Integrated Energy Methodologies for Urban Ecological Transition

Transforming Kombinat into a Model of Renewable Energy Communities

DOI: 10.37199/o41011111

Karla CAVALLARI
PhD IDAUP / University of Ferrara

Abstract - *Kombinat, in Tirana, is an area historically shaped by the urban planning of the communist regime, centered around the old textile factory. Originally designed as an industrial community, the region reflects the vision of industrialization and urban expansion from the 1950s and 1960s. Today, its strategic location and diverse urban characteristics make it a promising site for sustainable redevelopment initiatives and energy transition projects.*

The methodology was defined based on criteria of urban relevance, availability of open geospatial datasets, and suitability for remote processing through Google Earth Engine (GEE). The analytical workflow followed six main steps: study area definition, conceptual framework, data search and validation, preprocessing, individual modeling of renewable sources, and integration of results. This structured process ensured transparency and reproducibility of the analysis. The research employed a methodology based on cartographic analyses and Geographic Information Systems (GIS) tools to study the urban, rural, and industrial fabrics of Kombinat. Land use, energy potential, and demand were mapped, considering the life cycle of materials and local energy reserves. Three primary fabrics were identified: the urban fabric, characterized by high density and energy consumption; the rural fabric, suitable for biomass generation; and the industrial fabric, optimal for solar energy and the recovery. Renewable Energy Communities (RECs) were proposed as an integrated solution, defined as citizen-driven associations that jointly produce, consume, and manage renewable energy, reinvesting benefits locally.

The analysis revealed that solar potential is high on rooftops and open surfaces, biomass can be derived from agricultural residues and organic waste, and small-scale hydro and wind have complementary though limited contributions. The results demonstrate that Kombinat has the capacity to host hybrid energy systems that link productive land use with conservation practices. By establishing RECs, the neighborhood can move towards energy self-sufficiency, environmental resilience, and local empowerment.

In conclusion, the study highlights that an integrated spatial methodology, combining open data, GIS tools, and participatory energy models, can transform Kombinat into a replicable example of urban ecological transition.

Keywords - Sustainable Redevelopment, Renewable Energy Communities (RECs), Urban Ecological Transition

Introduction

Global urbanization has intensified the challenges related to energy sustainability in cities. The dependence on fossil fuels, combined with population concentration and the disorderly expansion of urban centers, has pressured existing energy systems, requiring innovative and integrated solutions. In this context, the pursuit of energy self-sufficiency in urban territories emerges as a key strategy to promote resilience, reduce greenhouse gas emissions, and ensure equitable access to energy. The energy transition is not only a technological matter but also a question of social justice and territorial governance. In this sense, renewable energy is recognized as a key factor in promoting climate mitigation and local resilience (IRENA, 2020).

The transition to renewable energy sources in cities is not only a technological issue but also a territorial one. Understanding the specifics of each neighborhood, its social dynamics, land use, and existing infrastructure is essential to identifying opportunities and challenges in implementing sustainable energy systems. The integration of geospatial data and remote sensing tools has proven to be an effective approach to map and analyze the energy potential of urban areas, providing a holistic and detailed view of the territory. This approach is increasingly applied in the study of Renewable Energy Communities (RECs), which, according to the European Directive RED II (2018/2001), are legal entities where citizens, local authorities, and small enterprises jointly produce, consume, and manage renewable energy, ensuring that benefits remain in the community. Beyond energy generation, RECs embody a form of social innovation, strengthening energy justice and local empowerment.

The capital and largest city of Albania, Tirana, is home to about 33.5% of the national population, which totaled 2,761,785 inhabitants according to the latest census published by INSTAT in January 2023. Due to rapid population growth and accelerated urban expansion in recent decades, the city is now facing a scenario of intense congestion, particularly in the mobility of people and vehicles. Traffic jams have become increasingly frequent, raising the number of accidents, daily delays, and compromising the urban environment. The absence of a multimodal public transport system significantly worsens the situation, making urban mobility one of Tirana's most pressing challenges. Such dynamics illustrate the vulnerability of Albanian cities, while the European Environment Agency (2019) identifies transport and air pollution as critical factors for urban sustainability across Europe.

In this context, this study aims to contribute to the construction of a spatial analysis methodology that considers multiple criteria—morphological, functional, social, and environmental—in the formulation of a project approach coherent with the local urban and environmental structure. The goal is to investigate the potential for renewable energy production and the formation of RECs as a vector for energy self-sufficiency and the sustainable transformation of the Kombinat area in Tirana. The focus on RECs is particularly relevant in Albania, where energy transition policies remain centralized, and community-based initiatives could provide a decentralized and inclusive alternative. This methodology aims to provide technical and conceptual support for urban interventions that link territorial regeneration and energy innovation, based on geospatial data and urban decentralization strategies.

The Kombinat area holds undeniable symbolic and strategic value. Historically, this area is anchored by the old textile factory, built during the Albanian communist regime and named after Stalin. Located to the west of Tirana, the factory was not only an industrial production center but also the central piece of a satellite city designed to integrate work, housing, and social life for the working class. With the intensification of urbanization and the saturation of central Tirana, there is an urgent need to reconsider the role of peripheral neighborhoods like Kombinat in the metropolitan urban structure. Today, Tirana lacks an integrated territorial approach that considers the interactions between the city and its surroundings and the potential for functional decentralization. Kombinat was chosen as a case study precisely because of these characteristics: the coexistence of abandoned industrial infrastructures, surrounding agricultural land, and residential areas offers both challenges and opportunities for sustainable redevelopment. Its hybrid nature makes it an ideal site to test integrated models of energy transition and urban regeneration.

In this regard, the proposal to reconceptualize urban nodes around the center of Tirana presents itself as an effective strategy to redistribute urban flows, reduce congestion, and diversify development hubs.

The Kombinat area emerges as a natural candidate for this transformation. Its strategic location and the legacy of existing infrastructure provide both material and symbolic foundations for an urban reconfiguration focused on sustainability.

However, this transformation requires an approach that articulates spatial, energy, and social parameters. The reuse of built heritage, combined with the introduction of renewable energy production systems, can form a platform for urban regeneration with a focus on self-sufficiency. Such a project demands a critical understanding of urban morphology and local socioeconomic dynamics, considering current uses, rehabilitation possibilities, and integration with sustainable mobility systems.

This perspective resonates with the broader literature on urban regeneration and sustainability, which emphasizes the importance of linking energy innovation to territorial and social dynamics (Bertolini, 2022). By transforming Kombinat into a vibrant urban center, it is possible to activate an alternative model of metropolitan growth: less concentrated, more resilient, and environmentally responsible. The construction of a spatial analysis methodology that enables this transition is, therefore, a fundamental theoretical and practical contribution to the challenges of contemporary urbanization in Albania.

Methodology

The study area is the Kombinat neighborhood, located in the city of Tirana, Albania. The choice of this location is due to its industrial history, its strong potential for urban development, and its relevance as a representative space for contemporary urban transformations. Kombinat was selected instead of other possible zones in Tirana because of its hybrid character: the coexistence of abandoned industrial infrastructures, surrounding agricultural land, and residential areas creates a unique laboratory for testing integrated renewable energy solutions. Its symbolic value as a former socialist satellite city, combined with its strategic location on the western edge of Tirana, makes it a significant area to evaluate how Renewable Energy Communities (RECs) can activate post-industrial neighborhoods as drivers of the energy transition.

The territorial analysis process to assess the renewable energy generation potential in Kombinat began with the definition of the study area, which was delimited based on criteria of urban relevance and the availability of spatial data. Below is the workflow for this work.

Next, the conceptual framework of the research was established, identifying the main categories of analysis: energy resources, land use context, analysis of physical energy infrastructure, and social structure. Within this framework, each category is directly connected to energy planning: energy resources define natural and technological potentials; land use highlights synergies and conflicts between urban, agricultural, and ecological functions; infrastructure refers to the technical capacity for distribution and connectivity; and social structure emphasizes the potential for community governance, in line with the REC model.

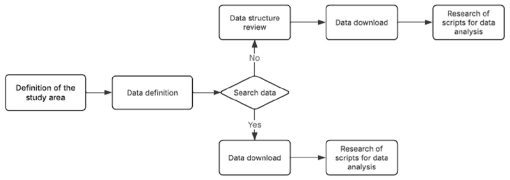


Fig 1/ : Workflow
source/ author (2025

With the structure defined, the data search phase began. The collection prioritized open, global-reaching datasets compatible with remote processing platforms, such as Google Earth Engine (GEE). Datasets used include Sentinel-2, ERA5-Land, Copernicus Land Monitoring Service, WorldPop, Global Wind Atlas, and MERIT Hydro. Institutional sources, such as the International Renewable Energy Agency (IRENA), the Institute of Statistics of Albania (INSTAT), and government platforms from the city of Tirana, were also consulted. During this phase, a meticulous curation process took place, validating the spatial resolution, temporal period, and coherence of the data with the analyzed territory. Some data required conversion or reprojection to ensure compatibility in the GEE environment. This phase revealed some challenges regarding official data sources from the Albanian government, with many datasets being absent, and in some cases, the primary available data source was the WMS service, which doesn't allow for extensive data manipulation. To ensure transparency and reproducibility, all datasets and processing steps were documented, and the scripts implemented in GEE are available in a GitHub repository.

Subsequently, the data preparation and analysis process began. First, the spatial data were reviewed and organized according to a hierarchical model that would facilitate the use of scripts in GEE. The logic of the scripts consisted of importing datasets, applying spatial masks (e.g., NDVI > 0.1 for biomass), reprojection, and raster algebra to calculate potentials per renewable source. Each script generated a standardized raster dataset in kWh, MWh, or feasibility classes, which were then compared with population and land-use layers.

Main Categories	Subcategories	Spatial Data Reference
1. Resources	Solar efficiency zones	Potential zones for solar energy investment
	Wind efficiency zones	Potential zones for wind energy investment
	Water resources	Potential surface water resources for hydropower generation
	Biomass	Potential areas for biomass energy generation
2.Land Use Context	Land cover	Residential and mixed-use areas
		Commercial areas
		Active/open green parking areas
		Public administration areas
		Social/cultural/educational/sports areas
3.Physical Energy Infrastructure Analysis	Energy infrastructure	Electric mobility/Heat Network infrastructure
	High/low voltage electricity grid and its area of impact	Existing EV chargers and their areas of impact
4.Social Structure	Population	Population density identified through spatial data
		Population projections for new development zones

Tab. 1. Categorie and subcategorie
source/ author (2025)

Regarding generation estimation, each renewable energy source was modeled individually. The solar potential was calculated from the annual sum of direct solar radiation (SSRD) from ERA5-Land, converted to kWh/m², and adjusted based on terrain slope and orientation, using data from the digital elevation model (SRTM). Expected productivity (PVOUT) was expressed in kWh/m²/year. The analysis also considered the total available surface for PV panel installation, distinguishing between rooftops, abandoned industrial sites, and open spaces. This enabled an estimation of the maximum deployable PV capacity in Kombinat.

For wind, the annual average wind speed data at 100 meters height from the Global Wind Atlas was projected over the study area and classified according to feasibility ranges. Wind speed analysis was conducted to evaluate whether microturbine implementation could complement other energy sources. The purpose of this analysis was therefore to test diversification scenarios rather than propose industrial-scale wind farms.

The biomass index was calculated from soil composition combined with the average annual NDVI derived from Sentinel-2, limited to values above 0.1 to exclude unproductive areas. This index was multiplied by an empirical factor to obtain biomass in tons per hectare per year and then converted into MWh. Real data from agricultural activity around Kombinat were also integrated, including crop residues, livestock manure, and organic waste volumes from municipal reports. These values allowed the modeling of biogas production potential, considering both energy output and environmental benefits such as waste reduction and circular economy practices.

The hydroelectric potential estimation considered two parameters: slope and drainage area (flow accumulation), both derived from MERIT-Hydro and SRTM. The normalized combination of these two indices generated a continuous raster, indicating higher suitability zones. The purpose of this analysis was not to propose large dams but to assess the feasibility of micro-hydropower systems in drainage channels and hillside streams. While Kombinat has hills rather than mountains, the modest slopes still provide opportunities for localized hydropower interventions.

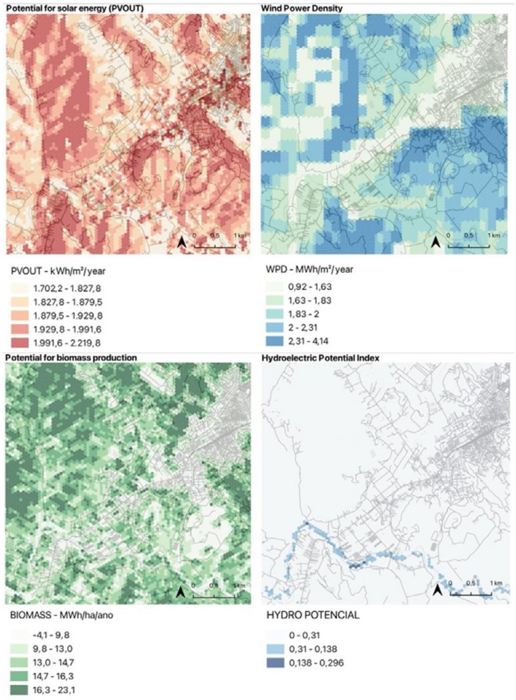


Fig 2/ : Energy production capacity
source/ author (2025

Residual thermal energy was addressed using data from the literature, considering urban consumption profiles and maps of industrial or densely built-up zones, as no specific publicly available raster was found.

For this, energy intensity values from European industrial case studies were applied to Kombinat's industrial building stock, providing an approximate baseline of waste heat recovery potential.

After running the scripts, it became clear that the Kombinat area has significant renewable energy production potential. Observing the scale of the study, it was noted that the mountainous areas have high energy production capacity, mainly due to their potential for wind and hydroelectric generation. However, considering the need to preserve the natural landscape and local biodiversity, intensive exploration of these areas is not recommended. Still, foothill areas offer a strategic opportunity for the development of distributed energy generation systems focused on local supply. Small-scale energy production integrated into the urban or peri-urban grid could directly meet the demand of nearby neighborhoods, promoting the re-signification of land use and encouraging decentralized and sustainable consumption models.

The land use data was analyzed in its original form, made available openly, ensuring a solid foundation for spatially evaluating the territorial dynamics of the studied region. Based on georeferenced information, it was possible to identify that areas around the Kombinat urban zone have significant agricultural production, which directly contributes to maintaining the quality of life for the local population by ensuring access to fresh food and strengthening the rural economy. This scenario highlights a productive territory with great potential for an energy transition based on renewable sources, particularly biomass. The utilization of agricultural and urban organic waste, such as crop residues, animal manure, and food waste, could be optimized through the installation of biogas production systems, contributing to thermal and electrical energy generation from local sources. Decentralizing this type of energy production would allow nearby agricultural communities to become not only self-sufficient but also energy providers for the local grid, promoting synergies between the agricultural and energy sectors. Furthermore, the detailed land cover analysis allowed for identifying areas that must be strictly preserved in future interventions such as native vegetation zones, urban green spaces, ecological corridors, and water recharge areas essential for ensuring the continuity of ecosystem services, biodiversity, and local climate balance. These areas also act as natural barriers against unchecked urban sprawl and should be considered strategic elements in sustainable territorial planning. On the other hand, the analysis also revealed land parcels with low occupancy, underutilized use, or in the process of abandonment, which could be strategically used for the implementation of renewable energy generation technologies.

Thus, the spatial analysis of land use not only reveals the current state of the territory but also illuminates a wide range of possibilities for sustainable energy development, integrated with local dynamics and adapted to the environmental and social reality of Kombinat. By linking productive land use with conservation practices and technological innovation, it is possible to create an energy model that is efficient, inclusive, and environmentally balanced.

For analyzing the energy infrastructure, open georeferenced data were also used, enabling a more accurate understanding of the spatial functioning of the existing infrastructure and its relation to the energy transition potentials in the territory. From these data, it was possible to evaluate different informational layers that make up the urban fabric of Kombinat, with particular attention to connectivity conditions, distribution of urban facilities, and structures supporting energy generation and distribution. First, a classification of building use was performed based on satellite images and cadastral data, allowing for the identification of the predominant function of each building type—whether residential, commercial, institutional, or industrial. This identification was crucial for pinpointing potential public infrastructure for energy distribution, for example.

Additionally, existing high-voltage power lines were mapped using open data from institutional platforms and collaborative networks, aiming to identify the main energy transmission axes within the territory. Proximity to these lines reduces infrastructure costs and increases the economic attractiveness of local generation projects.

The analysis of urban mobility infrastructure also played a key role in the territorial diagnosis. The strategic location of bus stops and high-traffic corridors can be leveraged for the installation of electric vehicle charging stations powered by renewable sources, promoting the decarbonization of urban mobility.

The cross-referencing of all these geospatial layers allowed for the development of an integrated approach that synergistically links the energy, urban, and social dimensions.

The comparative analysis between population data for 2020, 2025, and 2030 revealed trends in urban expansion and population density, especially at the urban fringe.

This dynamic, when correlated with local energy production data, highlighted imbalances between supply and demand and, above all, pointed out areas that, in the future, may face greater pressure on existing energy systems.

The energy demand mapping also served as a basis for spatially comparing the overlap between areas with higher consumption and areas with greater renewable generation potential, allowing for the identification of opportunities for implementing microgrids, renewable energy communities, and energy self-sufficiency systems. This approach strengthens the idea of decentralizing energy production, enhancing system resilience, and promoting energy justice, as it enables access to clean energy for communities that often face energy vulnerability.

Furthermore, the integration of population density data and land use revealed areas of conflict and synergy between energy production and urban, agricultural, or ecological activities. For example, regions with intensive agricultural activity and low population density were identified as ideal for biomass projects, while urban sectors with high density and good solar exposure were prioritized for residential or collective photovoltaic installations. Sloping areas with significant water flow but low occupation appeared as potential sites for small hydropower systems, provided that environmental and landscape criteria are respected.

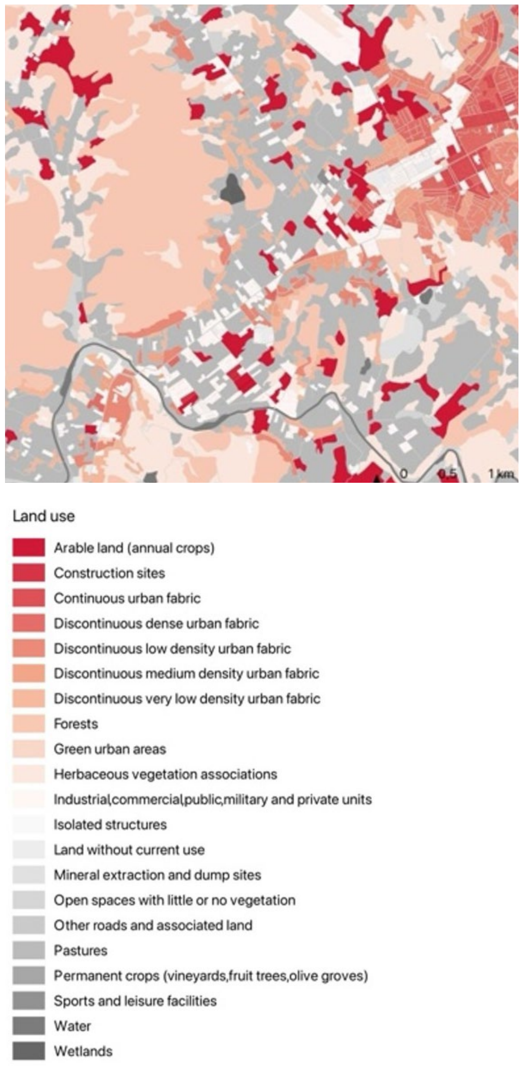


Fig 3/ : Land Use
source/ author (2025

Conclusions

Given the set of analyses conducted in this study, the relevance of integrating territorial and energy approaches to understand the possible paths toward energy self-sufficiency in urban neighborhoods, such as the case of Kombinat in the outskirts of Tirana, Albania, became evident. By utilizing a methodology based on geospatial data, remote sensing, and open information, it was possible to build a solid foundation to identify potential sites for renewable energy production and consumption, associating them with land use characteristics, infrastructure, and population dynamics.

The process began with the definition of the study area and the establishment of a work structure composed of six main steps: defining data and categories, data search, review and download, script research, and implementation in Google Earth Engine (GEE). This structure allowed for the systematization of the analyses and ensured the traceability of the decisions made throughout the research.

To estimate the solar potential, data on average horizontal radiation and the PVOUT index were used, which indicates the performance of photovoltaic generation per unit of installed capacity. The result revealed a broad feasibility for the use of solar panels, especially in built-up areas, rooftops, and shadow-free surfaces. Despite the limits imposed by urban density, the peripheral and elevated areas of the neighborhood show potential for exploitation, especially if aimed at self-consumption or small-scale installations. These findings are consistent with European case studies that highlight the role of urban photovoltaics as the most effective renewable technology in compact urban fabrics.

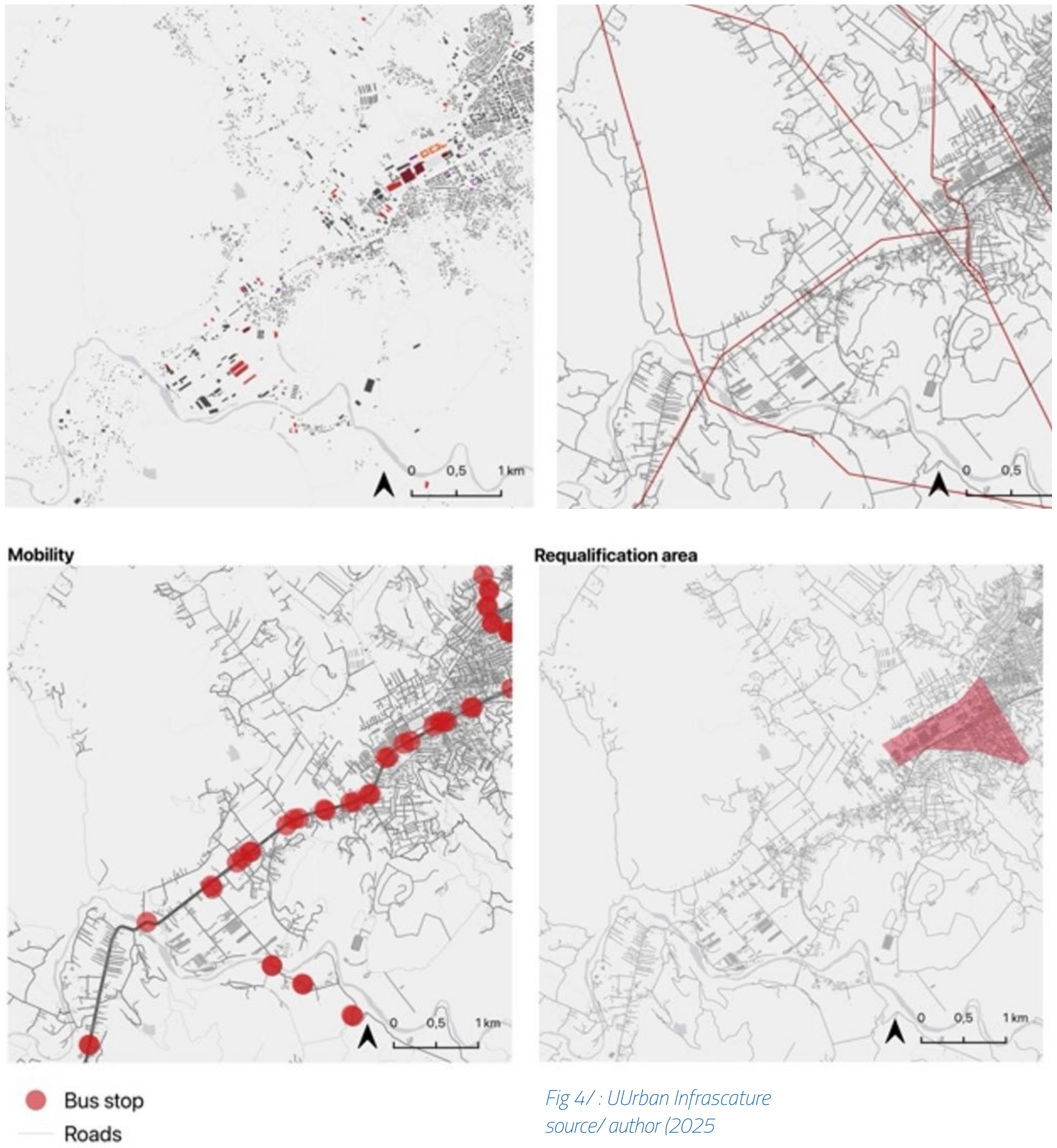


Fig 4/ : UUrban Infrascature
source/ author (2025

The biomass potential estimation was based on Sentinel-2 images, derived from the calculation of the annual average NDVI. In this study, the biomass index was strengthened by considering soil composition, which allowed for a more realistic estimation of productivity. The results indicated significant areas with relevant production, particularly in agricultural zones and green spaces near the urban perimeter, which could contribute to local energy supply through agricultural residues or community-based biodigestion projects.

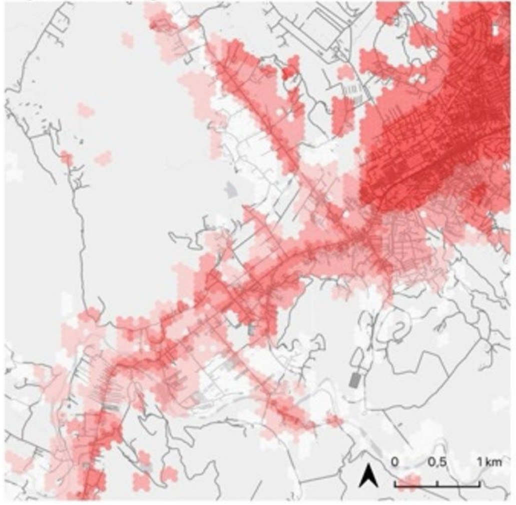
Hydropower was estimated based on two main factors: terrain slope and drainage area, obtained through MERIT Hydro data. Although urban scale limits this type of exploitation, the edges of the urban area and zones with existing hydrological infrastructure may benefit from small-scale systems. While modest in scale, micro-hydropower could contribute to diversification, echoing studies that recognize its role in hybrid energy systems in peri-urban areas (EEA, 2019).

Land use and land cover analysis played a central role in identifying the restrictions and opportunities for energy development. The reading of original land use, based on open data, highlighted the presence of agricultural zones around the urban fabric, which, in addition to their food function, reveal potential for biomass generation and solar panel installation. These areas should be considered strategic both for ensuring quality of life and for creating synergies with distributed energy systems. Furthermore, preservation areas and zones with dense vegetation were identified as sensitive regions, where any intervention should consider environmental and social impacts in order to preserve biodiversity and the local landscape.

Another important axis of the research was the analysis of existing energy and urban infrastructure. Georeferenced data were used to map high-voltage networks, transport infrastructure, buildings, and spaces in the process of degradation or with potential for revitalization. This critical reading allowed the identification of viable connection points, priority areas for intervention, and the possibility of incorporating energy solutions into future urban projects. The combination of low-density built-up areas and existing infrastructure creates unique opportunities to test local energy community models adapted to the specificities of the territory. The consideration of infrastructure also provides insights into potential synergies with urban mobility, such as the installation of EV charging stations powered by renewable energy, which is increasingly emphasized in sustainable city planning (EEA, 2019).

To understand energy demand, a population raster with a 1 km resolution was used, calibrated with official data from INSTAT (Albanian Institute of

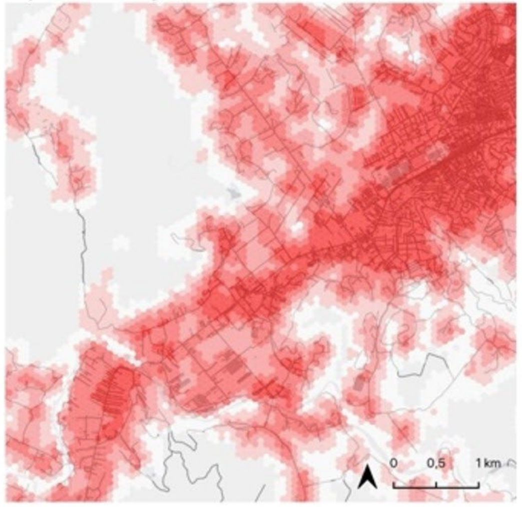
Population density 2020



2020 - hab/km²

3,5 - 5,2
5,2 - 8,9
8,9 - 15,1
15,1 - 39,4
39,4 - 141,4

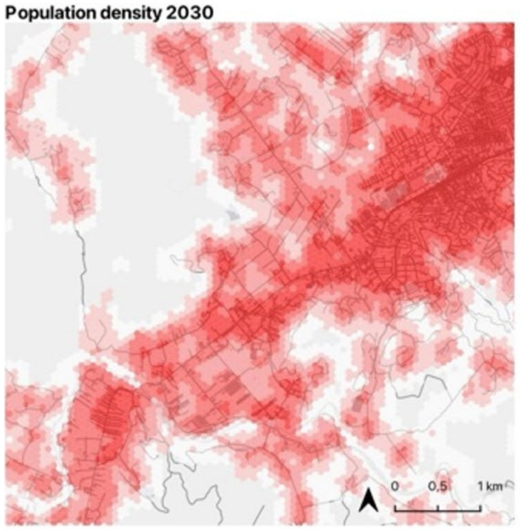
Population density 2025



2025 - hab/km²

0,01 - 0,87
0,87 - 2,39
2,39 - 5,2
5,2 - 17,12
17,12 - 124,1

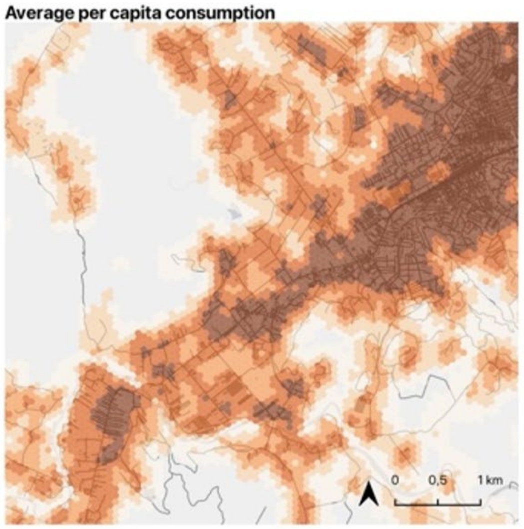
Population density 2030



2030 - hab/km²

0,01 - 0,96
0,96 - 2,65
2,65 - 5,39
5,39 - 17,81
17,81 - 126,82

Average per capita consumption



kWh/Km2/ano

25 - 2.400
2.400 - 6.625
2.625 - 13.475
13.475 - 44.525
44.525 - 317.050

Fig 5/ : Population density
source/ author (2025

Statistics). This calibration helped to improve the accuracy of estimates and provided a continuous reading of population density by pixel. Subsequently, energy demand was estimated based on average per capita annual household consumption, multiplied by population density. The result was a continuous raster representing the estimated energy demand by area, in kWh/year, which allowed direct cross-referencing with the previously mapped generation potentials.

Thus, it was possible to establish areas with greater imbalance between supply and demand, as well as identify areas with technical and environmental feasibility to meet their needs locally. This analytical model creates the conditions for decentralized energy planning, based on the proximity between production and consumption, reducing losses and increasing the resilience of the urban system.

One of the main findings of the research refers to the complementarity between renewable energy sources. While solar can serve dense and consolidated areas, biomass and wind energy find space in peripheral zones and transition areas. Hydropower, in turn, can be activated complementarily at strategic points. The combination of these sources allows the creation of hybrid systems adapted to local needs and capable of operating at different scales.

As a continuation of this research, a study is proposed to overlay the georeferenced layers analyzed, with the aim of identifying specific portions of the Kombinat neighborhood that meet the ideal conditions for the implementation of sustainable energy infrastructure, integrated with urban revitalization projects. This step will allow for a deeper planning of concrete actions in the territory, promoting solutions that simultaneously consider technical, environmental, and social aspects. The goal is to transform these areas into pilot hubs for local energy production and management, reinforcing local autonomy and promoting the energy transition as an integrated strategy for urban development.

In summary, this research reinforces the role of the territory as a central element in the construction of just, resilient, and sustainable energy solutions. The articulation between open data, geospatial tools, and urban planning offers a promising path for the transformation of cities, based on their singularities and potentialities. The case of Kombinat shows that even in peripheral and challenging contexts, it is possible to build viable, sustainable, and replicable alternatives when technical knowledge is combined with a commitment to collective well-being. Nevertheless, the study has some limitations, including the lack of detailed official datasets from Albania, reliance on open global datasets, and the absence of cost–benefit or policy impact analysis. Future research should address these limitations by integrating local measurements, socio-economic data, and governance frameworks. If replicated, the methodology could support not only Kombinat but also other post-industrial districts in the Balkans, positioning them as laboratories for the development of Renewable Energy Communities (RECs) and participatory energy governance.

References

BERTOLINI, Marina. Energy Efficiency in Urban Context: An Overview of European-Funded Projects with the Analysis of an ELENA Case Study. Sustainability 2022, 14, 10574. https://doi.org/10.3390/su141710574

EUROPEAN UNION. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources. Official Journal of the

EUROPEAN ENVIRONMENT AGENCY. The European environment – state and outlook 2020: knowledge for transition to a sustainable Europe. Copenhagen: EEA, 2019.
LEFEBVRE, Henri. A revolução Urbana. Belo Horizonte: UFMG, 1999. (LEFEBVRE, 1999)

LEFEBVRE, Henri.O direito à cidade. Tradução de Rubens Eduardo Frias. São Paulo: Centauro, 2001.

FRIEDMAN, Yona. Arquitetura da Sobrevivência. Barcelona: Gustavo Gili, 1978.

FABIAN, L.; GIANNOTTI, E.; VIGANÒ, P. (Eds.). Recycling City: Lifecycles, Embodied Energy, Inclusion. Pordenone: Giavedoni Editore, 2012. ISBN 978-88-98176-01-4.

IRENA. Renewable Energy Communities: Collective action for the energy transition. International Renewable Energy Agency, Abu Dhabi, 2020.

STREMKE, S. Designing Sustainable Energy Landscapes: Concepts, Principles, and Procedures. 2010. Thesis (PhD) – Wageningen University and Research, Wageningen, 2010.