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Assessment of CO_2 Emissions from the Private Housing Sector in the City of Kokshetau and Analysis of Temperature Trends in the Context of Regional Climate Change

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Abstract

In the context of accelerating climate change and increasing urbanisation, the private housing sector is becoming a significant source of carbon dioxide (CO_2) emissions, which contribute to anthropogenic pressure on the urban atmosphere and require detailed quantitative assessment. The aim of this study is to assess CO_2 emissions in the private residential sector and compare their spatial distribution with observed temperature trends in the context of regional climate change. Carbon footprint calculations were performed using data on fuel and electricity consumption, complemented by geoinformation analysis to map emission patterns. On average, a single household in Kokshetau accounts for 19.27 tons of CO_2 emissions per year from electricity and coal use. A clear trend of annual warming has been identified. The obtained value of Zs = 2.14 confirms the statistical significance of the temperature increase. A stable warming rate (Q_{med} = 0.03 °C/year) has resulted in a total rise of 1.14 °C since 1986, indicating a long-term shift in the regional climate toward warming. The use of remote sensing data and GIS analysis enabled detailed zoning of the territory based on thermal characteristics. The proposed decarbonization scenarios demonstrate that no single measure can fully achieve the targeted indicators. Maximum efficiency (over a 50% reduction in emissions) is achieved only under a combined scenario.

Keywords: CO_2 emissions; housing sector; carbon footprint; energy efficiency; local climate change; Kokshetau; GIS analysis

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1. Introduction

Modern climate change necessitates accurate accounting and analysis of anthropogenic greenhouse gas emissions. According to the Intergovernmental Panel on Climate Change (IPCC), more than 30% of global CO_2 emissions originate from the residential sector [1]. In cities across Kazakhstan, including Kokshetau, a significant share of residential buildings relies on coal and natural gas, which increases the carbon burden on the atmosphere.

Climate change driven by rising concentrations of greenhouse gases is one of the most pressing environmental issues of our time. Kazakhstan, possessing substantial hydrocarbon reserves and an energy-intensive economy, is among the countries with the highest per capita carbon dioxide (CO_2) emissions—approximately 15 tons of CO_2-equivalent per year, exceeding the levels of most Central Asian states [2]. Despite government measures aimed at reducing the national carbon footprint, including the Sustainable Development Goal 13 (SDG 13): Climate Action and the Strategic Development Plan to 2025, which envisions a

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15% reduction in emissions, the challenge of maintaining the sustainability of the urban environment remains highly relevant [3].

One of the significant yet insufficiently studied sources of CO_2 emissions is the private housing sector, particularly in medium-sized and small cities in Kazakhstan, where a large portion of the population lives in individual houses that rely on solid fuels. In cities such as Kokshetau, the heating season lasts up to seven months a year, and the predominance of coal-based heating creates substantial local carbon loads. While research on urbanization and industrial contributions to greenhouse gas emissions is actively developing [4–6], the role of the housing sector in the regional structure of carbon fluxes remains only partially explored.

The relevance of this study is due to the need for a quantitative assessment of the contribution of private households to the total CO_2 emissions of the city of Kokshetau, as well as a comparison of their spatial distribution with observed temperature trends and characteristics of the urban environment in the context of regional climate change. As research on urbanized regions of Kazakhstan has demonstrated [2], there is a direct relationship between building density, energy consumption levels, and the concentration of pollutants, including carbon dioxide and particulate matter ($PM_{2.5}$, PM_{10}). These processes exert a cumulative effect on the city's climate system, intensifying local warming and deteriorating air quality.

Therefore, the assessment of CO_2 emissions from the private housing sector in Kokshetau and the analysis of their spatial distribution make it possible to establish the relationship between the energy efficiency of the housing stock, the types of fuel used, and the dynamics of local climatic changes. Such research aligns with the priorities of Kazakhstan's National Strategy for Achieving Carbon Neutrality by 2060 and contributes to the development of scientifically grounded measures to reduce the regional carbon footprint.

Air quality studies in the Central Kazakhstan region have shown that even household emissions and the residential sector—not only large factories and transportation—make a significant contribution to air pollution and increased local CO_2 concentrations. In the analyzed area, CO_2 levels exceeded permitted limits several times, and a strong correlation between pollution levels and the spatial distribution of emission sources was observed [7].

Consequently, it is relevant and necessary to study the contribution of the private housing sector in Kokshetau to CO_2 emissions, as well as to analyse the spatial distribution of temperature characteristics, humidity and pollution within the city limits in the context of regional climate change. This research not only allows for the quantitative assessment of emissions but also helps to understand their spatial patterns, their relationship with heating types and building conditions, and, ultimately, to formulate measures for reducing the carbon footprint and adapting the urban environment to a changing climate.

The aim of the study is to assess CO_2 emissions in the private residential sector and compare their spatial distribution with observed temperature trends in the context of regional climate change, and develop recommendations for reducing the carbon footprint.

Research objectives:

To collect and analyze data on energy consumption in private households and to calculate CO_2 emission volumes using the carbon footprint methodology.

To conduct a spatial analysis of emission distribution using GIS technologies and to assess the impact of emissions on local climatic parameters.

To develop recommendations for reducing emissions and improving energy efficiency.

2. Materials and Methods

Kokshetau (53°17′30.0″ N, 69°23′30.0″ E) is located in the northern part of Kazakhstan, on the southwestern edge of the West Siberian platform plain, on the southeastern shore of the large freshwater lake Kopa, within the southern part of the Ishim Plain and along the northern slopes of the Kokshetau Upland, whose foothills surround the city from the south and west. The city lies at an elevation of approximately 234 m above sea level, at the foot of Mount Bukpa [8].

The population within the city limits is 182,369 people (as of 1 September 2025), with an average population density of 477.8 persons per km^2 [9].

The climate of Kokshetau is classified as a humid continental climate with significant precipitation (Köppen classification: Dfb). According to Alisov's classification, the climate of Kokshetau, situated deep within the continent, is characterized as temperate, with high variability in temperature, humidity, and other meteorological parameters, both diurnally and annually. Four distinct seasons are observed: hot and humid summers, cool and rainy autumns, relatively dry and cold winters, and relatively humid and cool springs.

Primary data were collected using statistical, field, and survey methods during the period from 1 March to 31 October 2025. The following sources were used:

- Household energy consumption data: obtained from regional energy suppliers, utility services, and direct household surveys. The information included annual fuel consumption (coal and electricity) for heating purposes.
- Climatic data: monthly indicators of air temperature, humidity, and precipitation for 1986–2024 were obtained from the "Kazhydromet" meteorological station.
- Spatial data: cadastral maps, land-use data, and high-resolution satellite imagery (Landsat 8) were used for mapping residential zones.
- Socio-economic data: demographic information and housing characteristics were sourced from the Akmola Regional Department of Statistics.

All datasets were standardized to a unified coordinate system (WGS 84/UTM Zone 42N) and integrated into a geodatabase using ArcGIS Pro 3.0 software.

The survey covered 850 households, which is 7.9% of the total number of private houses in the city. The selection was made on a territorial basis, taking into account the types of buildings. The questionnaire included questions about the type of fuel, annual energy consumption, the year of construction of the house, and the presence of thermal insulation.

CO_2 emissions from the residential sector were calculated in accordance with the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Volume 2: Energy). The following basic equation was applied:

$$CO_2 = \sum (A_i \times EF_i) \tag{1}$$

where

- (A_i)—the volume of fuel consumed (in tons, m^3, or kWh)
- (EF_i)—the emission factor (kg of CO_2 per unit of fuel).

The emission factors were taken from the IPCC (2006) [1] values and refined for regional conditions:

- Coal—2.42 t CO_2 per ton of fuel
- Natural gas—1.88 t CO_2 per 1000 m^3
- Electricity (average value for Kazakhstan)—0.68 kg CO_2 per kWh

Thermal zone analysis was carried out based on the calculation of brightness temperature (BT) and land surface temperature (LST) using Level-2 eight-band Landsat 9 imagery.

Although L2 images already include atmospheric correction results, it is necessary to additionally remove pixels containing smoke or cloud shadow. For this purpose, the

QA_PIXEL file was used. NDVI and NDSI indices (for winter scenes) were also calculated. In this study, the scene from 27 January 2025 was examined. Based on the NDVI imagery, snow-covered areas, coniferous forests, urban zones, and pixels containing cloud cover or smoke were identified.

Brightness temperature was calculated using Band 10. First, the spectral radiance was computed according to Equation (2):

$$R = M_R \cdot Q + A_R \tag{2}$$

Brightness temperature is a parameter used in physics and astronomy to describe the radiation intensity of an object, expressed as the temperature of an ideal blackbody that would emit radiation of the same intensity at a given wavelength (Figure 1).

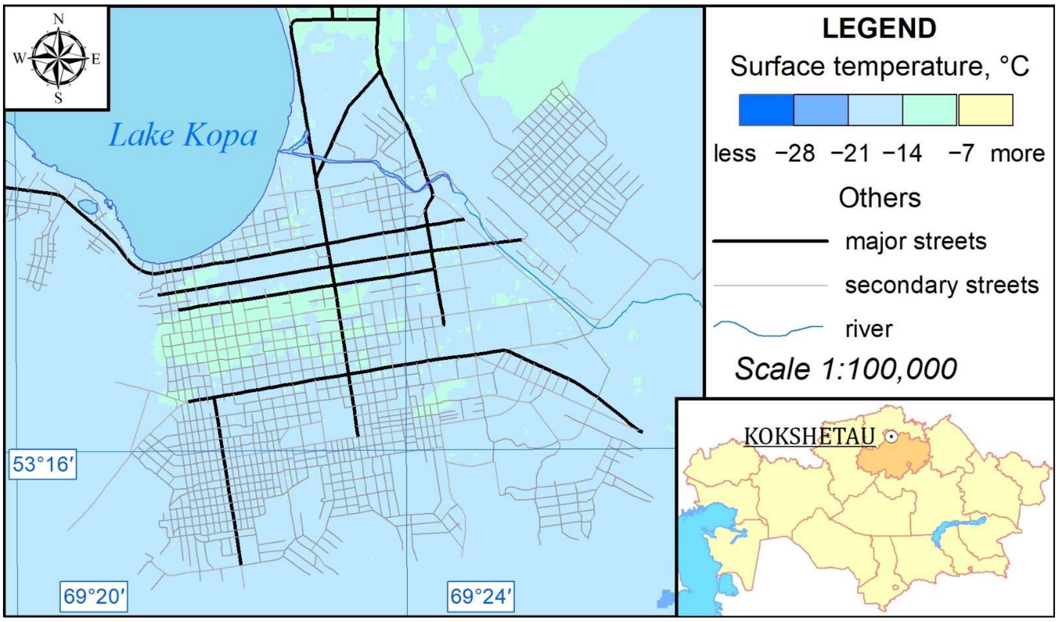

Figure 1. Brightness Temperature.

Brightness temperature was calculated using Equation (3):

$$T = \frac{K_2}{ln(\frac{K_1}{R} + 1)} - 273.15 \tag{3}$$

For further analysis, it is preferable to use the temperature values in Celsius. The data for the city demonstrated elevated temperature values across the entire urban area.

Brightness temperature may differ significantly from the actual surface conditions. Therefore, it is necessary to calculate the true land surface temperature. The overall calculation of this temperature was performed using Equation (4):

$$LST = \frac{T_b}{1 + \frac{\lambda \cdot T_b \cdot Ln\ \varepsilon}{\rho}} \tag{4}$$

where T_b is the brightness temperature, λ is the wavelength of Band 10 in meters (10.895×10^{-6} m), ε is the emissivity coefficient, and ρ is a constant parameter calculated using Equation (5).

$$\rho = \frac{h \cdot c}{\sigma} \tag{5}$$

where h is Planck's constant, 6.626×10^{-34} J·s; c is the speed of light, 2.998×10^{8} m/s; σ is the Boltzmann constant, 1.381×10^{-23} J/K.

To assess the impact of CO_2 emissions on local climatic changes, a comparative analysis was conducted between zones with high and low emission density. The following indicators were analyzed:

- ✓ long-term trends in land surface temperature change (1986–2024);
- ✓ the intensity of the urban heat island (UHI), determined from thermal satellite imagery;
- ✓ correlation between emission density and near-surface temperature anomalies.

To identify statistically significant trends, the Mann–Kendall test and Sen's slope estimator were applied.

Based on the results of the spatial analysis, measures aimed at reducing emissions and improving energy efficiency were proposed, including:

- ✓ improving housing energy efficiency (thermal insulation, energy-efficient equipment);
- ✓ transitioning to cleaner fuels and renewable energy sources;
- ✓ developing municipal programs to incentivize carbon footprint reduction.

To assess the potential effect of implementing various measures, the LEAP (Long-range Energy Alternatives Planning System) model was used, which allowed for estimating possible emission reductions under different scenarios.

In preparing this scientific article, the authors used large language models (LLMs), in particular ChatGPT GPT-4.1. (OpenAI), as an intellectual support tool. The use of AI was purposeful and limited to specific tasks, without replacing the author's critical thinking and academic expertise.

The authors bear full responsibility for the content, accuracy, and scientific integrity of this work. The use of generative AI does not negate the need for author supervision. All conclusions, statements, and findings presented in the article are the result of the authors' intellectual work.

3. Results

3.1. Assessment of Emissions CO_2

According to data from the Department of Statistics, there are 10,671 private houses registered in the city of Kokshetau. Among them, 1124 are one-room, 2037 two-room, 3315 three-room, 2604 four-room, 872 five-room, and 719 houses with six or more rooms (Figure 2).

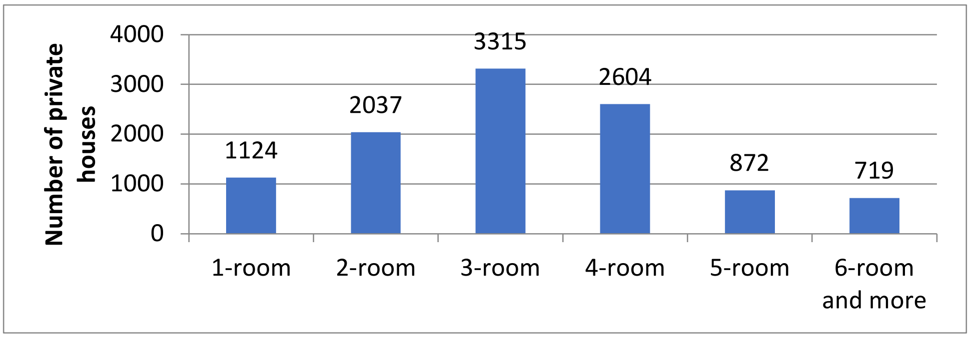

Figure 2. Number of private houses by number of rooms.

By wall material, 1623 houses are brick, 56 are large-panel constructions, 46 are monolithic, and 8940 are built from other materials [9].

During the study, surveys of private homeowners were conducted to obtain information such as the year of construction, wall materials, availability of thermal insulation, type of fuel used, and volumes of coal and electricity consumption. According to the survey results, most houses were built in the 1960s–1980s, reflecting low energy efficiency and significant heat losses.

The average amount of fuel consumed during the heating season was 6.8 tons of coal (range: 4–20 t). The average electricity consumption was approximately 340 kWh per month, although the data show considerable variation (from 100 to 1400 kWh), which is associated with differences in house size and energy sources.

The overwhelming majority of respondents use coal as the primary source of heat, while thermal insulation is almost entirely absent, which significantly increases fuel consumption and CO_2 emissions.

According to the IPCC (2006) [1] methodology, the combustion of coal releases an average of 2.42 tons of CO_2 per ton of fuel. Thus, the average annual emissions of a single household account for approximately:

$$6.8 \text{ t of coal} \times 2.42 = 16.5 \text{ t of } CO_2/\text{year}.$$

If these values are extrapolated to 10,671 private houses, the total annual emissions may exceed 175,602 tons of CO_2, which has a significant impact on air quality city.

To calculate the carbon footprint from electricity consumption, the average Kazakhstan emission factor of 0.68 kg CO_2/kWh was used. If an average household consumes 380 kWh per month, the annual consumption is 4080 kWh, resulting in:

$$4080 \text{ kWh} \times 0.68 \text{ kg } CO_2/\text{kWh} = 2774.4 \text{ kg } CO_2/\text{year} = 2.7744 \text{ t } CO_2/\text{year}.$$

Thus, the total carbon footprint of a household in Kokshetau (electricity + coal) amounts to 19.2744 t CO_2/year. The largest contribution to the total footprint comes from coal heating—16.5 t CO_2/year, which accounts for more than 85% of all household emissions. The high values are driven by the carbon intensity of the local energy system and the climatic conditions of the region, which require significant heating energy during the long winter period.

The results confirm that the residential sector of Kokshetau is one of the substantial sources of direct CO_2 emissions.

According to the Department of Statistics, in 2024 a total of 134,327 tons of pollutants were emitted into the atmosphere from stationary sources in Kokshetau. Of these, 91.1% were captured by purification filters. The remaining 11,988.131 tons represent the total anthropogenic burden on the city's atmosphere, with 84% accounting for gaseous and liquid pollutants (Table 1).

Table 1. Volume of atmospheric pollutant emissions, tons.

	Total Volume of Pollutions from All Stationary Sources	Pollutants Received by Treatment Facilities	Total Pollutants Released into the Atmosphere
Total	134,326,693	124,811,854	11,988,131
Solid pollutants	125,157,680	124,810,957	1,871,170
Gaseous and liquid pollutants	9,169,013	0.896	10,116,961
Sulfur dioxide (SO_2)	6,634,095	x	6,989,833
Hydrogen sulfide (H_2S)	1180	-	1558
Carbon monoxide (CO)	1,288,075	x	1,701,333
Nitrogen oxides (calculated as NO_2)	995,897	x	1,043,721
Ammonia	3736	x	3804
Hydrocarbons (excluding volatile organic compounds)	115,324	-	115,324
Volatile organic compounds (VOCs)	132,212	-	264,021

A critically important aspect is the dominance of sulfur dioxide (SO_2) emissions—6989.833 t/year, as well as the substantial volume of solid particulates—1871.17 t/year.

These substances serve as direct indicators of the widespread use of solid, high-sulfur coal for heating.

3.2. Analysis of Temporal Trends in Temperature and Precipitation

Figure 3 presents data on long-term trends in the mean annual temperature in Kokshetau over a 39-year period (1986–2024). The average annual temperature for this period is 3.4 °C. A gradual increase in mean temperature is observed. Over 39 years, the average temperature has risen by 0.7 °C compared to the long-term multi-year average of 2.7 °C. The linear trend indicates that the mean temperature in Kokshetau will continue to increase.

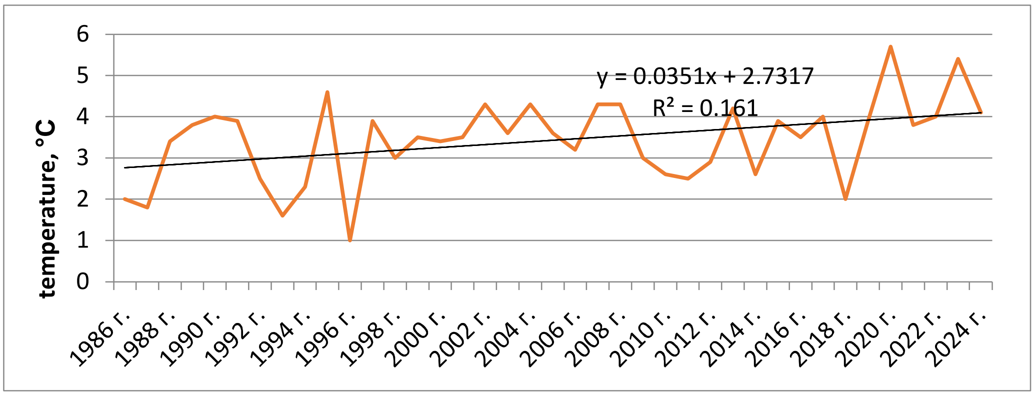

Figure 3. Trends in mean annual temperature change in Kokshetau.

The application of nonparametric statistical tests—specifically, the Mann–Kendall test (Zs) and Sen's slope estimator (Q_{med})—to meteorological data for the period 1986–2024 reveals a clear and statistically significant warming trend in the city of Kokshetau. The results presented in Table 2 demonstrate a heterogeneous yet pronounced increase in air temperature across different seasons and on an annual scale.

Table 2. The average air temperature by season and annual (°C) for 1986–2024.

Station	Test Trends	Winter	Spring	Summer	Autumn	Annual
Kokshetau	Zs	0.45	2.67	0.67	0.92	2.14
	Q_{med}	0.01	0.08	0.01	0.03	0.03

Z_s: Mann–Kendall test, Q_{med}: Sen's slope estimator.

The most striking finding is the accelerated warming during the spring period. The Zs value of 2.67 is highly significant and indicates a strong, non-random upward trend. This is confirmed by the Sen's slope value, Q_{med} = 0.08 °C/year, which quantifies the rate of change. This means that the average spring temperature has been increasing by approximately 0.08 °C per year, resulting in an overall warming of more than 3.0 °C over the 39-year study period.

On an annual scale, the warming trend is also unambiguous. The Zs value of 2.14 confirms a statistically significant upward trend. The Sen's slope value of Q_{med} = 0.03 °C/year indicates a steady increase in mean annual temperature, resulting in a total rise of approximately 1.14 °C since 1986. This provides strong evidence of long-term climate warming in the region.

The trends for the other seasons, although positive, are less pronounced. Autumn shows a noticeable warming trend (Zs = 0.92) with a rate of 0.03 °C/year. Summer and winter exhibit the lowest rates of warming among the seasons, both with Q_{med} = 0.01 °C/year. The lower Zs values (0.67 and 0.45, respectively) suggest that, although the trends are positive, they are weaker and may be subject to greater interannual variability compared to spring.

Overall, the analysis convincingly demonstrates that over the past four decades, the climate of Kokshetau has undergone significant warming, characterized by especially intense temperature increases during the spring months and a persistent upward trend in mean annual temperature.

Figure 4 presents the dynamics of annual precipitation in Kokshetau for the period 1986–2024. The time-series analysis shows that precipitation levels varied between 180 and 520 mm per year, exhibiting substantial interannual fluctuations.

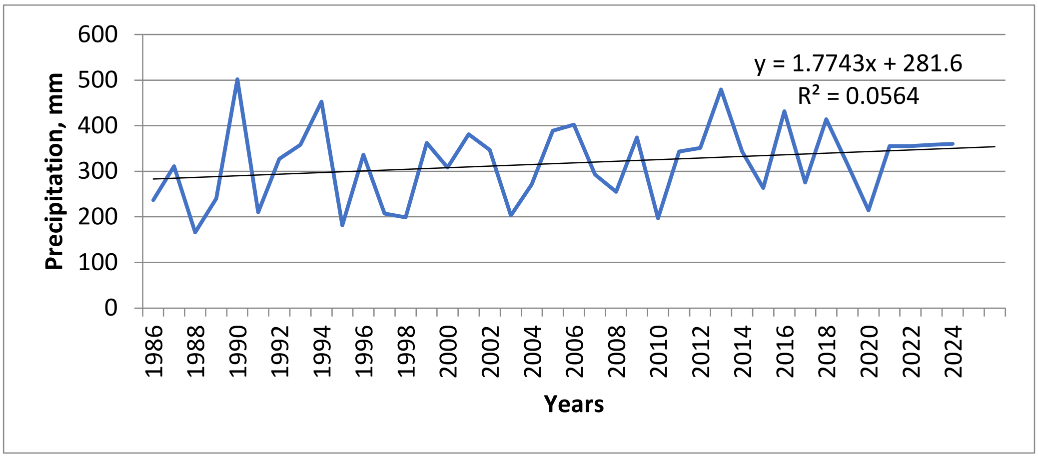

Figure 4. Annual precipitation from 1986 to 2024.

The linear trend indicates a weak tendency toward an increase in annual precipitation—approximately 1.7 mm per year. However, the coefficient of determination $R^2 = 0.0564$ suggests a low degree of dependence and a high natural variability of precipitation in this region. The Mann–Kendall test of 1.73 shows that there is no trend from 1986 to 2024.

Over the study period, a slight increase in mean annual precipitation is observed, which may offer potential opportunities for agricultural development. However, the pronounced interannual and seasonal variability of precipitation limits these benefits and increases agroecosystem vulnerability, highlighting the need for adaptive management strategies.

3.3. *Spatial Analysis of Temperature Distribution Using GIS Technologies*

The calculation of emissivity coefficients was performed using a raster dataset with selected classes such as snow-covered areas, urban territories, and coniferous forests (Figure 5). Using the raster calculator, emissivity coefficients were assigned as follows: 0.985 for snow-covered areas, 0.98 for coniferous forests, and 0.93 for bare soil and urban areas (practically absent). Remaining areas with cloud cover were excluded from the raster.

The calculation algorithm is as follows:

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Con(“mask_raster” == 1, 0.985, Con(“mask_raster” == 2, 0.98, 0.93))
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Areas with a high emissivity coefficient (snow and coniferous forests) demonstrate the greatest capacity for thermal radiation. This may indicate that these zones cool more rapidly during nighttime, which is characteristic of natural landscapes with minimal anthropogenic pressure.

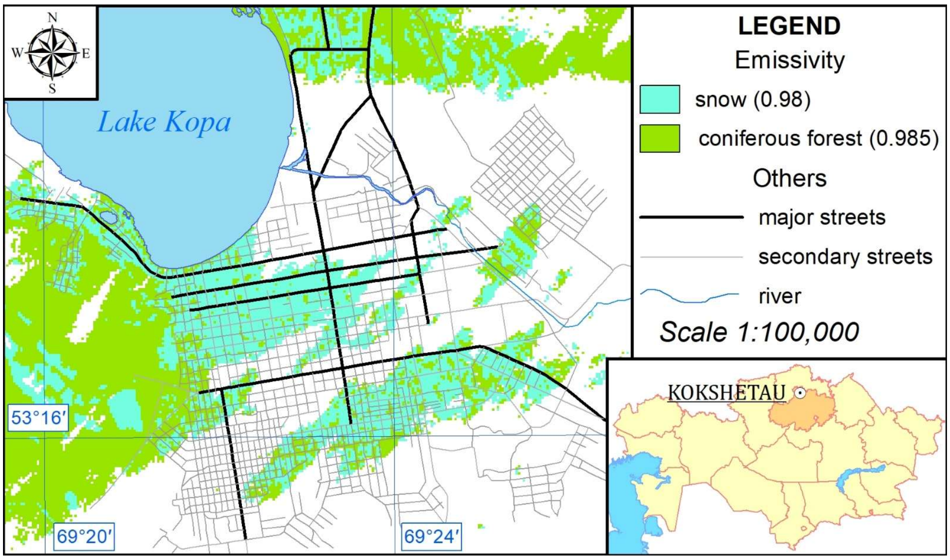

Figure 5. Emissivity coefficient.

Urban territories and bare soils have a lower emissivity coefficient (0.93), which is associated with the properties of materials used in urban construction (asphalt, concrete) and the absence of vegetation cover. This may reflect the urban heat island effect, where urban surfaces retain more heat.

The calculated land surface temperature turned out to be noticeably overestimated. The most likely reason is the presence of smoke pollution over the city, partially missed by the QA mask, which led to distortions in brightness temperature (Figure 6).

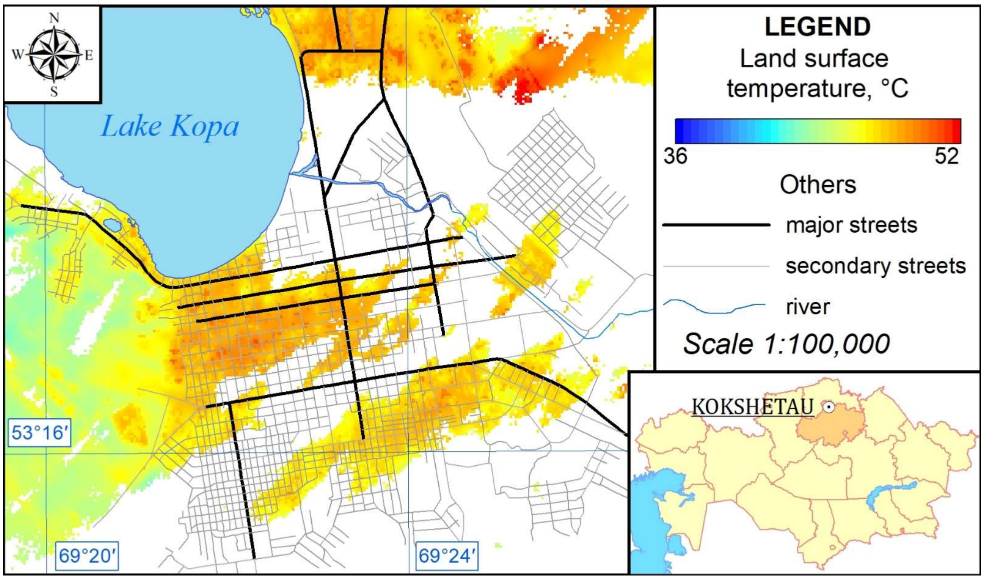

Figure 6. Actual land surface temperature, degrees Celsius.

Thus, three main surface types with distinct thermal properties can be identified within the territory of Kokshetau. The prevalence of low emissivity coefficients within the urban area indicates the potential influence of urbanized zones on the local climate, particularly causing higher temperatures compared to natural landscapes. The use of remote sensing data and GIS analysis made it possible to perform detailed zoning of the territory according to thermal characteristics, which may be useful for urban planning and environmental monitoring.

3.4. Development of Emission Reduction Scenarios

Based on the survey results obtained, several measures were proposed to reduce emissions and improve energy efficiency. To assess their potential impact, several scenarios were developed (Table 3):

Table 3. Effectiveness of emission reduction scenarios for the city of Kokshetau.

Scenario	**Description of Measures (Key Policies)**	**Reduction in Annual CO_2 Emissions by 2040 (Relative to BAU), tons**	**Relative CO_2 Reduction (Relative to BAU)**	**Cost of Reducing 1 ton of CO_2 (USD/t)**
Baseline (BAU)	Continuation of current trends.	0	0%	–
Scenario 1: Energy Efficiency	Thermal modernization of private houses (façade insulation and window replacement) for 100% of households by 2040.	40,290	30.0%	≈23.5 USD/t
Scenario 2: Decarbonization	Transition of 50% of coal-fired stoves to gas or high-efficiency heating solutions (5000 houses).	31,550	23.5%	≈17.3 USD/t
Scenario 3: Combined	Combination: thermal modernization of all houses + 75% transition to clean heating (gas/heat pumps).	73,447.5	54.7%	≈24.0 USD/t

Scenario 1: Energy efficiency and thermal modernization of private houses—façade insulation and window replacement.

Scenario 2: Decarbonization—transitioning 50% of coal-fired stoves to natural gas or high-efficiency heat pumps.

Scenario 3: Combined—a combination of thermal modernization and 75% transition to clean heating technologies.

The conducted study made it possible to quantitatively assess the potential for reducing CO_2 emissions in the city of Kokshetau by 2040 through the modeling of three key scenarios in comparison with the baseline scenario. Analysis of the calculations demonstrates the limited effectiveness of individual measures when implemented in isolation for achieving decarbonization targets. The greatest environmental effect—a reduction in emissions by more than half—is achieved only through the implementation of a comprehensive approach that combines energy-saving measures with a transition to low-carbon energy sources.

From an economic perspective, the decarbonization of heating systems appears to be the most cost-effective option at the initial stage, while energy-efficiency measures contribute the largest individual reduction in emission volumes.

4. Discussion

The air temperature and precipitation results presented in this study were obtained from historical records (1986–2024) of the Kokshetau meteorological station. Indicators such as average fuel consumption during the heating season and monthly electricity use were derived from household surveys. Temporal trends in temperature change were examined, and household carbon footprints were calculated to assess climate change impacts.

In the context of growing urbanization and its contribution to climate change, assessing the carbon footprint at the city level—particularly in the residential sector—has become a key direction for mitigation efforts. Studies show that households make a substantial contribution to greenhouse gas emissions, primarily through residential energy use and heating. Analyses conducted in cities around the world demonstrate that the structure of household consumption—especially in the housing and transport sectors—is a defining factor of the carbon footprint. Jones and Kammen argue that household consumption accounts for a significant share of greenhouse gas emissions in North America; according to their estimates, households generate up to 80% of total GHG emissions in the United States. This is due to the high carbon intensity of the residential sector, which involves direct fossil fuel combustion, fossil-fuel-based electricity production, and transport use [10].

In the work of Bityukova et al., which established the dominant influence of stove fuel on local air pollution, calculations for Kokshetau confirm that decentralised heat sources account for a significant proportion of anthropogenic pollution [11]. Given the observed rise in average temperatures and changes in the nature of the heating use seasonal fuel consumption, more pronounced temperature fluctuations and more frequent extreme weather events could, on the contrary, trigger an increase in peak energy consumption. Thus, the identified CO_2 emissions are not a static value but depend on climate trends, which must be taken into account when developing long-term strategies for low-carbon development of the city. The data obtained emphasise the need to include the individual residential construction sector in the climate monitoring and planning system, since, as shown by the example of the Baikal region, it is precisely dispersed sources, often remaining outside the scope of official statistics, that make a significant and poorly regulated contribution to the total volume of emissions per season; this factor requires special attention. An increase in the duration of the warm period could potentially be read.

The assessment of CO_2 emissions from the private housing sector in Kokshetau allows for a broader interpretation of the results within global debates on the role of cities in climate change. As convincingly demonstrated in Dodman's analysis [12], in most cases, per capita GHG emissions in cities are lower than national averages in the countries where they are located.

The private housing sector of Kokshetau can be viewed not only as a source of the problem but also as a platform for implementing solutions. The experience of cities such as Barcelona and Toronto [12] shows that compact urban planning, building thermal modernization, and the transition to cleaner fuels can substantially reduce per capita emissions.

A study by Thomas A Deetjen et al. shows that the environmental and economic impact of switching to heat pumps critically depends on the carbon intensity of the local energy system, the type of heating fuel used, and climatic conditions. For Kokshetau, located in a region with a sharply continental climate, a key factor is the reduction in the performance of air source heat pumps during periods of extremely low winter temperatures, which can lead not only to increased operating costs but also to an increase in peak load on the electricity grid. In addition, in the context of coal-fired power generation, which is characteristic of part of Kazakhstan's energy system, the benefits of reducing direct CO_2 emissions in the residential sector may be partially offset by an increase in pollutant emissions (SO_2, NOx, PM2.5) from power plants, which requires consideration of the associated damage to public health. Thus, the heating decarbonisation strategy should be developed taking into account the parallel decarbonisation of the electricity sector and may be most effective for households using electricity or solid fuels, while for natural gas consumers, the economic feasibility of the transition may be limited. The temperature trends obtained in our study, which indicate warming, may improve the long-term economics of heat pumps by reducing the duration of the heating season and the load on equipment [13].

The assessment of CO_2 emissions from the private housing sector in Kokshetau reveals a specific carbon footprint structure shaped by the city's climatic and infrastructural characteristics. Unlike megacities with hot climates, such as Bangkok, where indirect emissions from electricity consumption dominate [14], in Kokshetau a substantial—if not predominant—share of emissions is likely generated by direct combustion of fossil fuels (coal, natural gas) for heating during the cold season. This creates fundamentally different pathways for mitigation policy.

The obtained results on the assessment of CO_2 emissions from the private housing sector of Kokshetau are consistent with the findings of Lu Miao, who identified population scale and income level as key drivers of increased energy consumption and carbon emissions [15]. However, unlike high-density Chinese megacities, Kokshetau is dominated by low-rise residential development, which creates a distinct emissions profile in which direct heating-related emissions constitute a substantial share.

The analysis confirms that urban compactness, measured through building density, is an important factor. In the context of Kokshetau, increasing compactness in new districts could help reduce energy intensity by optimizing heating systems and shortening transport distances. The results highlight the necessity of accounting for local characteristics of urban form and climate when designing climate policies aimed at reducing emissions from the residential sector.

The Mann–Kendall test applied in this study revealed that the temperature in Kokshetau exhibits an increasing trend [16,17]. However, it cannot be said with certainty that CO_2 emissions and other greenhouse gases have contributed to climate change. Nevertheless, appropriate measures must be taken to mitigate the effects of climate change.

In this context, the international experience described in detail by Alkhani in his analysis of climate action implementation in London and Copenhagen [18] is highly relevant. These cases demonstrate that an effective strategy requires not isolated actions but a coherent, systemic approach grounded in several key principles:

Strong urban leadership and clear regulatory frameworks. As the example of Copenhagen shows, the active role of the municipality—establishing binding requirements through local plans—enables consistent engagement of the private sector and leads to real emission reductions. For Kokshetau, this implies the need to develop and firmly implement a climate action plan integrated into urban planning policy.

Promotion of green innovations and pilot projects. Both European cities created platforms for collaborative learning, where public authorities, businesses, and academic institutions jointly tested new technologies. A similar platform in Kokshetau could help identify and implement the most effective solutions for local climatic conditions in building energy efficiency and renewable energy.

Integration of climate measures into urban planning and the development of green infrastructure. The study emphasizes that climate adaptation and mitigation measures are most effective when embedded in comprehensive territorial development. The experience of London and Copenhagen with nature-based solutions—green roofs, large-scale urban greening—not only contributes to CO_2 sequestration but also directly helps cities adapt to warming-related challenges, such as heatwaves and intensified rainfall, which are increasingly relevant for Kokshetau.

One of the main limitations of this study is the lack of long-term and consistent statistical data on CO_2 emissions from the private residential sector of Kokshetau for the period 1986–2023. Due to the absence of continuous historical emission datasets, it was not possible to perform a reliable correlation analysis between emission dynamics and observed trends in temperature and precipitation. Future studies may overcome this limitation by reconstructing historical emission data using indirect indicators such as fuel consumption patterns, housing stock characteristics, and energy efficiency parameters.

Thus, the identified positive trend in temperature change in Kokshetau should be considered primarily in the context of adaptation processes, rather than exclusively as a negative manifestation of climate change. The developed green infrastructure indicates the favourable climate and environmental status of the city. In these conditions, the further development of nature-based solutions should be considered not as a compensatory measure to achieve carbon neutrality, but as a way to increase the sustainability of the urban environment and the quality of life of the population. Consequently, the priority for Kokshetau is not the large-scale adoption of universal international models, but the adaptation of climate and environmental practices taking into account local natural and socio-economic characteristics, which allows Kazakhstan to be viewed in a more balanced and positive light in the context of a changing climate.

5. Conclusions

The study has shown that the private housing sector of Kokshetau is a significant source of CO_2 emissions. Most private houses in the city were built in the 1960s–1980s and lack adequate thermal insulation. As a result, more coal is consumed during the cold season—on average, 6.8 tons per household per year. In addition, the majority of private houses rely on autonomous stove-based heating systems. According to the calculations, the annual greenhouse gas emissions generated by an average household in Kokshetau from coal and electricity consumption amount to 19.3 tons of CO_2-equivalent.

Statistical analysis clearly indicates a warming trend on an annual scale. The calculated Zs = 2.14 confirms a statistically significant upward temperature trend. The median rate of increase, 0.03 °C per year, has resulted in an overall warming of approximately 1.14 °C since 1986. These findings provide strong evidence of long-term climate warming in the region.

The statistically significant warming trend observed in Kokshetau aligns with global climate change patterns and necessitates urgent measures for both mitigation and adaptation. International experience demonstrates that an effective response to climate challenges is possible only through a comprehensive and systemic approach. Based on the conducted analysis, the following key action directions can be recommended for Kokshetau.

A first priority is the development and adoption of a mandatory City Climate Action Plan, integrated into the master plan and land-use and development regulations. This document should establish clear, measurable targets for greenhouse gas reduction and embed them into all urban planning decisions.

To develop and implement the most effective technologies suited to local conditions in the fields of building energy efficiency and renewable energy use, structured platforms for collaboration between local authorities, research institutions, and the business community are essential. Such platforms would help accumulate expertise, attract investment, and launch pilot projects.

Given Kazakhstan's energy profile, which has significant nuclear energy potential, there is a long-term opportunity to significantly reduce carbon emissions through the decarbonisation of electricity and heat supply, which goes beyond local urban measures but is an important strategic direction.

With Kokshetau's population projected to grow to 500,000 by 2050, the city's further development requires integrated planning, including an accurate assessment of future energy needs and a scientifically based calculation of the optimal amount of urban green space. This approach will ensure a balance between energy consumption growth, climate sustainability and the preservation of a favourable urban environment.

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