Monitoring and Improving Air Quality in the Zhytomyr Community through Strategic Environmental Tools

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Abstract. This study analyzes the current state of atmospheric air quality in the Zhytomyr municipal territorial community and outlines strategic directions for improvement. The purpose is to identify key pollution sources, assess monitoring capacity, and develop measures aligned with national and global environmental goals. The methodology combines analysis of official monitoring data (from two stationary state stations and six mobile laboratory points), statistical data (enterprise reporting on pollutant emissions), with a SWOT analysis. The study's novelty lies in integrating SWOT analysis results with national air quality policy and combining state, mobile, and community-based monitoring data to develop locally tailored strategic solutions. As a result of the research has determined that the main problems are significant pollution levels from mobile sources, insufficient efficiency of existing purification systems, and limited monitoring capabilities, resulting in unsatisfactory air quality in the community. In 2022–2023, nitrogen dioxide concentrations exceeded the maximum permissible daily average by 2.0–2.5 times, with occasional sulfur dioxide and carbon monoxide exceedances in high-traffic areas. Stationary sources emitted 1,456.7 t of pollutants in 2023, dominated by nitrogen compounds (34%), carbon monoxide (28%), and sulfur compounds (13%). The main contributors are manufacturing, energy production, and road transport. A SWOT analysis was conducted to categorize and evaluate the community's key environmental challenges and resource potential, which allowed for identifying strengths and weaknesses and external opportunities and threats. Based on the results, strategic goals and operational tasks were formulated, including creating a modern air quality monitoring system, reducing vehicle impact, and gradually decreasing fossil fuel usage. Implementing the proposed measures will contribute to achieving long-term environmental priorities, improving the population's quality of life, and fulfilling national and global sustainable development goals.

1. Introduction

At the current stage of societal development, the concept of balanced (sustainable) development, aimed at integrating economic, social, and environmental components of development, is gaining increasing significance in international, national, and regional policy. Urban areas are critical leverage points of influence for sustainable development interventions, creating resilient local economies, reducing environmental impacts, and improving quality of life.

Developing the Environmental Strategy of the Zhytomyr Municipal Territorial Community aims to help municipal and regional authorities, developers, and other urban professionals build a sustainable future by focusing on whole-system change. Urban challenges, both social and environmental, are often closely interconnected and stem from several key root causes. By addressing these root causes, we can build new systems that will create healthier and more sustainable cities.

For the Zhytomyr Municipal Territorial Community (ZMTC), clean air is a key environmental priority, as it directly affects public health and overall urban livability. The community faces a specific set of post-war challenges: increased industrial emissions due to production recovery, a growing dominance of outdated vehicle fleets, and limited capacity of the air quality monitoring network, which currently consists of two state-operated stationary stations and six mobile laboratory points, and several public monitoring posts. These limitations create data gaps, especially under wartime reporting constraints, and hinder timely environmental management decisions.

Strategic environmental tools can improve community air quality monitoring and management under current post-conflict conditions by combining technological modernization, multi-source data integration, and policy alignment.

This paper addresses the lack of integrated, locally adapted strategies for air quality monitoring in mid-sized Ukrainian communities. The proposed framework combines SWOT analysis with multi-source monitoring data (state, mobile, and community-based networks) and aligns the results with national air quality policy. This study is among the first to propose an integrated monitoring and strategy framework for post-conflict urban communities in Ukraine, enabling the development of locally tailored, evidence-based measures for pollution reduction and long-term environmental resilience.

2. Analysis of literary sources dedicated to studying the problem of atmospheric air monitoring

Atmospheric air quality is a determining factor in ensuring public health, ecosystem stability, and achieving sustainable development goals in urbanized regions. While many studies document the harmful impacts of pollution — from respiratory and cardiovascular diseases to climate change — the challenge lies in translating scientific knowledge into actionable, locally adapted strategies. According to the World Health Organization [1], over 90% of the global population lives in areas exceeding recommended air quality limits, highlighting the urgency of effective monitoring and management.

Recent global trends show a shift from traditional, stationary air monitoring networks to flexible, integrated systems that combine mobile sensors, IoT technologies, satellite data, and community-based observations. Kumar et al. [2] and Maag et al. [3] emphasize the potential of low-cost sensors and calibration frameworks to generate high-resolution pollution maps, but also stress the persistent problem of data reliability.

Zhang et al. [4] note that institutional integration must accompany technological solutions, including urban planning, open data policies, and public engagement. European policy frameworks, such as the European Green Deal, set ambitious targets for “zero pollution” by 2050, but implementation at the local level remains uneven. Zaporozhets et al. [5] identify outdated monitoring networks, fragmented legislation, and insufficient coordination as significant barriers in Ukraine.

Industrial cities, such as Kamianske, have increased anthropogenic load: Levytska and Rusakova [6] identified systematic exceedances of maximum permissible concentrations near a metallurgical plant. In Zaporizhzhia, pollution levels decreased due to the pandemic and military actions [7]. Nadtochii, Rybchynska, and Savenets [8] showed that military actions caused a reduction in NO_2 and CO concentrations by 34% and 17% respectively, with parallel changes in fuel combustion efficiency. These examples illustrate how external factors can significantly alter emission patterns and highlight the need for adaptable and locally relevant environmental management approaches. The decentralization of environmental governance in Ukraine requires locally driven monitoring strategies; this paper proposes one for Zhytomyr.

Innovative approaches in Ukrainian cities, such as IoT-based monitoring in Kharkiv and Kyiv [9, 10, 11], demonstrate how sensor integration with GIS platforms and predictive models can enhance spatial coverage.

Applying machine learning (ML) methods and neural networks (LSTM, XGBoost, CNN) demonstrates high accuracy in predicting PM2.5, NO_2, and ozone concentrations. According to Chen et al. [12] and Gao et al. [13], such models are more adaptive to seasonal and spatial changes than classical regression methods. Despite advances in sensor technology and AI-based air quality prediction, localized strategic planning tools in Ukraine remain fragmented and poorly evaluated.

Public monitoring networks, such as in Poltava [14], play an important role in increasing the transparency of environmental information. Nevertheless, their integration into official decision-making remains limited, often due to data validation and legal status questions.

Shelestov et al. [15] and Savenets et al. [16] describe Sentinel-5P satellite data for evaluating indicator 11.6.2. This aligns with sustainable monitoring principles: openness, repeatability, and accessibility.

However, Zaporozhets et al. [5] note that key barriers to implementing sustainable strategies are outdated monitoring station networks, legislative fragmentation, and insufficient coordination between authorities and the public.

Similarly, while Ukraine's commitment to SDGs 3.9 and 11.6 has led to adopting national indicators and climate strategies, local implementation is hindered by resource constraints, inconsistent enforcement, and insufficient stakeholder coordination.

Literature analysis indicates the presence of comprehensive approaches to air quality monitoring, including cutting-edge technologies, data analytics, public participation, and integration into sustainable development. Ukraine is moving toward European integration, gradually harmonizing its regulatory framework with EU Directives.

However, critical gaps remain in:

- translating national policy goals into operational, community-level strategies,
- integrating heterogeneous data sources (state, mobile, and public networks) into unified platforms, and
- ensuring adaptability of monitoring systems under post-conflict conditions.

This study addresses these gaps by developing an integrated monitoring and strategy framework specifically for Zhytomyr, aligning local initiatives with national environmental goals and EU integration requirements.

3. Methodology

The purpose of this study is to assess the state of ambient air quality in the Zhytomyr Municipal Territorial Community (ZMTC), analyze the existing monitoring system, and develop proposals for its modernization in line with European requirements, as well as to formulate strategic goals

and tasks in the field of air quality protection. The general methodology combines the analysis of official monitoring data, enterprise statistical reports, calculated estimates of the transport sector's impact, and the results of a strategic SWOT analysis involving stakeholders.

A comprehensive assessment of the community's existing state air quality monitoring system was conducted, including its technical specifications, station location, and territorial coverage. The results of the assessment were compared with the requirements of the European Parliament and Council Directive 2008/50/EC [17], which made it possible to identify existing gaps and key directions for modernization — in particular, increasing the number of monitoring stations, expanding the list of measured pollutants, and introducing an automated data collection and processing system.

The air quality assessment was based on official data from organizations responsible for state air quality monitoring in the territory of the Zhytomyr community:

- Zhytomyr Regional Hydrometeorological Center – two stationary state-operated stations, measurements were taken daily, with subsequent aggregation into monthly and annual averages;
- State Institution "Zhytomyr Regional Laboratory Center of the Ministry of Health of Ukraine" – six mobile laboratory points, measurements are conducted twice a month.

The monitored pollutants included nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), particulate matter, and heavy metals (cadmium, iron, manganese, copper, nickel, lead, chromium, zinc).

All stations are certified, and measurement methods comply with Ukrainian state standards. Assessment of atmospheric air quality is carried out based on annual average concentrations in terms of multiples of exceedance of average daily maximum permissible concentrations and presented as exceedance ratios to indicate the level of potential health risk.

The impact of stationary sources on the state of atmospheric air was determined using statistical information from the Main Statistics Department in the Zhytomyr region (according to 2-TP (air) data submitted by enterprises). 2-TP (air) data is an official state report in which enterprises declare the volumes of atmospheric pollutant emissions, their composition, and the types of fuel and raw materials used. Reports are submitted once a year. In 2022, 80 enterprises in the community submitted 2-TP (air) data. As a result of the statistical analysis identified the central polluting enterprises in the community and industrial sectors with the most significant impact on air quality and the shares of various pollutants in the total volume of emissions.

To analyze the current state of the impact of transport in the Zhytomyr urban territorial community on the state of atmospheric air, data provided in the Sustainable Mobility Plan of the city of Zhytomyr [18] and the Action Plan for Sustainable Energy Development and Climate of the Zhytomyr urban territorial community [19] were used. The contribution of vehicles to air pollution was determined using a calculation method based on the number of vehicles, types, and amounts of fuel consumed. Calculation coefficients were taken from methodologies approved by the Ministry of Environmental Protection of Ukraine [20]. Data on the transport fleet and fuel consumption volumes were sourced from the Zhytomyr Sustainable Urban Mobility Strategy, ensuring a realistic estimate of the transport sector's contribution to overall emissions.

A SWOT analysis was carried out to identify key problems, strengths, opportunities, and threats in air quality management. Its use in this context is justified as it enables a comprehensive evaluation of internal and external factors influencing air quality, thus supporting the development of well-grounded strategic priorities. The analysis was conducted during an open meeting with the participation of community members, local authorities, business representatives, and academics. The event was held in a mixed format (offline and online),

ensuring broad stakeholder engagement. The methodological basis was the "World Café" technique, which encourages active discussion and solution-oriented dialogue. The SWOT analysis results were made public for further discussion, and all comments and recommendations were considered in the final version.

Based on the results of all stages of the study, strategic goals for the Zhytomyr community in the field of air quality protection were defined, along with the specific tasks required to achieve them. Target indicators were set to monitor progress for 2030, 2040, and 2050, enabling phased evaluation of achievements.

The proposed framework integrates scientific rigor with practical applicability, while explicitly accounting for the socio-economic context of the Zhytomyr community. Its implementation is expected to enhance the efficiency of environmental monitoring, mitigate pollution levels, contribute to public health improvement, and foster long-term ecological sustainability.

4. Air Quality Monitoring System in the Territory of Zhytomyr Community

Air pollution problems are important and relevant for maintaining sustainable development and a clean environment. For Ukraine, air quality assessment problems are particularly relevant due to the large number of emissions from stationary and non-stationary pollution sources and the low level of development of the monitoring system.

The location scheme of the stationary, mobile, and public air monitoring posts within the community is shown in Figure 1.

Currently, state monitoring of atmospheric air pollution in the territory of the Zhytomyr Municipal Territorial Community is carried out at two stationary monitoring stations located in Zhytomyr city by the Zhytomyr Regional Hydrometeorological Center: monitoring station No. 1 is located at 31 Vitruka Street; monitoring station No. 2 is located at 14/20 Mykhaila Hrushevskoho Street.

The atmospheric air content of four primary pollutants is determined – dust particles, sulfur dioxide, nitrogen dioxide, carbon monoxide, and heavy metals (cadmium, iron, manganese, copper, nickel, lead, chromium, zinc).

Sample analysis is performed by the Central Geophysical Laboratory named after B. Sreznevsky, except for carbon monoxide, the concentration of which is determined by an instrument, gas analyzer SM-2-CO.

Information about the state of atmospheric air pollution in the territory of Zhytomyr Territorial Community is submitted to the Department of Ecology and Natural Resources of Zhytomyr Regional State Administration, where it is published on the official website https://eprdep.zht.gov.ua/ (section "Environmental State").

The State Institution "Zhytomyr Regional Laboratory Center of the Ministry of Health of Ukraine" monitors the atmospheric air quality in Zhytomyr city for such indicators as dust particles, sulfur dioxide, nitrogen dioxide, carbon monoxide, benzene, and lead. Measurements are conducted twice a month. The locations of mobile monitoring points are approved once a year. Currently, measurements are conducted at six monitoring points during April-November (Figure 1).

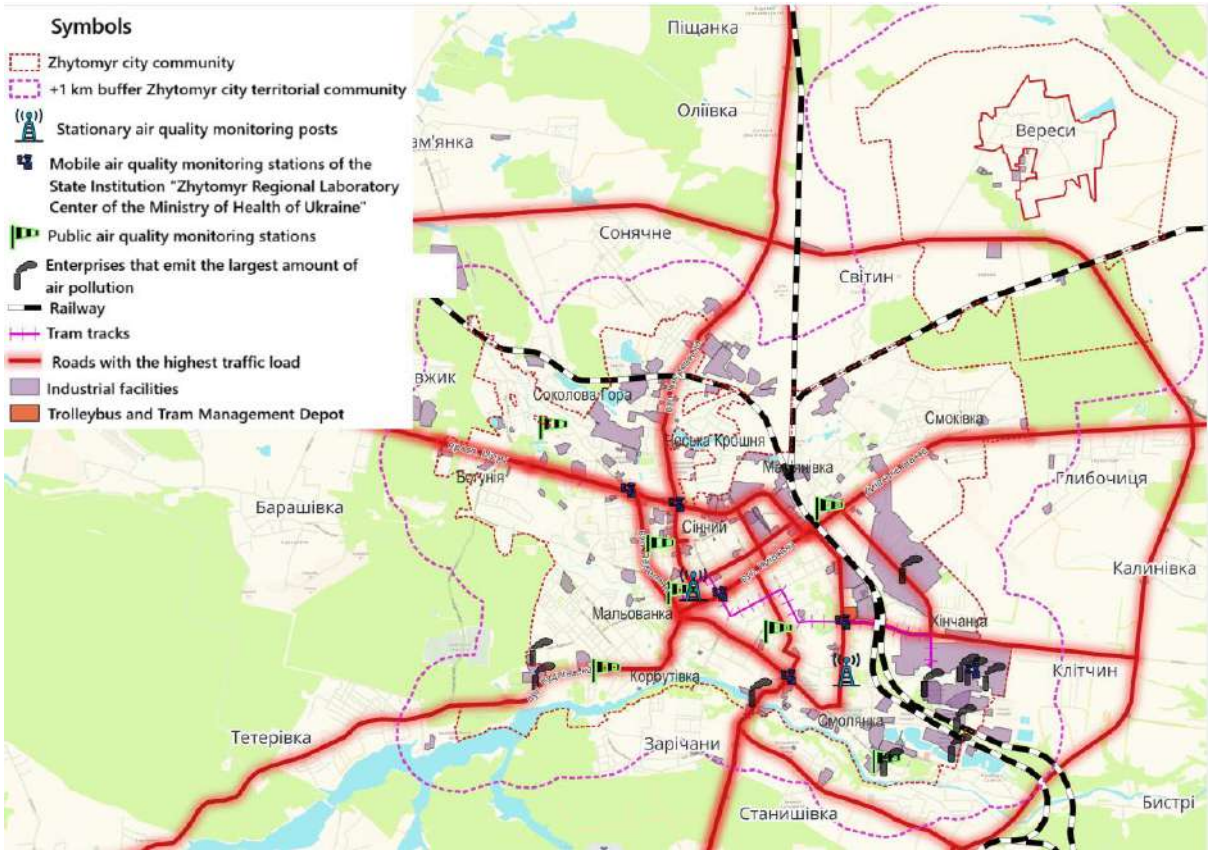

Figure 1. Locations of atmospheric air monitoring points as of 01.10.2024, created within the framework of the development of the Environmental Strategy of the Zhytomyr Urban Territorial Community

Alongside the state monitoring system, a public atmospheric air quality control station network operates in the city's territory. This system is fully automated and allows online monitoring of control results. Overall, there are 7 currently operating stations in the territory of the Zhytomyr community (Figure 1). The stations have different sets of sensors, but they generally allow monitoring of parameters such as dust particles, carbon monoxide content, nitrogen dioxide, ammonia, and radiation background.

The number of monitoring stations and their equipment is insufficient for the territory of the community. 2 stationary atmospheric air monitoring posts are located in places of potential highest pollution (city center and industrial district of the city) and are not able to provide full information on the state of atmospheric air in the territory of the community. 6 mobile observation posts slightly compensate for the lack of the required number of stationary posts, however, the measurement frequency (twice a month) does not allow to control sudden changes in concentrations and the consequences of emergency emissions. In addition, the list of indicators monitored by stationary and mobile posts differs from each other and does not meet the requirements of EU legislation.

As part of implementing the European Parliament and Council Directive 2008/50/EC [17], a modern atmospheric air monitoring system must be developed and implemented in Ukraine. As a result, amendments were made to Ukrainian legislation, which oblige each territorial community to modernize the existing one or create a new atmospheric air monitoring system.

Following the implementation of the Resolution of the Cabinet of Ministers of Ukraine dated August 14, 2019 No. 827 "Some Issues of State Monitoring in the Sphere of Atmospheric Air Protection" [21], the Program of State Monitoring in the Field of Atmospheric Air Protection for the "Zhytomyr" Agglomeration for 2023-2027 [22] was developed and approved in the appropriate procedure.

Following the Procedure for the Location of Air Quality Monitoring Stations in Zones and Agglomerations [22], the Commission determined that, in the territory of the city of Zhytomyr, in addition to those currently operating, it is necessary to provide for the installation of 6 stationary automated air quality monitoring stations. These stations will be of the transport and industrial type. They will measure the state of the air according to such parameters as dust particles (PM 2.5, PM 10), nitrogen dioxide, carbon monoxide, sulfur dioxide, benzene, mercury, nickel, cadmium, arsenic, lead, benzo(a)pyrene, and ozone.

The automated environmental monitoring system will allow one of the most important tasks to be implemented: to obtain reliable information about the content of pollutants in the air. However, due to military operations in Ukraine and a lack of funding during 2023 and 2024, none of the measures envisaged by the program were implemented.

5. Current State of Atmospheric Air in the Territory of Zhytomyr Municipal Territorial Community

Assessment of atmospheric air quality in the territory of Zhytomyr Municipal Territorial Community is carried out based on annual average concentrations in terms of multiples of exceedance of average daily maximum permissible concentrations by Annex 2 of the Cabinet of Ministers Resolution No. 827 dated 14.08.2019 for pollutants of List A.

Annual average concentrations of pollutant admixtures determined in 2022 did not exceed average daily maximum permissible concentrations, except for nitrogen dioxide, the average concentration of which equaled 2.3 MPC a.d.

Exceedance of nitrogen dioxide concentration by 2.0-2.5 times in atmospheric air in the community territory has been observed over the last 5 years, confirmed by Zhytomyr Regional Hydrometeorological Center measurements. This sustained exceedance of NO_2 levels presents a risk to public health and reflects critical infrastructural deficiencies requiring intervention.

Additionally, the State Institution "Zhytomyr Regional Center for Disease Control and Prevention of the Ministry of Health of Ukraine" recorded periodic exceedance of standards for such indicators as sulfur dioxide and carbon monoxide in the central part of the city, which may be related to significant traffic load in these areas.

The overall level of city pollution for the year according to the atmospheric pollution index (API), which takes into account the degree of atmospheric air pollution from five priority pollutants, was characterized as low and amounted to 3.8, which is significantly lower than the average indicator for Ukraine, which is 6.5 and was assessed as elevated.

The state of atmospheric air radiation pollution in the community territory is monitored by the Zhytomyr Regional Hydrometeorological Center (Zhytomyr RHC) at meteorological stations subordinated to the center. According to data from the Zhytomyr RHC, the state of atmospheric air radiation pollution in 2022 in Zhytomyr city, based on daily observations of gamma radiation exposure dose levels, was within the natural radiation background (10-20 μR/h).

6. Dynamics of Pollutant Emissions into Atmospheric Air

Under conditions of increasing anthropogenic load, ecological equilibrium is disrupted, and changes in quantitative and qualitative indicators of the environment are observed. The primary sources of atmospheric air pollution in Zhytomyr Municipal Territorial Community are industrial enterprises, energy facilities, and motor transport.

The volumes of pollutant emissions from stationary pollution sources into atmospheric air from enterprises, institutions, and organizations of Zhytomyr region are determined by conducting an inventory of stationary sources of pollutant emissions into atmospheric air, types and volumes of pollutant emissions into atmospheric air by stationary sources, and dust and gas cleaning equipment at enterprises – economic entities of the territorial community. The main source of information regarding volumes of pollutant emissions into atmospheric air from stationary emission sources is statistical information from the Main Statistics Department in the Zhytomyr region (according to 2-TP (air) data submitted by enterprises).

According to subparagraph 1 of paragraph 1 of the Law of Ukraine "On Protection of Interests of Reporting Entities and Other Documents During Martial Law or State of War", [25] natural persons, natural persons-entrepreneurs, legal entities, except those vested with budgetary powers according to legislation, submit accounting, financial, bookkeeping, calculation, audit reports and any other documents, the submission of which is required according to current legislation norms in documentary and/or electronic form, within three months after termination or cancellation of martial law or state of war for the entire period of non-submission of reports or obligation to submit documents.

Currently, during martial law, the norm regarding reporting submission is recommendatory; however, the obligation to submit relevant reports has not been canceled and will be restored after the cancellation of martial law or state of war.

In connection with this, most information regarding emissions from stationary sources may be clarified in the future. In 2022, the total number of enterprises emitting pollutants into atmospheric air was 80 units (according to the number of statistical reporting forms 2-TP (air) submitted by enterprises). It should be noted that there has been growth in volumes of pollutant emissions into the atmospheric air in recent years. In 2019, the total volume of emissions was 1,626 tons compared to 1,538 tons in 2018. 2021 there was a significant (36%) increase in gross emissions. However, military actions reduced production in the territory of Zhytomyr Municipal Territorial Community in 2022 and consequently decreased pollutant emissions. Thus, in 2022, gross pollutant emissions decreased by 41%, totaling 1,300 tons.

The total volume of pollutant emissions into atmospheric air from stationary sources 2023 was 1,456.7 tons. The structure of pollutant emissions from stationary sources within the Zhytomyr community is presented in Figure 2. The main toxic ingredients were nitrogen compounds (34% of total volumes), carbon monoxide (28%), sulfur compounds (13%), solid suspended particles (13%), and non-methane volatile organic compounds (11%).

It should be noted that the Plan of State Statistical Observations and Systematization of Information on Pollutant Emissions into Atmospheric Air from Mobile Pollution Sources in Zhytomyr Municipal Territorial Community is not provided for and is not conducted.

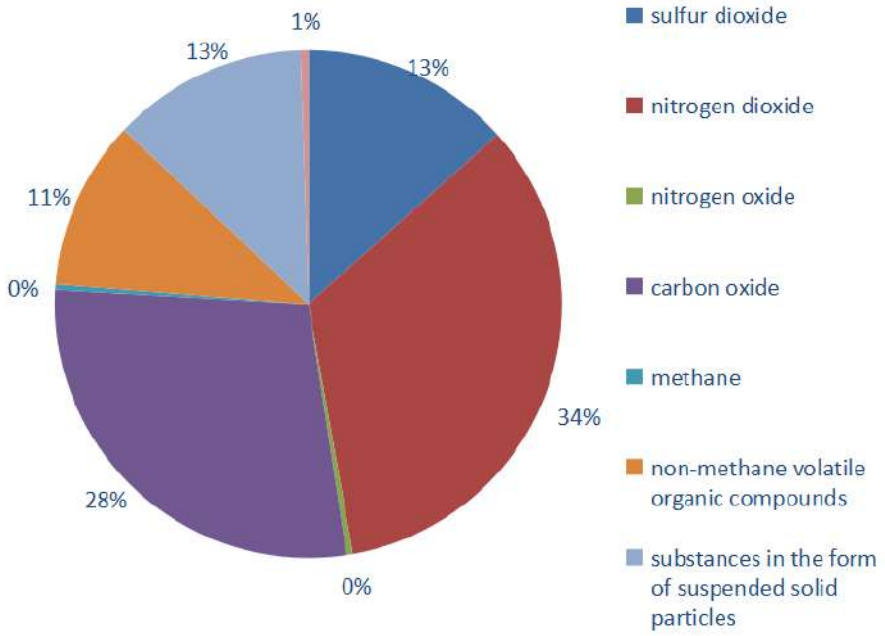

Figure 2. Structure of pollutant emissions into atmospheric air from stationary sources, 2023, created by the author based on statistical information from the Main Statistics Department in the Zhytomyr region

Analyzing the dynamics of emission volumes of main pollutants (Figure 3) into atmospheric air from stationary pollution sources of Zhytomyr Municipal Territorial Community, it should be noted that there was relatively rapid growth in nitrogen dioxide and sulfur dioxide emissions until 2022.

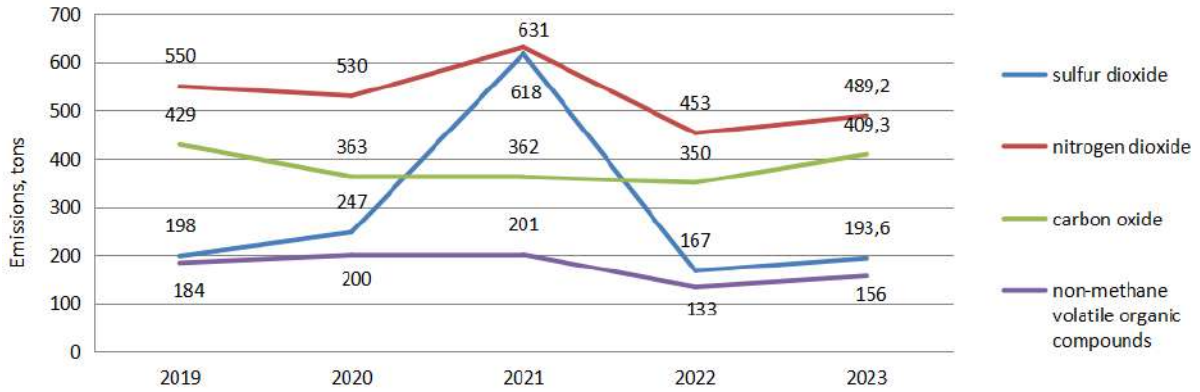

Figure 3. Dynamics of emissions of main pollutants from stationary pollution sources into atmospheric air for 2019-2023, created by the author based on statistical information from the Main Statistics Department in the Zhytomyr region

The level of carbon oxides and non-methane volatile organic compounds emissions did not undergo significant changes. However, a decrease in emission volumes can be observed for all pollutants in 2022. Thus, sulfur dioxide emissions decreased by 73% in 2022, nitrogen dioxide by 28%, carbon monoxide by 34%, and non-methane volatile compounds by 31%.

An important generalizing indicator that characterizes the state of the air basin as a whole is the total volume of pollutants released per capita and per 1 km^2 of territory.

The density of emissions from stationary pollution sources per square kilometer of the Zhytomyr territorial community had a general upward trend, and in 2021, it reached 23.5 tons of harmful substances per km^2. However, in 2022, due to martial law, cessation of activities, or reduction in production volumes of many enterprises, this indicator decreased and amounted to 13.9 tons per 1 km^2.

The volumes of harmful substance emissions per person of the territorial community as of 2021 were 8.4 kg/person, compared to 10.02 kg/person for the Zhytomyr region and 54.2 kg/person for Ukraine. In 2022, due to military activities and a reduction in production capacities, this indicator decreased to 5.0 kg/person.

It should be noted that while the presented quantification is based on certified methods and official monitoring data, certain uncertainties remain. Potential underreporting may occur due to gaps in wartime data collection, temporary shutdowns of monitoring stations, and limited coverage in some urban districts. Additionally, short-term variability in pollutant concentrations can be influenced by meteorological conditions such as wind speed, precipitation, and temperature inversions, which may cause deviations from long-term averages.

7. Main Atmospheric Polluters

Zhytomyr Municipal Territorial Community significantly impacts the atmospheric air quality of the Zhytomyr region. Mobile and stationary pollution sources cause air pollution. In 2022, the total number of enterprises emitting pollutants (according to submitted reporting forms) was 80 units. Monitoring emissions from stationary sources is conducted based on annual statistical data from enterprises. The assessment of the impact of transport on the state of atmospheric air in the Zhytomyr urban territorial community was carried out based on data obtained within the framework of the implementation of the Project "Integrated Urban Development in Ukraine II" [18].

Atmospheric air pollution is also associated with violations of environmental legislation, particularly non-compliance with technical regulations, which can lead to emergency emissions, or with untimely updating of treatment equipment, which affects the concentration of pollutants in enterprise emissions.

7.1 Industrial enterprises

The total amount of pollutant emissions from stationary sources in the community constitutes 19.6% of pollutant emissions in the region (according to 2023 data).

The main atmospheric air polluters in the territory of Zhytomyr territorial community by types of economic activity (Figure 4) remain manufacturing industry – 72.00% and the sector "Supply of electricity, gas, steam and air conditioning" – 16.15%, whose pollutant emissions constitute 88.15% of the total volume of atmospheric air emissions from stationary emission sources in Zhytomyr Municipal Territorial Community.

Significantly smaller shares in the overall pollution level are contributed by the sectors "Public administration and defense; compulsory social insurance" and "Water supply; sewerage, waste management and remediation activities," accounting for 4.69% and 3.54% of total emissions, respectively.

At the same time, the least impact on atmospheric air quality is exerted by construction, trade, transport, telecommunications, financial and insurance activities, real estate operations,

administrative and support service activities, education, and healthcare. These sectors together account for 3.62% of the total volume of pollutant emissions.

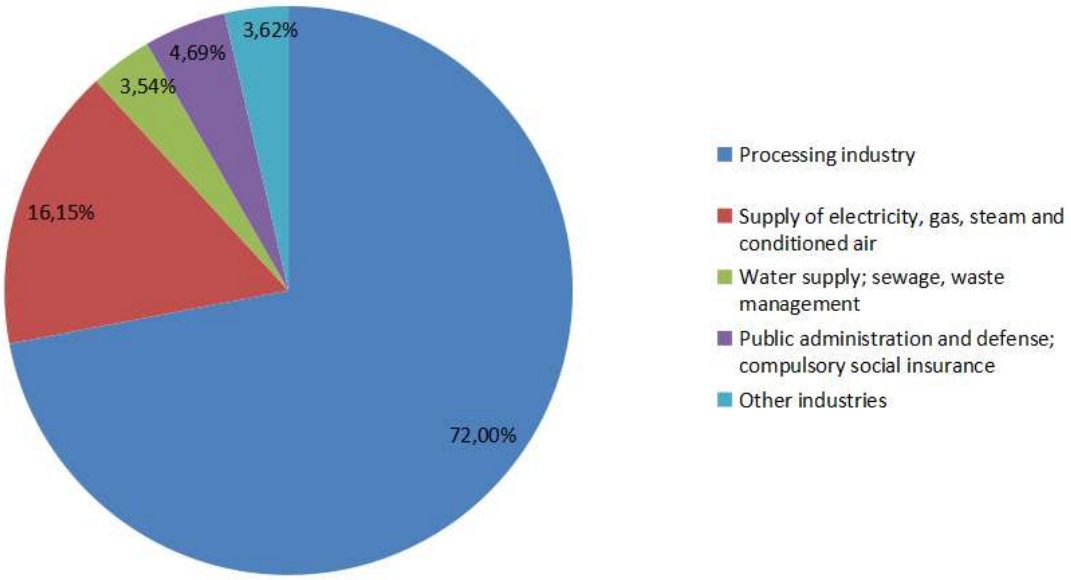

Figure 4. Distribution of pollutant emissions from stationary emission sources by types of economic activity, 2023, created by the author based on statistical information from the Main Statistics Department in the Zhytomyr region

Analyzing the dynamics of emissions from stationary emission sources in the Zhytomyr community for 2019-2023, it can be observed that prior to the full-scale invasion, there was a clear upward trend in emission volumes from manufacturing industry enterprises by 55% from 2019 to 2023. In 2022, emission volumes decreased by almost half; however, their gradual increase occurred (by 19% in 2023).

According to the data from the "Environmental Passport of Zhytomyr Region for 2023," LLC "Obio" [26], which manufactures high-quality thermal and acoustic insulation boards, and Municipal Enterprise "Zhytomyr Teplokomunenergo," which produces and distributes heat, are classified as environmentally hazardous facilities in the Zhytomyr region.

The largest atmospheric air polluters are concentrated primarily in the industrial zone of Zhytomyr city. The industrial zone is located in the eastern part of the city, on the leeward side, and is separated from the central part of the city by a railway branch.

Sanitary protection zones have been established between industrial enterprises and residential areas, along railway and automobile routes. This contributes to reducing the technogenic impact of industrial facilities on atmospheric air quality in the residential part of the city. However, such dense concentration of industrial facilities may lead to the formation of local territories with elevated concentrations of pollutants in the atmospheric air.

This makes it necessary to encourage the largest polluting enterprises of the Zhytomyr community to implement green technologies, install treatment equipment, and switch to renewable energy sources.

7.2 Thermal Energy Enterprises

Centralized heat supply systems, electricity supply systems, and natural gas supply systems represent the energy system of the Zhytomyr municipal territorial community. In addition,

alternative fuel resources such as firewood, peat briquettes, and straw pellets are used for heating in parts of private residential development in Zhytomyr city, Veresy village, and some municipal facilities.

A small hydroelectric power station and private solar power stations of low capacity represent local electricity production in the community. The total energy output from all energy supply sources in the Zhytomyr municipal territorial community in 2022 amounted to 74.0 million kWh, and the thermal energy output was 650.7 thousand Gcal. The installed electrical capacity for all types of power-generating units 2022 was 85.9 thousand kW, and the installed thermal capacity was 958.0 Gcal/h.

Energy enterprises account for 16% of all pollutant emissions in the community. The third place among the largest atmospheric air polluters in the Zhytomyr municipal territorial community is occupied by Municipal Enterprise "Zhytomyrteplokomunenergo" of the Zhytomyr City Council, which carries out the production and supply of thermal energy. There is a tendency toward increased use of solid biofuel by enterprises, organizations, and institutions of the community. The share of thermal energy produced from energy sources operating on biofuel (solid) in 2022 was 24.2%.

With the aim of energy resource conservation, improvement of heat supply services, and reduction of costs in thermal networks, measures for boiler house modernization, replacement of boilers with increased heat generation efficiency, and reconstruction and optimization of heat supply networks are continuously implemented.

In 2022, the district boiler house RK-10 was reconstructed by installing a thermodynamic combined heat and power generation unit "Organic Rankine Cycle (fuel – wood chips)" with a total capacity of 1.2 MW electrical and 7.1 MW thermal energy. In 2023, the technical re-equipment of two boiler houses' heat-generating equipment was conducted by installing modular solid-fuel boiler houses with a capacity of 1.8 MW and 0.7 MW (fuel – wood chips).

Re-equipment of boiler houses RK-8, RK-6, RK-11 with a total capacity of 30 MW (fuel – wood chips) and construction of a combined heat and power plant with a capacity up to 30 MW thermal and up to 8.5 MW electrical energy (fuel – wood chips; RDF) are planned.

Heating activities have a particularly significant impact on air quality during the cold season. The use of solid biofuels, while contributing to renewable energy targets, produces more ash than natural gas, which increases particulate matter emissions. Under certain meteorological conditions, such as calm weather and temperature inversions, these emissions do not disperse effectively and form localized pollution hotspots with elevated particulate concentrations. Data from public monitoring stations periodically record such exceedances in winter mornings in the central part of the city. This highlights the importance of considering the air quality implications of heating practices in urban planning and energy policy decisions.

The energy policy of the Zhytomyr municipal territorial community is directed toward energy efficiency and transition to renewable energy sources, which will reduce pollutant emissions to the atmospheric air from energy infrastructure facilities [18, 27, 28].

7.3 Transport

Automobile transport is the most significant atmospheric air polluter in the Zhytomyr municipal territorial community. The significant impact of vehicles on atmospheric air quality is determined by the high level of private transport use due to an insufficiently developed network, a lack of prioritization of public transport, and outdated vehicles.

In addition, transport substantially impacts atmospheric air quality, as roads of international and European significance pass through the Zhytomyr municipal territorial community (M06, E40, E583, M21).

To analyze the current state of the impact of transport in the Zhytomyr urban territorial community on the state of atmospheric air, data provided in the Sustainable Mobility Plan of the city of Zhytomyr [18] and the Action Plan for Sustainable Energy Development and Climate of the Zhytomyr urban territorial community [19] were used.

A network of automobile roads, a public transport system, and pedestrian infrastructure provides mobility for the population of the Zhytomyr municipal territorial community. In Zhytomyr city, bicycle infrastructure elements are installed but not interconnected.

According to the mobility study of Zhytomyr city, most of the population uses public transport. The share of public transport users is 46%. At the same time, a significant portion of movements is made on foot – 37.8% of the total number [18].

Zhytomyr's transport network has a high density of public transport coverage: 96.14% of Zhytomyr city's population lives within a 500-meter accessibility zone to public transport. Public transport in Zhytomyr is represented by buses, trolleybuses, and one tram route.

Table 1 shows the volume of passenger transportation by public transport in the territory of the Zhytomyr community by mode of transport in 2018-2021 — information provided by the Department of Economic Development of the Zhytomyr City Council [18].

Table 1. Passenger transportation volumes by mode of transport (according to the Department of Economic Development of the Zhytomyr City Council) [18]

Indicator name	**Years**			
	2018	**2019**	**2020**	**2021***
Total, thousand people:	76296	71068	44198	54472
automobile	29849	29193	18314	18536
tram	7490	7282	4546	5077
trolleybus	38957	34593	31338	30859

*Statistical information for 2022-2023 is not provided by the Law of Ukraine "On Protection of the Interests of Subjects of Reporting and Other Documents during the Period of Martial Law or War" [25]

According to the results of the passenger flow study of Zhytomyr territorial community, the average daily transportation volume in 2021 by bus routes was 54,472 passengers, by trolleybuses – 30,859 passengers, and by tram – 5,077 passengers.

Overall, in recent years, there has been a decrease in passenger transportation volumes by public transport; however, the ratio between transportation by type remains stable. As of 2018-2021, automobile transport accounts for 39-41% of all transportation, trolleybus transport 48-56%, and tram transport 9-10%.

Recently, there has been an increase in the number of private motor vehicles. Due to this, the city's central streets are becoming overloaded with automobile transport; during peak hours, traffic accumulates on these streets, and problems with disorganized car parking emerge.

The level of motorization is constantly growing. In 2019, this figure was 194 cars/1000 inhabitants. Most cars imported to Ukraine, mainly diesel engines, have outdated emission control technologies. Data for recent years are missing due to changes in the system of collection, processing, and access to this category of statistical data. Nevertheless, the general trend towards an increase in the number of private vehicles continues.

Within the Project "Integrated Urban Development in Ukraine II" framework [18], a calculation of CO_2 emissions from road transport in the city of Zhytomyr in 2019 was carried out. The contribution of vehicles to air pollution was determined using a calculation method according to the Methodology for Calculating Emissions of Pollutants and Greenhouse Gases into the Air from Vehicles approved by the State Statistics Committee, using the formula:

$$B = П_{інп} \cdot К_i \cdot К_{тс} \quad (1)$$

B_{ij} – greenhouse gas emissions from the use of a certain type of fuel;

$П_{інп}$ – annual consumption of a certain type of fuel (gasoline, diesel fuel, natural gas);

$К_i$ – average specific greenhouse gas emissions for vehicles from the consumption of a certain type of fuel;

$К_{тс}$ – coefficients of the influence of the technical condition of vehicles on greenhouse gas emissions.

According to the results, private and commercial transport consume the most fuel. In 2020, this category of vehicles used 186,445 MWh of fuel. In percentage terms, this is 33.3% gasoline, 39.2% diesel fuel, and 27.5% gas. Unlike private and commercial transport, diesel fuel is predominant for public and municipal transport.

Figure 5 shows the structure of CO_2 emissions in the Zhytomyr community by type of transport and fuel used. The data indicate that the dominant share of emissions originates from private and commercial vehicles running on diesel fuel. In contrast, municipal and public transport make a comparatively minor contribution.

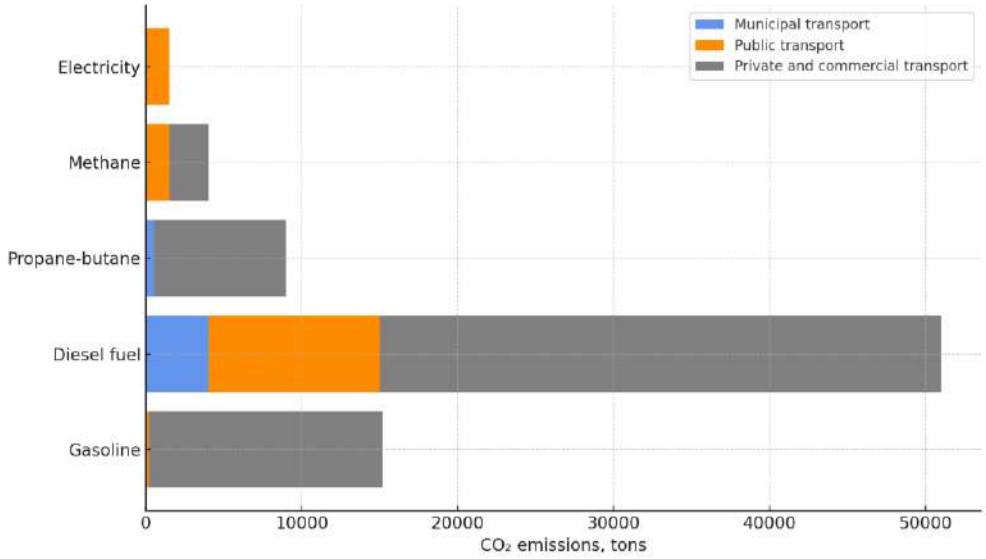

Figure 5. CO_2 emissions from vehicles by fuel type in Zhytomyr, 2020 (calculated within the framework of the Project "Integrated Urban Development in Ukraine II") [18]

In 2020, vehicles in the city of Zhytomyr produced 62.9 thousand tons of carbon dioxide, of which 74.4% were private and commercial transport, 19.8% public transport, and 5.8% municipal transport.

By fuel type, the most significant amount of CO_2 was generated from the operation of transport with diesel engines, which is natural, since the share of diesel fuel use by road transport prevails in the city of Zhytomyr.

Thus, the main environmental problems in the transport sector in Zhytomyr are excessive dependence on private vehicles and the use of an outdated fleet of cars. Therefore, to reduce the negative impact of transport on air quality in the Zhytomyr community, a comprehensive approach is necessary: updating the public transport fleet to more environmentally friendly types (electric vehicles, modern buses with low emissions), developing bicycle and pedestrian infrastructure, and encouraging residents to use public transport instead of private cars.

8. SWOT Analysis of Atmospheric Air Quality in Zhytomyr Community Territory

A comprehensive SWOT analysis was conducted to assess the current state of atmospheric air quality and determine priority directions of environmental policy within the Zhytomyr municipal territorial community (ZMTC) (Table 2). The analysis was conducted during an open meeting with the participation of community members, local authorities, business representatives, and academics. Before conducting the analysis, the results of previous studies of the state of atmospheric air in the Zhytomyr community and its sources were highlighted. Unlike typical applications, in this study, SWOT is closely integrated with the results of previous sections (monitoring system gaps, transport impact, industrial emissions) and directly informs the formulation of strategic goals (Section 9). This ensures that SWOT is descriptive and prescriptive, serving as a bridge between evidence-based diagnosis and targeted interventions.

This tool enabled the systematization of both internal (strengths and weaknesses) and external (opportunities and threats) factors affecting air quality in the community. We present a description of key aspects that require priority attention from management structures.

Most Important Strengths

One of the main advantages of ZMTC is the availability of qualified personnel, accredited laboratories, and certified equipment for air quality monitoring, which ensures high reliability and promptness of environmental observations. It is also important to note the active participation of the public in environmental initiatives, which increases the level of control over local pollution sources and contributes to the formation of environmental culture.

Another significant positive factor is the implementation of energy monitoring and decentralization of heating in educational institutions, which has reduced energy resource consumption and, accordingly, atmospheric emissions.

Most Critical Weaknesses

The most substantial problem is the dominance of emissions from mobile sources, particularly automobile transport, which consists of technically outdated models. This causes elevated concentrations of harmful substances in the air, especially within transport hubs.

Simultaneously, the insufficient technical equipment at air monitoring stations and the absence of current statistical information during the martial law period limit possibilities for systematic analysis and rapid response.

A separate problem is the low level of renewable energy source implementation and the absence of incentives for industrial enterprises to modernize equipment. This delays the transition to a more ecological economic model.

Key Opportunities

Against the background of the aforementioned problems, the community has several potential opportunities to produce a tangible positive effect from a medium-term perspective.

Table 2. SWOT Analysis of Community Atmospheric Air Quality, 2023

Strengths	**Weaknesses**
• Availability of advanced practices in the application of modern treatment equipment at industrial enterprises • Active participation of the public in solving environmental problems related to atmospheric air pollution • Availability of accredited laboratories, certified equipment, and qualified personnel • Availability of the biogas collection system at the solid waste landfill of Zhytomyr MTC • Competent control by regulatory authorities • Decentralization of heating systems in educational institutions • Energy monitoring of educational institutions • Moderate technogenic load on atmospheric air • Availability of a sustainable urban mobility plan for Zhytomyr city	• Insufficient level of industrial facilities equipped with treatment equipment • Low level of implementation of measures to reduce noise pollution • Significant dominance of emissions from mobile sources of atmospheric air pollution • Absence of statistical information during the period of martial law • Outdated data on the number of atmospheric air pollution sources in the community territory • Insufficient number and low level of technical equipment of stationary air quality monitoring stations • Absence of a unified methodology for calculating greenhouse gas emissions • Absence of public transport priority • Low level of renewable energy technology implementation
Opportunities	**Threats**
• Stimulating the largest city polluters to modernize equipment, install additional treatment systems, and reduce atmospheric pollutant emissions • Reducing noise pollution through implementing measures for technical equipment modernization, screening, greening, etc. • Stimulating energy efficiency and resource conservation in production, housing, and communal services, promoting the use of alternative energy sources • Upgrading the public transport fleet to more energy- and environmentally-friendly vehicles • Increasing the number of stationary and mobile atmospheric air monitoring posts, expanding the list of indicators subject to control • Reducing air basin pollution through the implementation of a comprehensive traffic organization scheme	• Absence of automated emission control systems for atmospheric air at enterprises • Insufficient level of interaction between state regulatory authorities • Uncontrolled growth in the number of motor vehicles and other transport vehicles, including outdated ones • Insufficient effectiveness of economic levers for environmental management, leading to legislation violations • Absence of control over atmospheric air emissions from the private sector • Increasing morbidity rates of the local population due to anthropogenic environmental pollution, including noise load

First and foremost, this is the renewal of the public transport fleet with a transition to ecological models and the implementation of a comprehensive traffic organization scheme, which will reduce transport load on the city.

An important opportunity is expanding the air quality monitoring network, including mobile stations, which will increase the accuracy and coverage of control.

Main Threats

Among external threats, the most dangerous is the absence of automated emission control systems at enterprises, which creates significant risks regarding hidden or uncontrolled pollution. Also, critical remains the uncontrolled growth in private transport, especially under reduced regulation during martial law.

The SWOT analysis directly guided the definition of strategic goals in Section 9. Thus, SWOT in this study goes beyond a diagnostic tool: it operates as a decision-making matrix, linking local evidence with strategic priorities.

9. Strategic Goals and Objectives for Improving Atmospheric Air Quality in Zhytomyr MTC

The SWOT analysis of the environmental situation in the Zhytomyr municipal territorial community has enabled the identification of existing challenges and threats, and forming a system of strategic goals and specific objectives. These became the foundation for developing a roadmap for changes toward achieving qualitative atmospheric air protection transformations by 2050 (Figure 6).

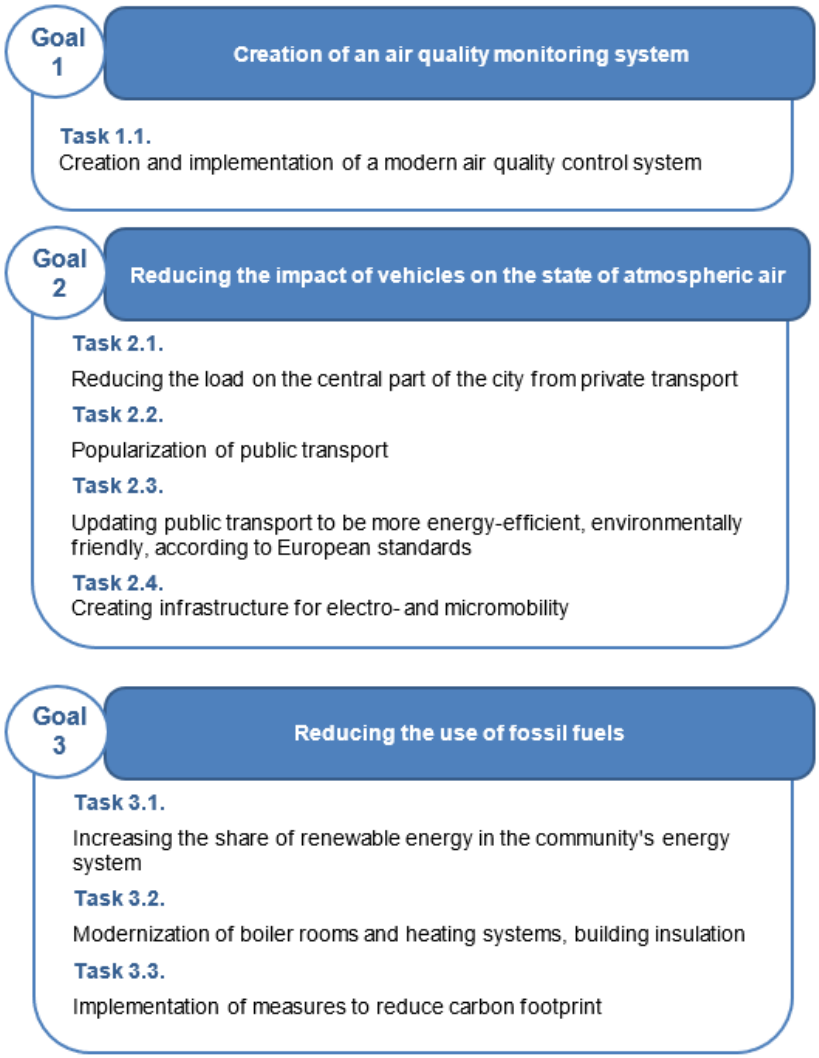

Figure 6. Strategic Goals and Objectives for Improving Atmospheric Air Quality in Zhytomyr MTC

Goal 1: Formation of a Modern Atmospheric Air Quality Monitoring System

One of the critical challenges identified during the analysis is the fragmentation and weak technical base of the existing monitoring system. The absence of complete and regular data collection on pollution levels makes operational air quality management impossible. In this regard, the primary objective is to create a modern, integrated, automated monitoring system.

The key task involves implementing an Automated Environmental Monitoring System for Atmospheric Air (AEMSA). This includes:

- modernization of existing observation stations,
- installation of new monitoring posts (eight in total),
- creation of a centralized geoinformation platform with open access,
- Implementation of a real-time air quality information system for the population.

The goal is directed at technical modernization and increasing transparency, communication, and public trust in the community's environmental policy.

Goal 2: Reducing Transport Impact on Atmospheric Air Quality

The transport sector is the largest source of air pollution in Zhytomyr MTC. Outdated public transport, low popularity of shared transportation, and infrastructure deficit for electric and micromobility necessitate comprehensive transportation system reform.

Main objectives within this goal:

- Reducing the central city area load from private transport through space redistribution in favor of public, pedestrian, and bicycle traffic.
- Popularizing public transport use through improving its convenience, regularity, and environmental friendliness.
- Updating the municipal transport fleet with modern energy-efficient models that comply with European emission standards.
- Creating conditions for electric and micromobility: developing bicycle infrastructure, charging station networks for electric vehicles, and conditions for using electric scooters and bicycles.

Successful implementation of this goal will not only reduce harmful emissions but also lower noise pollution levels, which is also important for public health.

Goal 3: Reducing Fossil Fuel Consumption and Decreasing Community Carbon Footprint

Fossil fuel use remains dominant in the community's energy supply system, leading to significant greenhouse gas emissions, particularly CO_2, and climate change intensification. The third strategic goal is aimed at transitioning to a low-carbon energy model.

Main objectives:

- Expanding the share of renewable energy sources (RES) in the community's energy balance. Development of solar, wind, and bioenergy is envisaged.
- Modernizing heat supply systems, including converting boiler houses to alternative fuel, improving building thermal insulation efficiency, and implementing low-temperature heating technologies.
- Reducing carbon footprint through changes in transport, energy, construction, and behavioral consumption patterns.

The goal is directed not only at environmental impact but also at enhancing the community's energy security, economic efficiency of consumption, and adaptation to climate change.

The proposed system of goals and objectives has a systematic and long-term character. It considers both local characteristics of the environmental situation in Zhytomyr and global challenges—climate change, urbanization load, and growing demand for energy resources. Its implementation will ensure sustainable environmental development of the community, strengthen population health, and create prerequisites for achieving carbon neutrality by 2050.

Target indicators were set to monitor progress for 2030, 2040, and 2050, enabling phased evaluation of achievements.

The Zhytomyr case demonstrates how a Ukrainian city can combine classical SWOT with elements of a logic model (input–output–impact chain) and policy impact assessment. This integrated approach can be a replicable model for other communities developing air quality strategies under limited resources and post-conflict constraints.

10. Conclusions

The conducted analysis of atmospheric air quality within the Zhytomyr municipal territorial community has revealed systemic environmental challenges related to high anthropogenic load, dominance of emissions from mobile sources, outdated monitoring infrastructure, and insufficient use of renewable energy. At the same time, the community demonstrates significant potential for transformation due to the availability of qualified personnel, active public engagement, and ongoing modernization initiatives [29].

The proposed strategy – built on creating a modern environmental monitoring system, reducing transport impact, and gradually decreasing fossil fuel use – is fully aligned with the UN Sustainable Development Goals. They are aimed at:

Improving population health through air quality enhancement (SDG 3),

Reducing the negative environmental footprint of the city and supporting a safe and sustainable urban environment (SDG 11),

Combating climate change through carbon emission reduction and strengthening the community's adaptive capacity (SDG 13).

However, successfully implementing the strategy will depend on overcoming considerable barriers. These include: lack of funding, limited wartime data, weak coordination between agencies, public acceptance, and behavioral change – reducing private car use and shifting to greener transport requires long-term incentives and infrastructure development.

Therefore, the proposed framework should not be seen as a guaranteed roadmap, but rather as a first step in a complex, iterative process of building a sustainable air quality management system. The strategy's value lies in integrating diverse data sources, aligning with national and EU policy, and providing a replicable model for other mid-sized Ukrainian cities.

By explicitly acknowledging both opportunities and constraints, the Zhytomyr case illustrates how local environmental governance can gradually evolve toward long-term sustainability while contributing to national climate change and public health protection commitments.

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