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EXPLORING THE POTENTIAL FOR AIR POLLUTION MITIGATION IN URBAN ENVIRONMENTS: A CASE STUDY OF VRANJE

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Abstract: *Air pollution in urban areas is becoming an increasingly significant issue, particularly during the winter season. This is primarily driven by higher energy demand for heating, combined with specific climatic conditions and urban settlement characteristics. Assessing the potential for reducing air pollutant emissions is therefore closely linked to energy planning processes. This paper presents the results of an integrated approach to planning the energy transition in the residential sector, with direct implications for air quality improvement. The approach is based on location-specific energy consumption patterns, whose transformation is guided by local stakeholders to develop a feasible and sustainable strategic plan, while also evaluating the achievable potential for air pollution mitigation.*

Keywords: *air pollution, households, heating, Vranje*

1. INTRODUCTION

Clean air, affordable and clean energy, good health and well-being, and sustainable cities and communities are among the United Nations Sustainable Development Goals that are strongly influenced by energy consumption patterns in cities and communities [1].

Urban air quality is determined by the complex interaction of natural processes and anthropogenic environmental influences. Natural factors, including meteorological conditions, topography, and seasonal variability, affect the dispersion, transformation, and removal of atmospheric pollutants. At the same time, human activities such as transportation, residential energy consumption, industrial production, and urban development represent the primary sources of air pollutant emissions in most cities [1]. Sustainable cities and communities require reducing the adverse environmental impacts associated with urbanization, with particular emphasis on improving air quality and enhancing municipal and other waste management systems [2, 3].

In modern society, human well-being and economic development rely heavily on a reliable, affordable, and sustainable energy supply. Ensuring universal access to clean, reliable, and affordable energy has become a key priority for achieving sustainable development and fostering resilient and low-carbon societies [4]. Securing an affordable and sustainable energy supply requires the implementation of comprehensive energy efficiency measures aimed at reducing overall energy demand while simultaneously increasing the share of renewable energy sources in the energy mix [4].

Meeting the aforementioned Sustainable Development Goals and reducing air pollution in cities and communities are directly connected to patterns of energy demand and supply. The transformation of energy systems, driven by the need to improve energy security, enhance energy efficiency, and reduce greenhouse gas and pollutant emissions, will inevitably influence air pollution levels, particularly in urban areas characterized by high population density and concentrated energy consumption.

Addressing the main sources of urban air pollution requires a particular focus on energy consumption in the transport and residential sectors, which represent significant contributors to pollutant emissions in cities [5]. However, practical experience demonstrates that achieving substantial and rapid changes in these sectors remains challenging, particularly in the short term. Unlike centralized energy systems, where technological and operational changes can often be implemented through coordinated decisions, energy consumption patterns in households and transport are determined by a large number of heterogeneous consumers with diverse needs, behaviors, economic conditions, and preferences [6]. A better understanding of consumer behavior and decision-making processes can be achieved through their active participation in the development of strategic planning documents. Involving consumers in energy planning processes enables the identification of their needs, preferences, constraints, and expectations, providing valuable insights into the factors that influence energy consumption patterns.

Households represent one of the largest final energy-consuming sectors, accounting for a substantial share of total final energy consumption worldwide. A significant proportion of household energy use, typically around two-thirds, is dedicated to space heating and cooling, making thermal comfort the dominant component of residential energy demand [7].

Household heating demands can be met either through centralized heat supply systems, such as district heating networks, or through decentralized, individual heating systems located at the point of consumption. Currently, most of the energy related to heating is relaying on fossil fuel consumption [7]. The main, and in many cases the only, renewable energy source used for residential heating is wooden biomass. Although biomass is generally considered a carbon-neutral energy source because the carbon dioxide released during combustion is theoretically balanced by the carbon absorbed during tree growth, its use can still result in significant environmental impacts. The combustion of wood biomass, particularly in small-scale residential heating systems with limited emission control technologies, is associated with the release of particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), and other harmful pollutants.

Evaluating the potential for reducing pollutant emissions in urban areas and establishing realistic and achievable emission reduction targets represent challenging tasks, particularly in cases where comprehensive energy balances at the city or municipal level are unavailable. This situation is common in the Western Balkan countries, where limited availability of detailed energy consumption data often represents a significant barrier to effective energy planning and the development of evidence-based environmental policies.

In order to overcame this gap, this paper presents an integrated energy planning approach which include participatory backcasting and expert based energy modeling, which can be utilized for determining energy related emissions and evaluation of the potential for air pollutant mitigation.

The proposed methodology is applied to the case study of the city of Vranje, with the aim of demonstrating its applicability for assessing urban energy systems, estimating emission reduction potentials, and supporting the development of sustainable energy and climate planning measures.

2. METHODOLOGY

The proposed methodology is based on an integrated energy planning approach that combines different tools and techniques for energy planning [8]. It integrates the development of expert-based models using appropriate software with a participatory backcasting approach, enabling the incorporation of stakeholders' knowledge, perspectives, and priorities into the planning process [9]. This combination

supports a more comprehensive assessment of future energy pathways while promoting active stakeholder engagement and informed decision-making.

In general, the methodology consists of the following main stages (Figure 1):

1. Analysis of the current state and assessment of annual pollutant emissions;
2. Identification and formulation of mitigation options and measures;
3. Development model of energy system and scenarios of energy development;
4. Evaluation of annual emissions under different scenarios;
5. Determination and assessment of the overall mitigation potential.

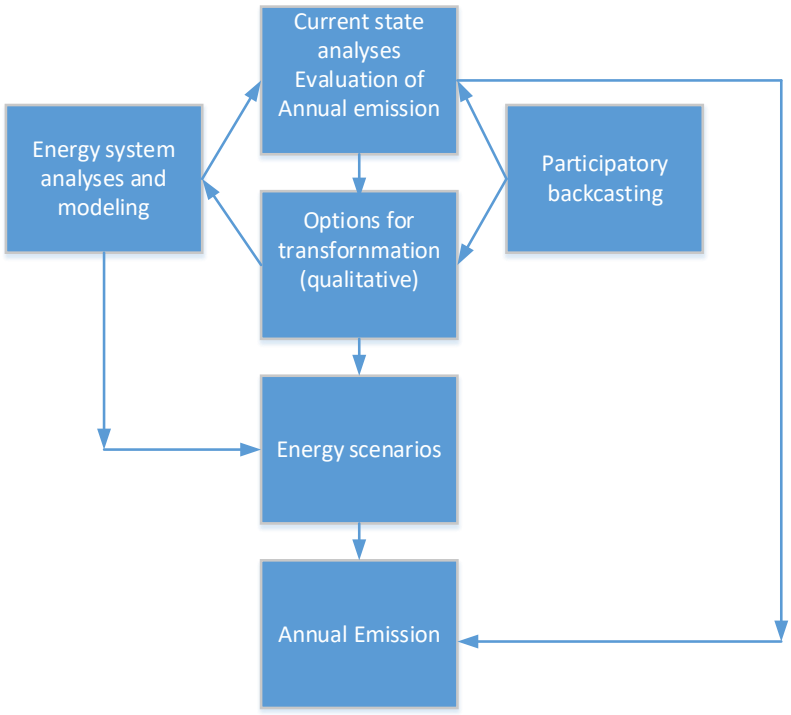


Figure 1. *Methodology for estimating potential for air pollution mitigation*

The current state analysis includes a comprehensive review of all available data related to energy consumption, such as energy balances, previous studies, surveys, census data, heated floor area, the evolution of the housing stock, and other relevant statistical information. These data are used to establish the baseline analyses for the selected base year and to characterize the current status of energy consumption.

The analysis provides information on the structure of heating systems, the fuel mix, the efficiency of heating appliances, useful energy intensity, and final energy consumption for space heating. The obtained results enable the identification of the strengths and weaknesses of the existing energy system and provide essential input data for the subsequent stages of the planning process, including the development and calibration of the energy model and the formulation of key issues to be addressed through the participatory backcasting process.

The participatory backcasting process aims to define a desirable long-term future by developing a shared vision formulated by relevant stakeholders. This vision formulation is typically qualitative in nature and reflects stakeholders' expectations, priorities, and development objectives. Since the desired future can be achieved through different development pathways, stakeholders formulate and discuss alternative pathways describing possible transitions from the current state toward the envisioned future.

The analysis of the qualitative outcomes from the backcasting process enables the identification of a range of mitigation options and measures. These options provide the basis for defining the assumptions used in scenario development within the energy modelling framework. The energy model is then applied to project future final energy consumption and changes in the energy mix over the analyzed planning period under different scenarios.

The outputs of the energy model are subsequently used to estimate annual emissions of air pollutants associated with each scenario. By comparing the environmental performance of alternative scenarios, the methodology quantifies their respective mitigation potentials.

Finally, the preferred mitigation pathway is selected by stakeholders through a multi-criteria evaluation process [9]. The assessment may consider criteria such as cost-effectiveness, security of energy supply, environmental benefits, technical feasibility, affordability, and other socio-economic aspects relevant to the decision-making process. This approach ensures that the selected scenario is not only environmentally effective but also technically feasible, economically justified, and socially acceptable.

The proposed methodology is applied and tested for the households heating system of the City of Vranje.

3. RESULTS AND DISCUSSION

Reliable data on the annual energy consumption for residential heating in the City of Vranje are not publicly available. However, establishing energy consumption in the base year is an essential prerequisite for energy planning and for the application of the proposed methodology. The baseline energy balance provides the reference point for describing and evaluating the current state of the energy system and serves as the foundation for assessing the impacts of future mitigation measures and transition pathways.

The 2022 Population and Housing Census conducted by the Statistical Office of the Republic of Serbia collected detailed information on the number and characteristics of dwellings, including the type of heating system and the primary fuel used for space heating. These data provide valuable information for reconstructing the existing residential heating structure. The distribution of dwellings in the City of Vranje that are not connected to the district heating network, classified according to the type of heating installation and fuel used, is presented in Tables 1 and 2.

Table 1. Number of dwellings with local central heating installations, [10]

	Total	Coal	Wood biomass	Residual fuel oil and heating oil	LPG/Natural gas	Electricity	Other	Unknown
Urban area	7591	94	6630	36	13	765	5	48
Other	1155	11	1127	1	-	12	-	4

Table 2. Number of dwellings without central heating installations, [10]

	Total	Coal	Wood biomass	Residual fuel oil and heating oil	LPG/Natural gas	Electricity	Other	Unknown
Urban area	9340	32	7899	4	30	1179	6	190
Other	4658	36	4474	-	2	36	1	109

According to the data published by the Serbian District Heating Association, 1,433 households in Vranje were connected to the district heating system during 2023 [11]. These data were combined with the results of the Population Census to establish the input dataset for the national energy system model developed in the LEAP (Low Emissions Analysis Platform) software.

Since detailed local information on the specific annual useful heat demand and the efficiency of heating technologies was not available, it was assumed that these parameters correspond to the average values estimated for the Republic of Serbia. Under this assumption, the residential heating energy balance for Vranje was reconstructed using the national LEAP model and subsequently adapted to local conditions. Based on the calibrated city-level model, the final energy consumption for residential space heating in the urban area of Vranje was estimated for the year 2023.The estimated final energy consumption for residential heating amounted to 17,747.2 tonnes of oil equivalent (toe) in 2023.

The results indicate that the residential heating sector in Vranje is strongly dominated by individual biomass-based heating systems. Approximately 57.1% of the total final energy consumption is associated with individual stoves using wood biomass, making this the predominant heating option. The second most significant category is individual central heating systems felled by wood biomass, accounting for 28.6% of total energy consumption. In contrast, only 4.5% of energy needed for heating are supplied from the district heating system, which is considerably below the national average for Serbia. This distribution reflects the limited penetration of centralized heating infrastructure and the high dependence on traditional biomass.

The structure of final energy consumption for heating by type of energy source used in the base year is shown in Figure 2.

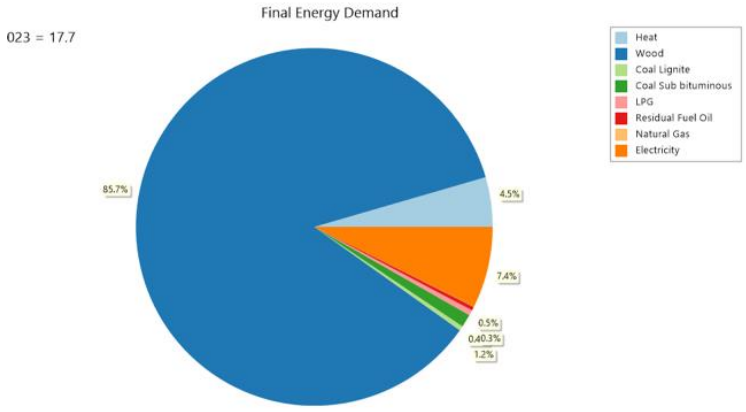
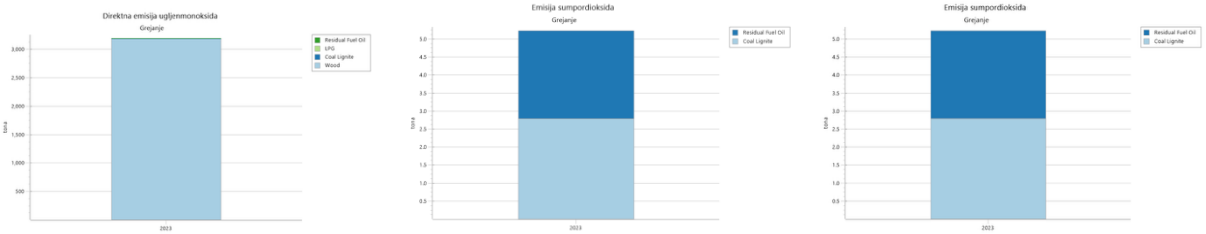


Figure 2. *The structure of final energy consumption for heating in the base year*

Based on the final energy consumption balance and the application of pollutant-specific emission factors, annual emissions of the main air pollutants associated with heating energy use were estimated. The assessment covers carbon monoxide (CO), nitrogen oxides (NO_x), and sulfur dioxide (SO_2), which are recognized as significant contributors to local air pollution and may adversely affect air quality, human health, and the environment.

The estimated annual emissions amount to 3,190.5 t of carbon monoxide (Figure 3a), 64.5 t of nitrogen oxides (Figure 3b), and 5.2 t of sulfur dioxide (Figure 3c). The results indicate that emissions of carbon monoxide and nitrogen oxides originate predominantly from the combustion of wood biomass reflecting its widespread use for residential heating. In contrast, sulfur dioxide emissions are primarily associated with the combustion of coal and petroleum products.

These findings highlight the strong influence of the fuel mix used for heating on local air pollutant emissions and emphasize the importance of transitioning toward cleaner heating technologies and lower-emission energy sources in order to improve local air quality.



a) CO b) NOx c) SO_2

Figure 3. *Structure of air pollutant emissions resulting from space heating.*

The transformation of the heating sector can be achieved through several development options. The main development options are proposed during the backcasting process and include include:

1. Reducing heating energy demand through energy efficiency improvements. This involves the energy renovation of residential buildings, including improvements to the thermal envelope, replacement of inefficient windows and doors.
2. Expanding district heating systems**.** Increasing the number of consumers connected to district heating networks can improve system efficiency and facilitate the integration of cleaner and renewable heat sources. Expansion of district heating infrastructure also enables the gradual replacement of individual heating systems, particularly those relying on solid fuels with high pollutant emissions.
3. Increasing the share and diversifying the use of renewable energy sources**.** This includes transitioning from combustion-based renewable fuels, such as biomass, toward non-combustion renewable heat technologies, including geothermal energy, large-scale heat pumps, and solar thermal systems.
4. Implementing demand-side management and innovative solutions. The introduction of smart energy management systems, thermal energy storage, digital monitoring and control etc.

Following the proposed methodology identified options are translated to energy scenarios which are developed in the LEAP modelling tool:

- Scenario 1- Exploring effects of energy efficiency improvement,
- Scenario 2- Exploring effects of energy efficiency improvement and diversification of renewable energy sources,
- Scenario 3-Exploring effects of expansion of district heating network,
- Scenario 4- Exploring effects of energy efficiency improvement, diversifying the use of renewable energy sources and expansion of district heating network,
- Scenario 5- Exploring effects of implementation of all proposed options,
- BAU-Reference scenario, representing effects of continuation of existing practice.

Scenario analysis provides a structured framework for evaluating the long-term consequences of different policy and technology pathways, allowing stakeholders to compare the effectiveness of proposed measures under various assumptions. This approach enables participants in stakeholder workshops to better understand the expected impacts of the proposed measures by translating qualitative assessments into quantitative results expressed through clearly defined indicators and measurable values.

A comparison of final energy consumption under the analyzed development scenarios is presented in Figure 4, while Figure 5 illustrates the projected consumption of wood fuels, which is identified as a main source of air pollution. Together, these results demonstrate how different combinations of energy efficiency measures, district heating expansion, and changes in the energy mix influence future heating demand and the structure of energy consumption, directly associated with pollutant emissions (Figure 6).

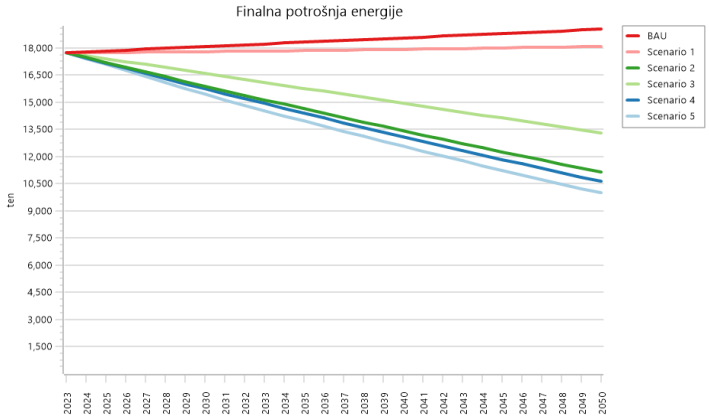


Figure 4. *Projections of final energy demand by scenario*

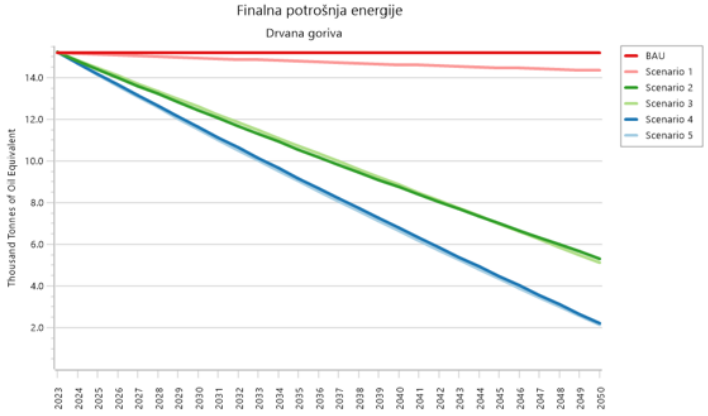


Figure 5. *Projections of final consumption of wood biomass by scenario*

The obtained results provide a basis for decision-making and the selection of the most suitable development option. The selection process is carried out within the backcasting framework and involves a broad range of stakeholders, ensuring that the preferred scenario reflects both technical feasibility and societal priorities. The evaluation is guided by a set of predefined criteria, which, within the proposed methodology, can be quantified and systematically assessed. This enables a transparent and objective comparison of alternative scenarios while supporting the identification of the most sustainable energy transition pathway.

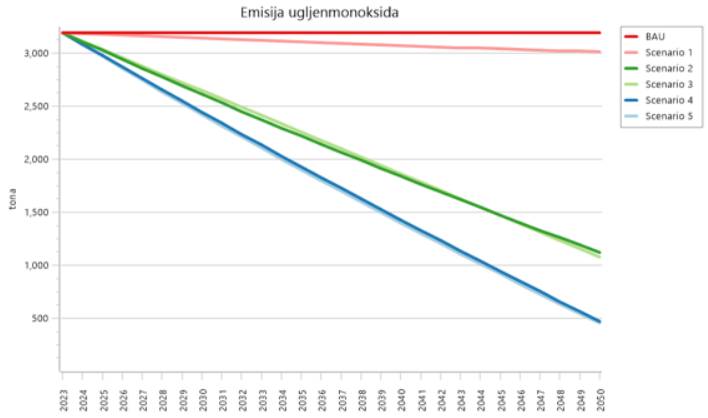


Figure 6. *Projections of carbon monoxide emission by scenario*

For the case study of the City of Vranje (Scenario 5), the projected emission reductions achieved through the implementation of the proposed measures are presented in Table 3. The results demonstrate the expected environmental benefits of the selected scenario and provide quantitative evidence of its contribution to reducing greenhouse gas emissions and conventional air pollutants from final energy consumption.

Table 3. *The expected annual emissions associated with the implementation of the selected scenario*

	2030	2035	2040	2045	2050
Annual GHG emissions from final energy consumption, t CO_2 eq	5015.8	3692.7	2535.6	1527.4	652.6
Annual CO emissions from final energy consumption, t CO	2234.4	1655.5	1149.1	707.6	324.3
Annual NO_x emissions from final energy consumption, t NO_x	45.2	33.5	23.2	14.3	6.5
Annual SO_2 emissions from final energy consumption, t SO_2	3.7	2.6	1.6	0.7	–

This reduction may be achieved only through a transformation of heating sector, both in the intensity of the demand and the structure technologies and energy sources (Figure 7).

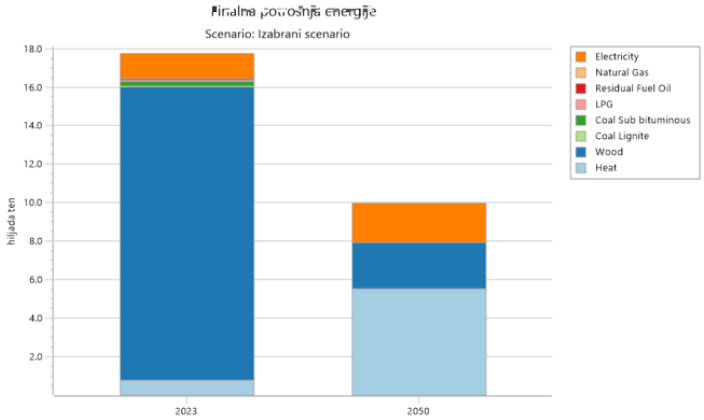


Figure 7. *Transformation of energy demand*

4. CONCLUSION

Reducing air pollution in urban environments has become an increasingly important challenge for sustainable development. Since air pollution is closely linked to emissions from the household and transport sectors, a carefully planned energy transition can play a key role in mitigating its impacts. This paper presents a methodology for assessing the potential for emission reductions under different development scenarios and assumptions. The proposed approach enables the evaluation of environmental benefits associated with alternative energy transition pathways while supporting informed decision-making.

Stakeholder involvement throughout the planning process is essential for ensuring the feasibility, acceptance, and long-term sustainability of the selected development option. The results presented in this paper provide a basis for the formulation of an action plan that should incorporate all relevant technical, economic, environmental, and social factors influencing the energy transition. Such a comprehensive approach can facilitate the implementation of effective measures aimed at reducing greenhouse gas emissions and improving urban air quality.

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