited action on waste management; all combustion resulted in increasing emission intensity in the city and regional airsheds and, subsequently, more ambient pollution. Among all the pollutants, $PM_{2.5}$ and PM_{10} (PM with aerodynamic diameter < 10 µm) continue to dominate the policy discussions. In Central Asia, the five capital cities—Almaty in Kazakhstan, Ashgabat in Turkmenistan, Bishkek in Kyrgyzstan, Dushanbe in Tajikistan, and Tashkent in Uzbekistan—are the most polluted, with an increasing trend in the annual average $PM_{2.5}$ concentrations [13,14]. Other pollutants of interest are sulfur dioxide (SO_2), nitrogen oxides ($NO_x = NO + NO_2$), carbon monoxide (CO), and ozone. Across Central Asia, the pollution control options in four sectors that need immediate attention are the following: energy efficiency at the power plants and district heating systems; promotion of clean fuels for cooking and space heating; infrastructure to integrate cycling, walking, and buses in urban planning; and enforcement of emission norms at the small and medium scale industries.

An effective air quality management plan requires an understanding of the pollution trends from monitoring and modeling exercises. While expanding the monitoring efforts can provide necessary information on the extent of pollution, the modeling efforts can strengthen the knowledge base with where the pollution is coming from and what the emission intensities are in various sectors. An emissions inventory representing the sectors across an urban airshed is often the missing piece of knowledge in the low- and middle-income countries. In this paper, for Bishkek city, we are presenting a high-resolution multi-pollutant emissions inventory, its application to understand the seasonality in ambient $PM_{2.5}$ concentrations and source contributions, and a discussion on the proposed emissions management plans to achieve clean air targets.

2. Bishkek: Materials and Methods

2.1. Bishkek Airshed

Bishkek, the capital city of the Kyrgyz Republic, with a population of over one million, and it spans 160 km^2 at an altitude of 800 m in the Chuy Valley. The city is geographically north of India and the Himalayan range, with peaks over 4000 m within 50 km from the city. The study domain for the Bishkek's airshed extends from 74.35° E to 74.85° E in longitude and 42.7° N to 43.1° N in latitude (Figure 1a). The airshed is further divided into 50 × 40 grids at a spatial resolution of 0.01° (which is approximately 900 m at these latitudes). All the available geospatial information, emission inventories, and modeled pollution data are maintained at this spatial resolution for interoperability.

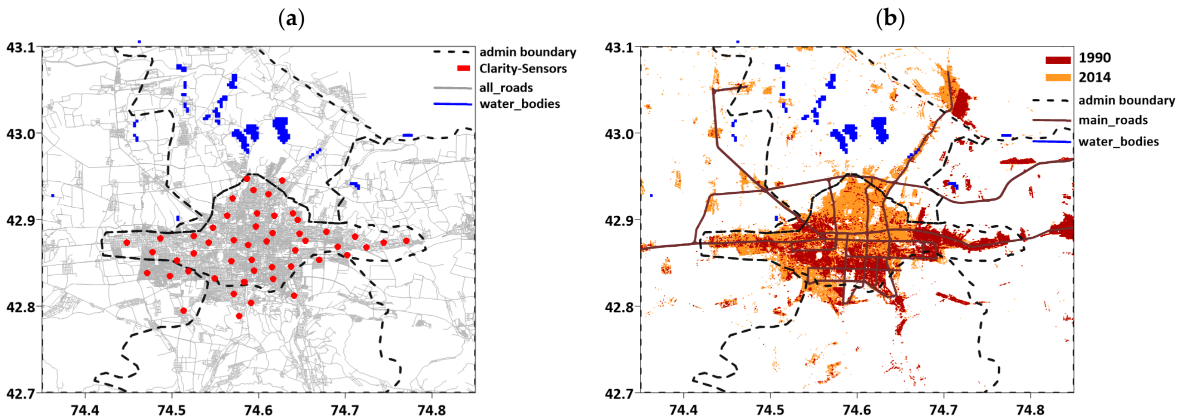


Figure 1. (**a**) Designated airshed for the Bishkek city covering the administrative boundary, neighboring satellite areas with the potential to influence the city's air quality. Grey lines indicate the road network extracted from OpenStreetMap's database. Red dots indicate the location of the Clarity low-cost sensor network operated by the KGZ Hydrometeorological Agency. (**b**) Built-up area identified by the European Space Agency's global human settlements program for 1990 and 2014. Black lines indicate the main highways in the city.

The road density information as primary, secondary, tertiary, and other roads is extracted from https://openstreetmap.org (accessed on 1 July 2024), along with commercial activity density as hotspots in the airshed, such as hotels, hospitals, schools, shops, buildings, traffic points, fuel stations, and other points-of-interest. The mapped operational road network is 7000 km, with approximately 600 km designated as primary roads, including highways. A total of 34,000 points-of-interest were mapped, including 24,000 building structures. The land use, landcover, and urban–rural classification information were extracted from the European Space Agency's (ESA) global human settlement (GHS) program for the period 1992 to 2020, which shows the urbanization trends—a proxy for the demand for electricity, residential, and industrial energy, commercial amenities, and personal mobility [15]. The urban built-up area in the airshed tripled from 1990 to 2014, expanding outside the main city district boundary (Figure 1b). The total gridded population information (not presented here) was extracted at the model resolution from the LANDSCAN program [16], which overlaps with the urban shades and high road density areas in the figures. A copy of all the geospatial information for the Bishkek airshed is included in the Data Repository.

2.2. Meteorology

Harsh winters (November to February) with near-surface temperatures below 0 °C for 50–80% of the time, accompanied by slow-moving winds under 2 m/s for more than 50% of the time, are characterized by freezing temperatures, heavy snowfall, and icy conditions (Figure 2a,b). Wintertime snow fall averages at 100 mm per month and peaks at 200 mm, with annual totals reaching 500 to 700 mm between November and February. In addition to snow, precipitation averages at 50 mm per month during the rainy and snowy seasons, with annual totals around 400 to 500 mm. Snow cover can persist for several weeks, impacting transportation and daily activities. The mixing layer (inversion) height, an important proxy for horizontal dispersion and vertical mixing of the emissions is lower in the winter months and lower during the night-time throughout the year, exacerbating the air pollution problems in the city (Figure 2c). A low mixing height means higher pollution levels for the same number of emissions. However, the winter months are also marked with higher emission intensity from space heating demand in the residential and commercial sectors, and this demand is met via combustion of coal and biomass fuels. The share of wind directions is consistent over the year, mostly originating from the south and west.

The meteorological summary in Figure 2 is extracted from a full year Weather Research Forecasting (WRF) model simulation, with the final resolution set at 1 km, using the lateral and boundary conditions from the global NCEP reanalysis fields [17,18]. A full summary of meteorological data, including wind speeds, wind direction, temperatures, relative humidity, precipitation, and inversion heights, is included in the Data Repository. Model-ready gridded meteorological data at an hourly temporal resolution are available as NetCDF files upon request.

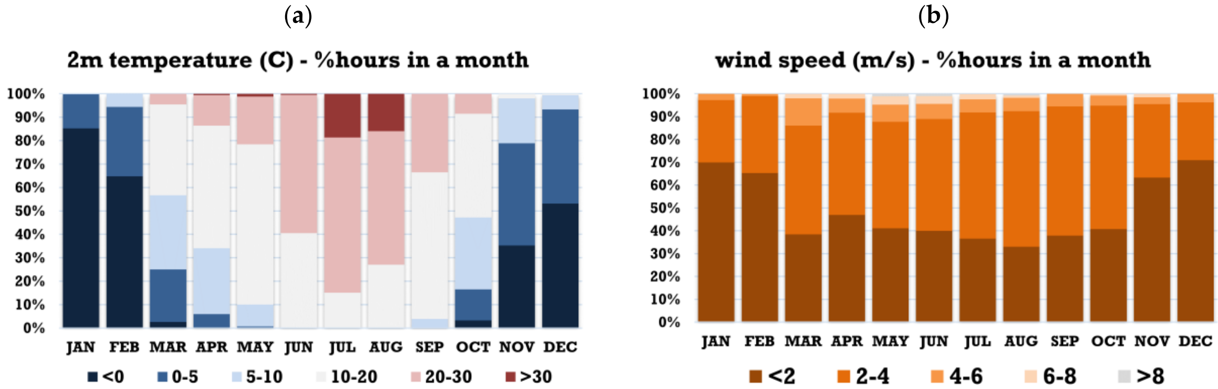


Figure 2. *Cont.*

(c) (d)

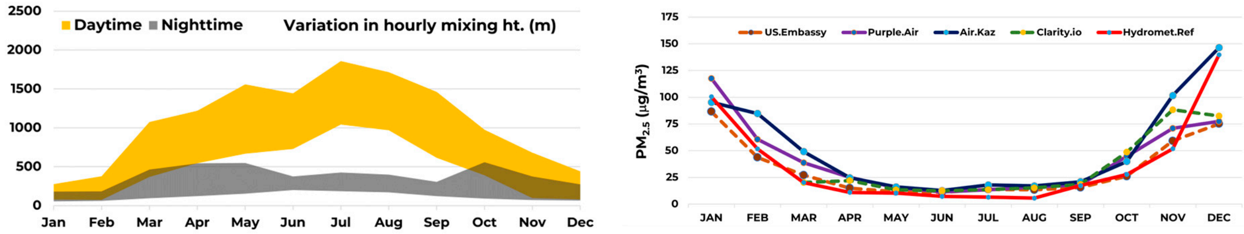


Figure 2. Percent hours in a month for (**a**) 2 m temperature and (**b**) wind speeds. (**c**) Variation in the mixing layer height in each month separated for daytime and night-time. All the meteorological data are extracted from the WRF model simulation for a full year at 0.01° spatial resolution and 1 h temporal resolution. (**d**) Summary of all the ambient monitoring data from reference-grade monitors operated by the U.S. Embassy and the KGZ Hydrometeorological Agency and low-cost sensors from three groups—AirKaz, Clarity, and Purple Air.

2.3. Ambient Monitoring Data

Reference-grade ambient monitoring networks in Bishkek are limited—one station operated by the KGZ Hydrometeorological Agency (KHA) and another station at the U.S. Embassy. The ambient monitoring needs of the city are supplemented by the low-cost sensor network, with periodic calibrations, from three different groups. The use of sensors is an emerging practice to fill the monitoring gaps in a hybrid mode and to keep the operating costs to a minimum [19,20]. The KHA installed 50+ sensors from Clarity, and it is the largest network with full spatial coverage across the main city (Figure 1a), and two independent groups installed 15 Purple Air and AirKaz sensors, with open access to the data. Figure 2d presents a summary of all the ambient monitoring data between 2019 and 2021. The annual average $PM_{2.5}$ concentration of all stations was 48 μg/m^3. Wintertime daily averages were more than 75 μg/m^3, with peaks reaching 200 μg/m^3, and summertime concentrations were as low as 10 μg/m^3. The calibrated sensors also displayed similar ranges across the city. The sensors located to the north of an imaginary line through the middle of the city (around 42.88° N latitude in Figure 1a) recorded 30–50% higher values than those below. This area also exhibits higher population density, higher commercial points-of-interest density, a large power plant, and a landfill. The diurnal cycle in the concentrations showed a typical pattern with highs during the morning and evening rush hours at 8 AM and 5 PM, respectively, and it also showed highs during the night-time with low mixing heights (Figure 2c), tapering off after midnight through 5 AM. The monitoring data are useful for validating the modeled concentrations and increasing the overall confidence in the emissions inventory for the city. A summary of cleaned monitoring data is included in the Data Repository.

2.4. Mapping Emission Sources and Emission Intensities

While methodologies and methods are well established to build detailed emission inventories, with multiple applications and examples to follow in global and regional inventories, the lack of model-ready information from the city(s) has always been a concern [21–24]. Uncertainty in the input data is an important concern in low- and middle-income countries (LMICs) [25], especially those like KGZ with limited information in the public domain that can immediately be utilized in the emissions models. A large part of the emissions modeling exercise in Bishkek was to locate the sources on a map, to build geospatial information necessary for representing various sectors, to construct model-ready inventories, and find proxies where ground data are not available. The Google Earth platform was useful to build these resources for Bishkek, along with physical inspection of select points of interest to assess the combustion and control processes in place.

The Central Heating Plant (CHP) (Figure 3a,b) was commissioned in 1961 with 24 power generation units and an installed capacity of 910 MW. The units were modernized in 2017 for newer boiler combustion technology and emission controls. On average, the plant annually consumes one million tons of local coal and 650,000 tons of coal from Kazakhstan. There is limited information on the abatement technology in practice—for PM, electrostatic precipitators (ESP) or cyclone bags are used; for SO_2, flue gas desulfurization (FGD) units are used; and for NO_x, absorption systems are used. Based on the conversations with the staff and information received from the ministry of natural resources, ecology, and technical supervision (MNRETS), standard operational efficiencies were used, such as 98% control efficiency at ESPs and no gaseous emission controls. Additionally, the calculations account for fugitive dust emissions from the coal stored outside the plant. A scan of the CHP area and a site visit confirmed that the coal storage is uncovered and located outdoors (Figure 3a). The exact area of the storage facility was marked using Google Earth image scanning.

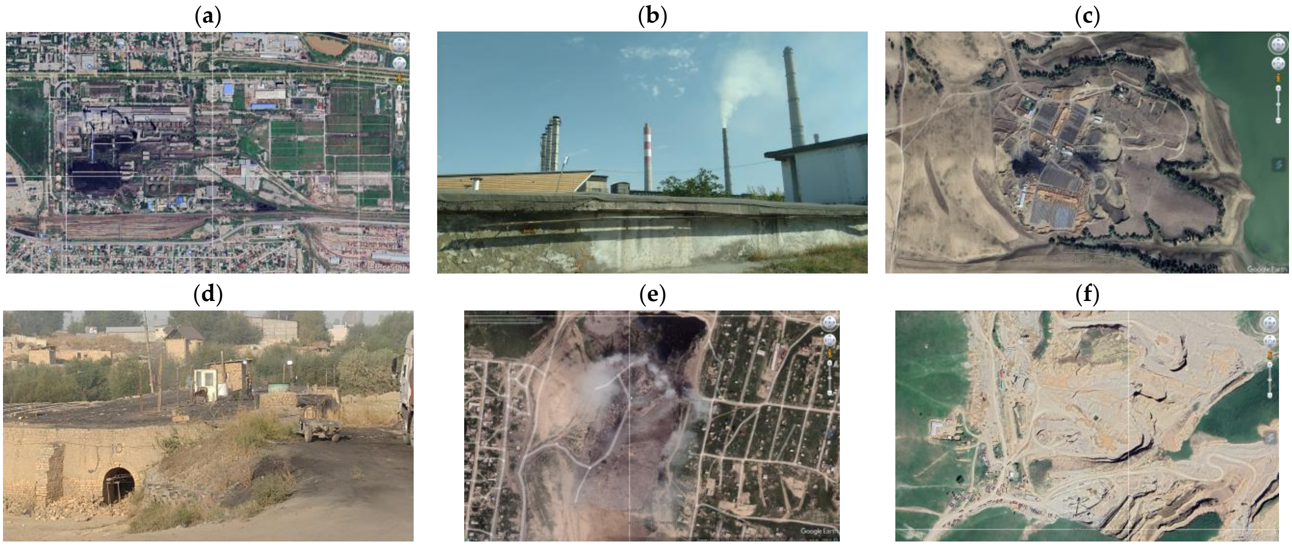


Figure 3. (**a**) Google Earth screenshot of the central heating plant. (**b**) Photo of the central heating plant stack. (**c**) Google Earth screenshot of a cluster of brick kilns to the north of the city. (**d**) Photo of an operational brick kiln in the airshed. (**e**) Google Earth screenshot of the landfill. (**f**) Google Earth screenshot of an operational quarry. Photos by the authors.

The city's cooking energy needs are supported by electricity from the CHP. However, a large share of the heating needs is dependent on non-electric sources. The surface temperatures in Bishkek during the winter months and during the nighttime are often under the threshold limit demanding space heating (Figure 2a). Multiple household surveys by MNRETS concluded that the average coal consumption for heating is 9 GJ/year/capita. This demand is met using heating from CHP, heat only boilers (HoBs), and in situ combustion of coal and biomass. The residential heating estimates utilized multiple data sources to distribute the emissions spatially and temporally with maximum accuracy. These sources included maps of the district heating infrastructure and HoBs locations, information on the percentage of Bishkek's population connected to the district heating network, and fuel consumption rates at the HoBs (Figure 4a). This network covered approximately 40% of the main city area and spread to the south, southeast, and southwest of the plant. On average, 60% of the population is connected to either CHP's district heating scheme or operate large scale HoBs, and the remaining 40% are single-family households that relied on coal using simple low-pressure boilers or traditional coal-fired stoves, characterized by low energy efficiency.

Google Earth imaging identified sixteen large open brick kilns in the airshed (Figure 4b). To gain a better understanding of the brick production scale, a site visit was conducted at one of these kilns. This visit provided valuable insights into the production processes, output volume, and operational practices at the kilns (Figure 3c,d). The open drying of the clay blocks, stacking of the semi-dry bricks in the kiln, infusion of coal and biomass mix into the kiln layers, and combustion process are like the styles observed in India and Bangladesh, but without a fixed chimney to direct the emissions above the surface layer [26]. The absence of a chimney turns the combustion emissions from the kiln into an area source, dispersing directly into the vicinity. In contrast, kilns in India and Bangladesh employ a 50 m stack to disperse emissions into the upper atmosphere, effectively diluting their impact. Based on the image scanning and site visits, it was estimated that on average 20,000 bricks are manufactured at these kilns per operational day. Since these are open kilns, most of the production happens during the non-snowy and non-monsoonal months. The transport equipment used at the sites is old (pictured in Figure 3d), supporting the transfer of raw material, semi-finished goods to the kiln, and movement of the finished products. Even though they are not likely to travel far from the site, the emission rates from diesel combustion are higher than normal, making the kiln areas an important hotspot for emissions. The area covered by the kilns for drying and processing (estimated from the Google Earth scans) also produce fugitive dust emissions. Apart from the CHP plant and the brick kilns, other industrial estates were also mapped for the airshed (Figure 4c). The total area mapped as industrial is approximately 30 km^2. The mix of industries in KGZ include metal processing, food and tobacco production, rubber, plastic, textile, cloths, footwear, leather, and other non-metal products. The total industrial emissions were estimated using energy balance tables and data from the National Statistical Committee (NSC). These tables provide a detailed overview of total energy consumption and distribution in the country and the city, essential for accurately calculating the industrial emissions. The mapped layers of industrial locations are an important proxy of origins and destinations for distributing the freight vehicle movement emissions in the airshed.

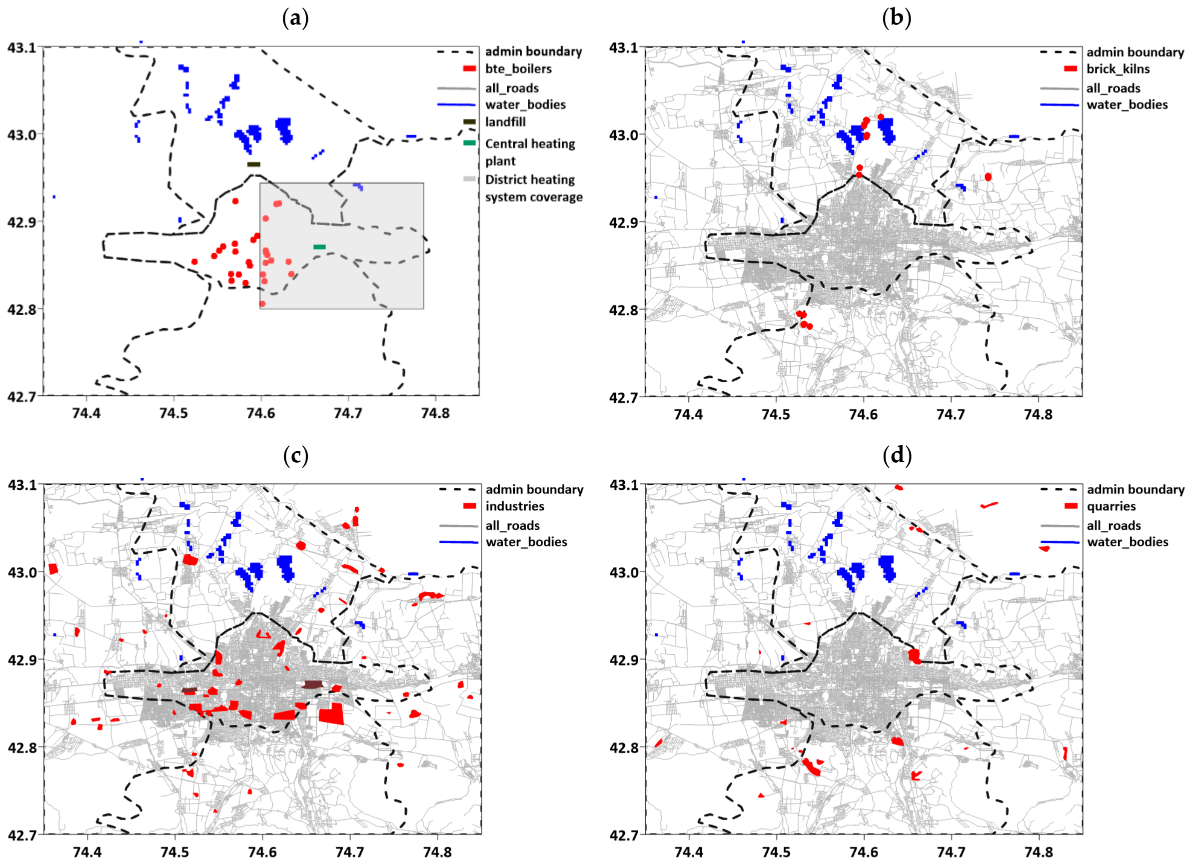


Figure 4. (**a**) Mapped location of the central heating power plant, heating only boilers (HoBs), and the landfill and the extent of the district heating system. (**b**) Mapped brick kiln locations in the airshed. (**c**) Industrial units and estates mapped across the airshed and (**d**) quarry areas mapped across the airshed. The exact location of these activities was mapped using Google Earth imagery.

The largest dumpsite in Bishkek is located to the northwest of the city (Figure 4a) and covers approximately 0.5 km^2 with an operational capacity of 200 tons per day. The city's average waste generation rate is 350 tons per day, leaving a significant amount of waste uncollected. In the wintertime, the collection rates are lower as the waste is also burnt in the heating boilers as a sporadic substitute for coal and biomass. Large sections of the landfill are often under open fire, spewing uncertain amounts of emissions into the immediate vicinity (Figure 3e).

A source not often registered as an emission source are quarries across the airshed. A total of 7.5 km^2 was identified as quarry area from the Google Earth scans (Figures 3f and 4d). While these are located outside the main city, the open nature of these quarries makes them susceptible to windblown erosion and this contributes to the PM_{10} fraction of the pollution in the city. Emissions from quarries originate from the crushing equipment using diesel, crushing activities, and transportation of the finished product—the concentration of heavy-duty trucks at one of the quarries in Figure 4d is an indication of the scale of the activity.

The urban and rural classification information and data on the construction rates from the statistics department were used to estimate the amount of area under construction each year, which was used as background information to calculate fugitive emissions from the construction sites. On average, it is assumed that 2% of the urban grid area is under construction. The activities at the brick kilns and the quarries are collectively part of the construction industry.

The vehicle stock information for Bishkek, vehicle usage characteristics, and statistics on passenger and freight movement were obtained from NSC and the Mayor's Office. More than 500,000 vehicles are registered in Bishkek, with most of them tagged as passenger vehicles. The public transportation system is called "marshurutki" comprising trollies, mini-buses, and buses—approximately one thousand. Data from NSC revealed that most vehicles registered in Bishkek are over 10 years old, with emission factors falling under the Euro 4 standard. The volume of cargo transport and passenger movement at the national level was downscaled to Bishkek, based on the city's population and socio-economic activity. The total passenger km traveled is approximately 7.0 billion km and total freight movement is approximately 2.0 billion ton/km. The estimated mileage was used to balance the fuel sales information, as a verification of the assumptions. The spatial variation in the vehicle exhaust emissions is built using data-rich geospatial information layers on population, urbanization, the road network, and points of interest (presented in the previous sections) and assigning appropriate weights for various vehicle types. The airport traffic information, as flight landing and takes-offs (LTO), was extracted from the following link: https://flightstats.com (accessed on 1 July 2024). On average, there are 70 LTOs per day. In addition to LTO emissions, the data were also used to include hotspot emissions at the airport for passenger pickup and drop-off and equivalent extra km of travel in the vicinity of the airport from support activities per LTO. The spatially distributed vehicle movement on the roads are also used to estimate the road dust resuspension emissions.

2.5. Models

The emissions inventory for the designated airshed is established using activity-based models, which for each known sector take into consideration the energy consumption data and an appropriate emission factor for the pollutants of concern [27]. These conventional approaches were utilized for building emission inventories for cities in Asia and Africa—all the methodologies, models, and necessary resource information, including the emission factor databases, are detailed in these references [23,27–30]. The multi-pollutant inventory was developed at the grid level for $PM_{2.5}$, PM_{10}, SO_2, NO_x, CO, and VOCs.

The chemical transport modeling to estimate total $PM_{2.5}$ concentrations was conducted using the CAMx model coupled with WRF for meteorological data [31]. The initial and boundary conditions for a full year simulation are extracted from the MOZART/CAMchem global chemical transport model [32]. The boundary conditions are necessary for simulating the contributions of sources outside the designated airshed. The CAMx model output as total $PM_{2.5}$ includes contributions from primary PM emissions and those from chemical transformation of gaseous species, like sulfates from SO_2 emissions, nitrates from NO_x emissions, and secondary organic aerosols (SOA) from VOC emissions via reactions with NOx and ozone. The modular nature of CAMx allows the user to select advection, scavenging (dry and wet), and chemical mechanisms suitable for the runs (https://camx.com—accessed on 1 July 2024). The model also allows for estimating source contributions to ambient $PM_{2.5}$ concentrations from select sectors and regions.

3. Modeled Results

3.1. Multi-Pollutant Emissions Inventory

A robust emissions inventory is the foundation for developing informed and effective policies for urban air quality management, as it provides a detailed baseline of information on the sources and quantities of emitting pollutants. The more data available, the better the decision-making power, enabling targeted strategies for emission reductions, improved regulatory measures, and more accurate forecasting of air quality (for short-term, like 3 days ahead, or long-term, like 5 or 10 years ahead). Summary of the total emissions estimated for Bishkek's airshed is presented in Table 2, and for convenience, the spatial and temporal break up of only $PM_{2.5}$ is presented Figure 5.

Table 2. Modeled total emissions for the greater Bishkek airshed region (2018–2019). All transport includes aviation emissions; residential includes emissions from cooking and space heating; all industries includes emissions from the central heating plant, heat only boilers, brick kilns, and other industrial estates; all dust includes dust from the roads due to vehicle movement and from the construction activities; and open waste burning includes emissions from landfill burning.

Tons/Year	$PM_{2.5}$	PM_{10}	NO_x	CO	VOC	SO_2	CO_2
All transport	1750	1750	13,500	54,650	6700	50	2,152,400
Residential	1400	1450	-	6750	5100	-	332,850
All industries	950	1550	6100	2300	400	5550	1,507,900
All dust	1100	7200	-	-	-	-	-
Open waste burning	150	200	-	800	150	-	1100
Diesel generator sets	100	100	600	1900	850	-	58,600
Total	5450	12,250	20,200	66,400	13,200	5600	4,052,850

The robustness of the inventory is in the temporal allocation of the total emissions with distinct monthly profiles for various sectors. For example, space heating emissions are present and dominate the winter months, despite the highest annual totals for the transport sector, which is present in all the months (Figure 5b). This includes space heating at the household level and the increment in the coal consumption patterns during the winter months to meet the demand in the district heating system. Likewise, urban dust emissions tend to rise during summer due to heightened construction activities, increased dust resuspension from roads, and lower soil moisture levels that promote wind erosion. Industrial emissions also have a stable share across the months of the year. The final model-ready emissions inventory for all the pollutants is available at 0.01° spatial resolution (included in the Data Repository). The spatial disaggregation of the total emissions is carried out using multiple layers of geospatial information layers. The black dot in Figure 5a represents the highest emission point—the CHP. Transport and road dust emissions used different road density maps for varied weights between personal and freight vehicles, commercial hotspots density and industrial estates maps for origin and destination weights, urban and rural classification for personal vehicle movement weights, grids covering the airport for in situ weights, and population density for smoothing weights. Industrial emissions were distributed to the corresponding layers. Open waste burning emissions, other than the landfill, were weighted between population density and urban–rural classification, with the urban areas getting the benefit of higher waste collection rates. The weights allocation was an iterative process, involving back-and-forth adjustments between the emissions and pollution models, which is combined with validation steps following the chemical transport modeling. In general, the higher density of emissions matches the areas with the highest population and road density in the airshed.

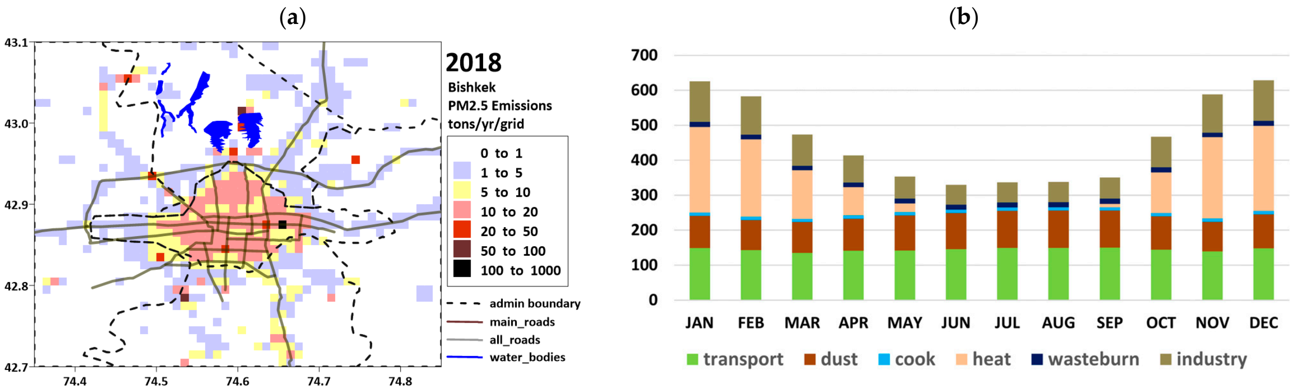


Figure 5. (**a**) Gridded annual $PM_{2.5}$ emissions and (**b**) monthly emission totals and shares of clubbed categories—transport emissions include aviation; dust includes resuspension on the roads and construction activities; heat includes the winter bumps at the central heating power plant and household combustion; and the industry includes brick kilns and other estates.

At the fuel level, coal and diesel are significant contributors to the total emissions of PM, SO_2, and NO_x. Burning coal, primarily at the CHP, HoBs, industrial facilities, and households during the winter months, produced most of the PM and SO_2 emissions. Older diesel engines in the already old vehicle fleet of Bishkek emitted most of the NO_x (a key ingredient to support the daytime ground-level ozone formation—a summary of ozone concentrations for the grid covering the Bishkek city from global reanalysis fields is included in the Data Repository).

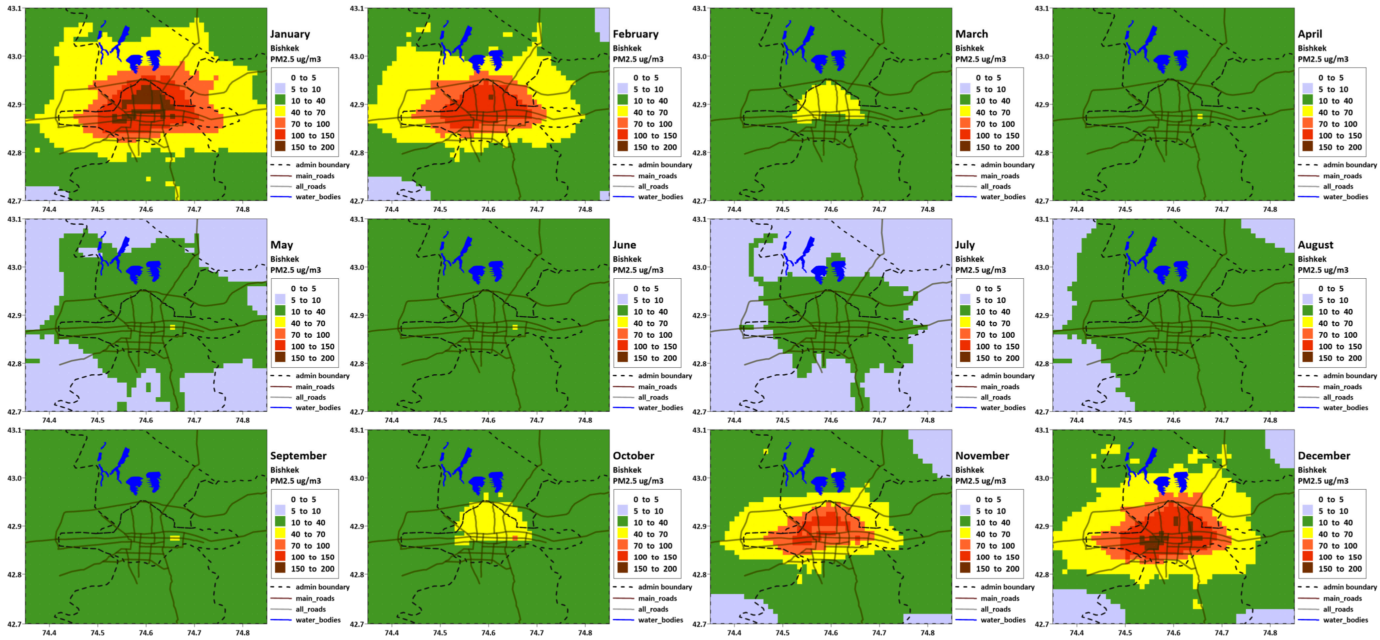
Uncertainty analysis involves assessing the reliability and variability of data in each of the sectors. This includes considering factors in transport (such as vehicle registration rates, vehicle usage rates, driving patterns, emission factors, and spatial allocation weights), residential activities (such as cooking and heating fuel demand, combustion efficiency by technology, and emission factors), power generation (such as total coal use for generation of MWh of electricity, control efficiencies, and emission factors), waste management (such as generate rates, collection rates, landfill management rates, and emission factors), and dust emissions (such as silt loading on various road types, vehicle speeds, and vehicle usage rates). These variables contribute to uncertainties in estimating pollutant sources and their impacts on air quality and health. By quantifying and understanding these uncertainties, we can improve the accuracy of models. The total uncertainty in Bishkek's emissions inventory is ±20–30% and the largest uncertainty is in open waste burning emissions, which is up to 50% in the collection and waste burning rates. The overall confidence in the inventories can be improved by conducting primary surveys to collect data on the variables listed above. The residential surveys can be part of the census data collection for regular updates on the types and amount of fuel consumed for cooking and heating; transport and waste management surveys can be part of the urban planning activities.

The emissions inventory will be updated as more data become available on these various factors, ensuring that it remains current and accurately reflects the latest information on pollution sources and quantities. This ongoing process allows for continual improvements in air quality management and policy development, adapting to new findings and technological advancements in various sectors.

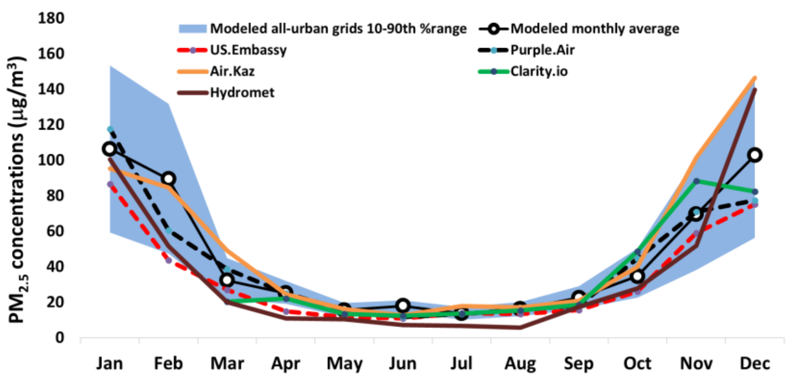
3.2. Modeled $PM_{2.5}$ Concentrations, Seasonality, and Validation

The modeled monthly average $PM_{2.5}$ concentrations from the WRF–CAMx modeling system for the Bishkek airshed are presented in Figure 6a as maps and Figure 6b as variation in the concentration among the urban grids of the airshed (blue shaded bar). In January and December, concentrations were more than 150 μg/m^3 (brown color shade), which was 10 times more than WHO's daily average guideline (15 μg/m^3). These findings were also utilized to pinpoint pollution hotspots within the airshed. Specifically, the northern, western, and eastern areas of Bishkek recorded the highest monthly average concentrations. These areas are primarily inhabited by single-family households that use coal for in situ heating, a trend corroborated by monitoring data from the Clarity sensor network. The total concentrations presented in the figure include contributions from primary particulate emissions and contributions from chemical conversion of SO_2 and NO_x gas emissions into sulfate and nitrate aerosols. The chemical reactions and gas to aerosols conversion processed are an integral part of the CAMx modeling system [31].

(**a**)



(**b**)



(**c**)

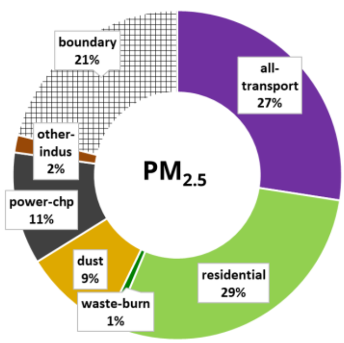


Figure 6. (**a**) Gridded monthly average $PM_{2.5}$ concentrations from the WRF–CAMx modeling system for Bishkek airshed. (**b**) Comparison of modeled (blue share bar) and measured $PM_{2.5}$ concentrations (lines represented data from various monitoring networks). (**c**) Modeled source contributions to annual average $PM_{2.5}$ concentrations.

In the validation process, the monthly average concentrations were compared against data collected from all monitoring networks in Bishkek (Figure 6b). The modeled concentrations in the blue shade represent the variation in the monthly average concentrations among the urban designated grids (the city administrative part of the airshed) and the measured concentrations are the monthly averages of all the stations under each of the networks. The model can qualitatively and quantitatively replicate the averages and variations observed in the measurements. A direct comparison of the average resulted in a fit with R^2 = 0.94 and RMSE of 5.5 $\mu g/m^3$. The match in the seasonality is primarily due to the seasonality introduced in the emission inventory, such as linking the surface temperature information from the WRF simulations to the space heating needs. For example, as the 3-h running temperature runs under a threshold or continues to dip lower, the need for space heating increases and, thus, the emissions increase also. This provides the necessary bump in the emission loads and, thus, decreases the chances of underpredicting the wintertime concentrations. In the rainy season, the gridded dust emissions were processed along with the gridded precipitation rates, and grids with at least 0.1 mm of rain at that hour were zeroed out. This temporarily reduced the emission loads and, thus, decreased the chances of overpredicting the concentrations or contributions of dust. A good fit between modeled and measured concentrations increases confidence levels and reliability of the emissions inventory and its spatial and temporal allocation scheme. This alignment ensures that the model accurately represents real-world conditions, making future scenario calculations useful for strategy development.

3.3. *$PM_{2.5}$ Source Apportionment*

Source apportionment is the analytical process used to identify and quantify the contributions of various emission sources to the total pollution levels in an area. For Bishkek, the same WRF–CAMx modeling setup was used to establish these shares (Figure 6c) for the sources inside the city (using the emissions inventory from this study) and the sources outside the city (using the boundary conditions in the chemical transport model). This information is vital because it allows policymakers to pinpoint the major source contributions to total $PM_{2.5}$ pollution and develop targeted strategies for emission reductions. As an annual average, major sources identified are residential cooking and heating (29%), transport emissions (27%), CHP (11%), dust (9%), and the transboundary (21%). For convenience, only the annual average is presented in the figures and the monthly/seasonal variation is included in the presentation slide deck in the Data Repository. Residential heating contributes the most to $PM_{2.5}$ concentrations in the winter months, reaching 40% in January and November. Windblown dust (from the airshed boundary conditions) has the highest contribution in the summer months when $PM_{2.5}$ concentrations are lower. Transport contributes differently throughout the seasons, ranging from 17% in spring to 30% in summer. It consistently ranks as the second most significant source of $PM_{2.5}$ concentrations across all seasons: in winter, following residential heating, and in summer, trailing windblown dust. The combined contribution of the CHP plant and the HoBs peaks in the winter, as expected. Their combined maximum modeled contribution is approximately 15%. Although the CHP plant is the largest contributor to emissions, these emissions are released from a 200 m high stack (Figure 3b) and, thus, reduces their impact on the immediate vicinity. Throughout the year, urban dust from construction activities and road resuspension remains consistently present, contributing between 7% and 10%. Similarly, the contributions of industries, excluding the CHP plant, and open waste burning remain steady and minor, each accounting for less than 2% annually.

4. Discussion: Policies for Emissions Management

We investigated a range of policies and measures and decided on a shortlist for the largest emitting sectors. A conservative shortlist of options is simulated in Figure 7, based on the source apportionment results. A 50% reduction in the vehicle exhaust emissions, space heating demand, dust management, central heating plant emissions, and regional contributions, has the potential to drop the annual average $PM_{2.5}$ concentrations from 48 μg/m^3 to 25 μg/m^3. Additional reductions are required to achieve the WHO guideline of 5 μg/m^3. The challenge of how to achieve these reductions is the crux of the clean air action plan for the city. The following sections explain the shortlisted policies and measures, highlighting their scope, expected impact, and feasibility. Table 3 provides a summary.

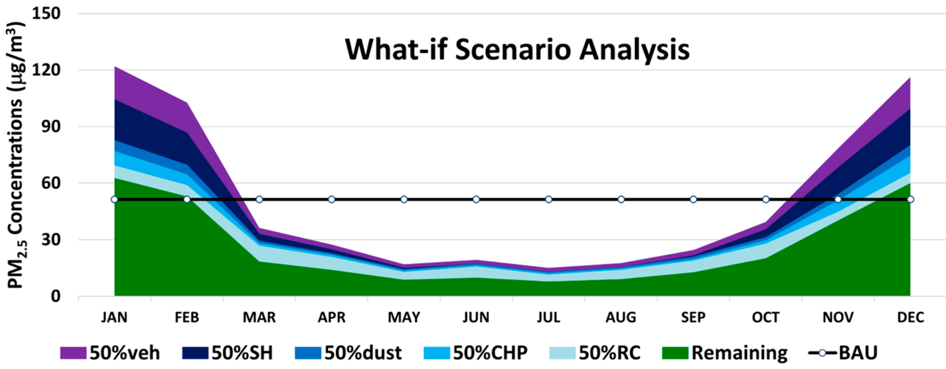


Figure 7. A hypothetical what-if scenario analysis over Bishkek's monthly urban average concentrations. BAU is the business-as-usual concentration using the baseline emissions inventory presented in this study and Remaining is the concentration after applying 50% cuts in the contributions from the five major sources—vehicles (veh), space heating (SH), dust, central heating plant (CHP), and regional concentrations (RC).

The CHP and HoBs are the largest emitters and largest contributors to ambient $PM_{2.5}$ levels and top the list of sectors to address in Bishkek's clean air action plan. One major option in discussion is the conversion of the plant and the HoBs to run on gas, pending feasibility studies on the supply chain and modernization of the boiler technology. An alternative is the promotion of electricity from renewables at the household level and reducing the demand for heat from large and medium size boilers running on coal, also as a co-benefit of the climate agenda programs [7]. The potential to improve energy efficiency measures at the households is high in Bishkek, due to old housing structures and building regulations. This primarily includes improvement in insulation techniques at the households using coal for heating and those connected to the district heating system. The former group has the highest potential to reduce ground level emissions and subsequent concentrations. Introducing heat pumps, albeit costly, could lead to significant emission reductions with only a slight rise in electricity demand from CHP. Transitioning from coal to electric heating offers comparable benefits, though it necessitates a greater increase in electricity supply compared to heat pumps. A complete switch from coal to cleaner fuels can result in up to a 29% reduction in the ambient $PM_{2.5}$ concentrations.

The operation and efficiency of ESPs have a large impact on CHP emissions, along with the control equipment for SO_2 and NO_x emissions, which also contribute to $PM_{2.5}$ concentrations in the form of secondary sulfate and nitrate aerosols. A reduction in the emissions at the largest source will have direct implications on ambient air pollution. An improvement in ESP efficiency from 98% to 99% can result in an immediate drop of 50% of the emissions. A lack of transparency in the operations of control equipment makes it difficult to verify reduction claims.

Road transport emissions are a major contributor to $PM_{2.5}$ concentrations in the city center and Bishkek has multiple options to address this source. The secondhand market for personal and freight vehicles is thriving, driven by factors such as affordability and availability of a wide range of models from China, Europe, Japan, Russia, and the United States. The car fleet has an average age of more than 10 years, and there are instances of removal of the catalytic converters from the newer imports because of their demand in the secondhand market. To ensure emissions compliance, it is essential for the secondhand market to gradually reduce. This can be achieved through institutional incentives, such as tax rebates for purchasing new, low-emission vehicles, or providing grants for scrapping older, high-emission vehicles. If the reduction in the secondhand market does not occur naturally through these incentives, stricter controls must be enforced to ensure emission compliance. This could include mandatory emissions testing for older vehicles, higher registration fees for high-emission cars and, eventually, the implementation of low-emission zones where only newer, compliant vehicles are allowed to operate within the city limits. Pollution under check: as part of an inspection and maintenance program, regular check-ups for tailpipe emission rates are performed, which are critical for success in this sector. Modernization of the fleet (personal and freight) to include firsthand cars more than secondhand is a long-term policy.

Table 3. Modeled changes in the $PM_{2.5}$ concentrations from implementation of individual measures using the emissions inventory presented in this study and the WRF–CAMx model results. The implementation rates and feasibility (as low, moderate, and high) assessment are authors estimates based on feasibility notes from local counterparts and published reports. Low and high scenarios refer to 20 and 40 percent, respectively, of houses using coal-implementing energy efficiency measures and/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 greening measures are used as natural dust controls primarily affecting windblown dust.

Sector	Specific Intervention	Reduction in Annual $PM_{2.5}$ Concentration (%)	Relative Feasibility of the Intervention
CHP and heat boilers	Combined heat and power (CHP) plant switch from coal to gas	9	Low
	All heat only boilers (HoBs) switch from coal to gas	2	High-Moderate
	30% more renewables in CHP and HoBs	4	Moderate-Low
Residential heating	Home insulation—low and high	2–3	High
	Residential coal to gas—low and high	6–12	High
	Residential heat pumps—low and high	5–13	Moderate-Low
	Residential more electric heating—low and high	5–9	Moderate
	Complete switch to clean heating	29	Long-term plan
Transport	Traffic management	3	High
	Road dust suppression	1	High
	Car emissions control—low and high	3–6	High-Moderate
	Marshrutka emissions control	1	High
	Buses emissions control	0.2	High
	Light and heavy-duty vehicles emissions control	3	Moderate
	Total of all transport measures combined	13	
	Complete switch to zero-emission vehicles	27	Long-term plan
Open waste burning	Control waste open burning	0.6	Moderate
	No open waste burning, including dump	1	Moderate
Natural dust	Natural dust controls—low	1–2	Low

Traffic demand management is a popular measure designed to reduce the demand for personal vehicle km traveled with substitution from public transport and non-motorized transport. The marshrutkas (bus and minibus) fleet is small (under 1000) and has the potential to expand at least 10 times in the medium term and contribute to reduction in personal vehicle usage and, thus, the total emissions. The city needs to explore ideas to boost bus travel to make it more affordable, convenient, and attractive. Promoting bus usage can be effectively achieved through a combination of targeted incentives and strategic pricing. Offering discounted or free bus passes to school-going children can encourage families to opt for public transportation over private cars, reducing traffic congestion and emissions. Implementing rush hour discounts can further incentivize commuters to use buses during peak times.

In a small city like Bishkek, where more of the points of interest can be reached within 20–30 min of travel, promoting motorcycles, especially in the form of electric vehicles (EVs) can play a crucial role in reducing emissions. Additionally, their smaller size compared to cars allows for more efficient use of the road space, helping to alleviate traffic congestion. Encouraging a shift from cars to electric motorcycles not only enhances mobility options but also makes transportation more flexible and adaptable to various urban settings. By offering incentives, such as tax rebates, subsidies for EV purchases, and investment in charging infrastructure, Bishkek can make EV motorcycles a viable and attractive option for commuters. This strategy not only supports reaching clean air targets but also can support the fight against climate change. This is also a long-term (5–10 year) policy option. It is important to note that EVs produce zero tailpipe emissions on the road, but the additional electricity demand at the CHP will have new emissions, which if the controls are fully operational mean lesser burden on city's air.

Bishkek's waste management problem is threefold: generation, collection, and management. The collection rates are about half of the generation rates and the landfill management is weak, often resulting in uncontrolled burning and aerial emissions. Effective strategies must address reducing waste generation at the source through behavior change and public awareness programs, improving the efficiency of waste collection systems through investments in trucks and personnel, and optimizing waste management through recycling and proper landfill usage. Each of these steps are critical for minimizing waste left behind, open waste burning, landfill fires and, thus, the emissions.

Dust in Bishkek comes from urban activities, like resuspension of dust on the roads from vehicle movement, construction activities, and windblown dust from the dry Central Asian desert region. Most of the dust activity is in the summer months. While the vehicle volume is relatively small compared to major cities like Beijing and Delhi, the presence of numerous unpaved roads means that each vehicle contributes to substantial dust generation. To manage and mitigate road dust, several strategies can be implemented. Paving unpaved roads is a fundamental measure that can drastically reduce dust emissions. Additionally, greening initiatives, such as planting trees and shrubs along roadsides, can help trap dust, and regular street cleaning and the application of dust suppressants can further control dust levels.

5. Conclusions and Way Forward

This study mapped $PM_{2.5}$ emission sources across the Bishkek airshed, encompassing an area of 1800 km^2, including both the city of Bishkek and its environs. Employing a dynamic emissions map and 3D meteorological data from the WRF model, the CAMx modeling system simulated $PM_{2.5}$ concentrations and assessed the contributions from various sources. Comparison of modeled $PM_{2.5}$ concentrations with data from the ambient air quality monitoring network demonstrated good agreement, capturing seasonal and spatial variations in Bishkek. This underscores the reliability of the emissions and pollution modeling framework, validating the study's findings for potential application in scenario analysis and cost-effectiveness assessments aligned with local stakeholder priorities.

The air quality management system of KGZ under the leadership of MNRETS has outlined an air quality master plan and identified institutions to take lead on some proposals. For example, to strengthen the technical capacity of the local institutions overseeing the statistics, monitoring, and modeling activities, to improve emissions inventory, ambient monitoring, chemical transport modeling, and health impact assessment capabilities (by KHA); to update the air quality standards, ambient monitoring protocols, and the measurement techniques used for quantifying emissions (by the ministry of health); to overhaul the emission standards for the industries, especially for the large point sources like CHP (by the ministry of energy); to propose inspection and maintenance programs, to tighten the vehicle standards of the imports, and upgrade the fuel standards for the road transport (by the ministry of road transport and communications); and finally, Bishkek's mayoral office to oversee a range of local activities including urban planning and development, management of HoBs and heating networks, traffic management, public transport, industrial audits, waste management, and other environmental initiatives.

Air quality management is a long-term endeavor that requires stakeholders to have a clear vision of emission sources and strengths. In Bishkek, there is now an operational emissions inventory and a holistic understanding of the source contributions. The challenge is in implementing planned activities effectively for successful outcomes. Every reduction in emissions, no matter how small, contributes to decreased pollution and significant health benefits. This can come from increasing the public transport fleet with 50 buses, reducing the car usage by 10%, increasing the green cover in the city by 5%, shifting 10% of households from using coal to gas, increasing the electricity usage by 10% for heating in the industries, and reducing the waste generation rates by 5%.

Additionally, robust governance and regular inspections are crucial to ensure compliance with regulations and track air quality improvements. Effective governance relies on long-term and consistent ambient monitoring data from a network of stations capable of spatially and temporally representing city-wide trends. Such a network can incorporate data from both traditional monitoring stations and low-cost sensors, enhancing coverage and accessibility of air quality information across diverse urban environments.

Author Contributions: Conceptualization and writing—original draft preparation, S.K.G. and V.B.Z.; formal analysis, S.K.G., V.B.Z. and K.C.S.; methodology, software, and validation, S.K.G. and S.K.D.; resources, investigation, data curation and visualization, S.K.G., V.B.Z. and S.K.D.; project administration and funding acquisition, K.C.S. All authors have read and agreed to the published version of the manuscript.

Funding: K.C.S. received funding from the World Bank Group. The authors declare that the funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article, or the decision to submit it for publication. The analysis and conclusions presented herein are exclusively those of the authors and do not represent the supporting organizations or the educational departments.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All the data compiled for this study are available at the following link: https://doi.org/10.5281/zenodo.12720883. These include GIS files, model-ready emissions inventory, WRF–CAMx model results, a copy of the cleaned monitoring data from the sensor networks, and a deck of PowerPoint slides with summaries and additional information not included in the manuscript.

Acknowledgments: Authors thank the four anonymous reviewers for their comments and suggestions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Rafaj, P.; Amann, M. Decomposing air pollutant emissions in Asia: Determinants and projections. *Energies* **2018**, *11*, 1299. [CrossRef]
2. Amann, M.; Kiesewetter, G.; Schöpp, W.; Klimont, Z.; Winiwarter, W.; Cofala, J.; Rafaj, P.; Höglund-Isaksson, L.; Gomez-Sabriana, A.; Heyes, C.; et al. Reducing global air pollution: The scope for further policy interventions. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2020**, *378*, 20190331. [CrossRef] [PubMed]
3. HEI-SoGA. *State of Global Air (SOGA). A Special Report on Global Exposure to Air Pollution and Its Health Impacts*; Health Effects Institute: Boston, MA, USA, 2024.

4. Vollset, S.E.; Ababneh, H.S.; Murray, C.J.L.; GBD-Collaborators. Burden of disease scenarios for 204 countries and territories, 2022–2050: A forecasting analysis for the Global Burden of Disease Study 2021. *Lancet* **2024**, *403*, 2204–2256. [CrossRef] [PubMed]
5. Li, C.; van Donkelaar, A.; Hammer, M.S.; McDuffie, E.E.; Burnett, R.T.; Spadaro, J.V.; Chatterjee, D.; Cohen, A.J.; Apte, J.S.; Southerland, V.A.; et al. Reversal of trends in global fine particulate matter air pollution. *Nat. Commun.* **2023**, *14*, 5349. [CrossRef]
6. Sicard, P.; Agathokleous, E.; Anenberg, S.C.; De Marco, A.; Paoletti, E.; Calatayud, V. Trends in urban air pollution over the last two decades: A global perspective. *Sci. Total Environ.* **2023**, *858*, 160064. [CrossRef]
7. Mehta, K.; Ehrenwirth, M.; Trinkl, C.; Zörner, W.; Greenough, R. The Energy Situation in Central Asia: A Comprehensive Energy Review Focusing on Rural Areas. *Energies* **2021**, *14*, 2805. [CrossRef]
8. Radovanović, M.; Filipović, S.; Andrejević Panić, A. Sustainable energy transition in Central Asia: Status and challenges. *Energy Sustain. Soc.* **2021**, *11*, 49. [CrossRef]
9. Veefkind, J.P.; Aben, I.; McMullan, K.; Förster, H.; de Vries, J.; Otter, G.; Claas, J.; Eskes, H.J.; de Haan, J.F.; Kleipool, Q.; et al. TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sens. Environ.* **2012**, *120*, 70–83. [CrossRef]
10. Miller-Schulze, J.P.; Shafer, M.; Schauer, J.J.; Heo, J.; Solomon, P.A.; Lantz, J.; Artamonova, M.; Chen, B.; Imashev, S.; Sverdlik, L.; et al. Seasonal contribution of mineral dust and other major components to particulate matter at two remote sites in Central Asia. *Atmos. Environ.* **2015**, *119*, 11–20. [CrossRef]
11. Almeida, S.M.; Manousakas, M.; Diapouli, E.; Kertesz, Z.; Samek, L.; Hristova, E.; Šega, K.; Alvarez, R.P.; Belis, C.A.; Eleftheriadis, K. Ambient particulate matter source apportionment using receptor modelling in European and Central Asia urban areas. *Environ. Pollut.* **2020**, *266*, 115199. [CrossRef]
12. Papagiannis, S.; Abdullaev, S.F.; Vasilatou, V.; Manousakas, M.I.; Eleftheriadis, K.; Diapouli, E. Air quality challenges in Central Asian urban areas: A PM2.5 source apportionment analysis in Dushanbe, Tajikistan. *Environ. Sci. Pollut. Res.* **2024**, *31*, 39588–39601. [CrossRef] [PubMed]
13. Tursumbayeva, M.; Muratuly, A.; Baimatova, N.; Karaca, F.; Kerimray, A. Cities of Central Asia: New hotspots of air pollution in the world. *Atmos. Environ.* **2023**, *309*, 119901. [CrossRef]
14. Dzushupov, K.O.; Buban, J.M.A.; Aidaraliev, A.A.; Ahmadi, A.; Chahal, P.; Ibrahim, M.; Lin, X.; Kouwenhoven, M.B.N. Air pollution in Bishkek, Kyrgyzstan: Driving factors and state response. *Public Health Chall.* **2022**, *1*, e22. [CrossRef]
15. Pesaresi, M.; Politis, P. *GHS-BUILT-S R2023A-Surface Grid Derived from Sentinel2 Composite and Landsat for Multitemporal Period (1975–2030)*; 2023 Data Catalogue; European Commission, Joint Research Centre (JRC): Ispra, Italy, 2023. [CrossRef]
16. Sims, K.; Reith, A.; Bright, E.; Kaufman, J.; Pyle, J.; Epting, J.; Gonzales, J.; Adams, D.; Powell, E.; Urban, M.; et al. *LandScan Global 2022*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2023. [CrossRef]
17. Powers, J.G.; Klemp, J.B.; Skamarock, W.C.; Davis, C.A.; Dudhia, J.; Gill, D.O.; Coen, J.L.; Gochis, D.J.; Ahmadov, R.; Peckham, S.E.; et al. The Weather Research and Forecasting Model: Overview, System Efforts, and Future Directions. *Bull. Am. Meteorol. Soc.* **2017**, *98*, 1717–1737. [CrossRef]
18. Kistler, R.; Kalnay, E.; Collins, W.; Saha, S.; White, G.; Woollen, J.; Chelliah, M.; Ebisuzaki, W.; Kanamitsu, M.; Kousky, V.; et al. The NCEP–NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation. *Bull. Am. Meteorol. Soc.* **2001**, *82*, 247–268. [CrossRef]
19. Bainomugisha, E.; Ssematimba, J.; Okure, D. Design Considerations for a Distributed Low-Cost Air Quality Sensing System for Urban Environments in Low-Resource Settings. *Atmosphere* **2023**, *14*, 354. [CrossRef]
20. Morawska, L.; Thai, P.K.; Liu, X.; Asumadu-Sakyi, A.; Ayoko, G.; Bartonova, A.; Bedini, A.; Chai, F.; Christensen, B.; Dunbabin, M.; et al. Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? *Environ. Int.* **2018**, *116*, 286–299. [CrossRef]
21. Crippa, M.; Solazzo, E.; Huang, G.; Guizzardi, D.; Koffi, E.; Muntean, M.; Schieberle, C.; Friedrich, R.; Janssens-Maenhout, G. High resolution temporal profiles in the Emissions Database for Global Atmospheric Research. *Sci. Data* **2020**, *7*, 121. [CrossRef]
22. Crippa, M.; Guizzardi, D.; Pisoni, E.; Solazzo, E.; Guion, A.; Muntean, M.; Florczyk, A.; Schiavina, M.; Melchiorri, M.; Hutfilter, A.F. Global anthropogenic emissions in urban areas: Patterns, trends, and challenges. *Environ. Res. Lett.* **2021**, *16*, 074033. [CrossRef]
23. Crippa, M.; Guizzardi, D.; Butler, T.; Keating, T.; Wu, R.; Kaminski, J.; Kuenen, J.; Kurokawa, J.; Chatani, S.; Morikawa, T. The HTAP_v3 emission mosaic: Merging regional and global monthly emissions (2000–2018) to support air quality modelling and policies. *Earth Syst. Sci. Data* **2023**, *15*, 2667–2694. [CrossRef]
24. Solazzo, E.; Crippa, M.; Guizzardi, D.; Muntean, M.; Choulga, M.; Janssens-Maenhout, G. Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) emission inventory of greenhouse gases. *Atmos. Chem. Phys.* **2021**, *21*, 5655–5683. [CrossRef]
25. Garland, R.M.; Altieri, K.E.; Dawidowski, L.; Gallardo, L.; Mbandi, A.; Rojas, N.Y.; Touré, N.d.E. Opinion: Strengthening research in the Global South–atmospheric science opportunities in South America and Africa. *Atmos. Chem. Phys.* **2024**, *24*, 5757–5764. [CrossRef]
26. Weyant, C.; Athalye, V.; Ragavan, S.; Rajarathnam, U.; Lalchandani, D.; Maithel, S.; Baum, E.; Bond, T.C. Emissions from South Asian Brick Production. *Environ. Sci. Technol.* **2014**, *48*, 6477–6483. [CrossRef] [PubMed]
27. UEinfo. Air Pollution Knowledge Assessments (APnA) City Program Covering 50 Airsheds and 60 Cities in India. 2024. Available online: https://www.urbanemissions.info (accessed on 15 June 2024).

28. Guttikunda, S.K.; Kopakka, R.V. Source emissions and health impacts of urban air pollution in Hyderabad, India. *Air Qual. Atmos. Health* **2013**, *7*, 195–207. [CrossRef]
29. Marais, E.A.; Wiedinmyer, C. Air Quality Impact of Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa). *Environ. Sci. Technol.* **2016**, *50*, 10739–10745. [CrossRef]
30. GAINS. Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS). Available online: https://iiasa.ac.at/models-tools-data/gains (accessed on 15 June 2024).
31. Emery, C.A.; Baker, K.R.; Wilson, G.M.; Yarwood, G. Comprehensive Air Quality Model With Extensions, v7.20: Formulation and Evaluation for Ozone and Particulate Matter Over the US. *Geosci. Model Dev. Discuss.* **2024**, *2024*, 1–48. [CrossRef]
32. Lamarque, J.F.; Emmons, L.K.; Hess, P.G.; Kinnison, D.E.; Tilmes, S.; Vitt, F.; Heald, C.L.; Holland, E.A.; Lauritzen, P.H.; Neu, J.; et al. CAM-chem: Description and evaluation of interactive atmospheric chemistry in the Community Earth System Model. *Geosci. Model Dev.* **2012**, *5*, 369–411. [CrossRef]