Future Building Energy Atlas of Sofia City

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Abstract

This study develops a Future Building Energy Atlas (FBEA) for Sofia, Bulgaria, integrating land-use change modelling and spatial energy-demand assessment within a GIS framework. Future land-use patterns toward 2074 are simulated using a hybrid Artificial Neural Network–Cellular Automata (CA-ANN) model, while building energy consumption is estimated using cadastral data, gross floor area calculations, and energy coefficients derived from more than 2,500 certified buildings across ten functional categories under the medium-energy consumption. Future energy demand is projected based on historical trends observed between 2000 and 2020, during which building energy consumption increased steadily. The results indicate continued urban expansion primarily at the expense of cropland and forest areas. Cropland is projected to decline from 36.4 km² to 26.5 km², while forest areas are projected to decrease from 16.7 km² to 14.4 km² by 2074. At the same time, building energy demand increases significantly. The daily mean maximum energy consumption is projected to increase from 35.2 W/m² in 2024 to approximately 115 W/m² by 2074. These results highlight the strong relationship between urban growth, land-use transformation, and increasing energy demand in the building sector.

1. Introduction

Urban regions are undergoing continuous spatial transformation driven by demographic growth (Kroll and Kabisch, 2012), economic development (Wu et al., 2017), and infrastructure expansion (Tian et al., 2021). These processes alter land-use configurations and significantly influence patterns of building energy demand (Wang et al., 2022). Because buildings are among the largest contributors to urban energy consumption, the spatial evolution of cities directly affects long-term energy requirements, environmental performance, and climate resilience (Zinzi et al., 2018).

Existing research typically addresses land-use change (Velli et al., 2019) and building energy assessment (Swan and Ugursal, 2009) as separate domains. While land-use forecasting models provide insight into spatial growth trajectories (Reginster and Rounsevell, 2006), they rarely quantify associated energy implications (Qian et al., 2022). Conversely, energy mapping initiatives often describe present-day consumption without incorporating long-term or future urban transformation scenarios (Pereira and Assis, 2013). Integrated approaches that link spatial urban development remain limited, particularly in Southeast European cities (Csoknyai et al., 2016; Ürge-Vorsatz et al., 2015).

Sofia, Bulgaria's capital, exemplifies these dynamics, expanding beyond its historical core over recent decades. The city is generating heterogeneous urban forms that combine dense central districts with rapidly developing peripheral neighbourhoods and a dense traffic network (Vitanova et al., 2026, 2025). Such spatial diversity results in an uneven distribution of energy demand (Koleva et al., 2024), caused by functional building types (Vitanova et al., 2023), land-use intensity, urban morphology (Pavlov et al., 2025), and varying levels of walkability (Petrova-Antonova et al., 2025). Anticipated urbanisation toward the second half of the 21st century further raises questions about how future land-use transitions will change the city's energy profile and affect the local climate (Vitanova et al., 2021). However, predictive frameworks that integrate future land-use scenarios with building energy demand modelling remain underdeveloped, particularly in Bulgaria and Southeast European cities.

To address this gap, the present study develops a Future Building Energy Atlas (FBEA) for Sofia with a projection horizon of 2074. The framework combines improved historical land-use analysis, a hybrid Artificial Neural Network–Cellular Automata (CA-ANN) simulation of future land-use and land-cover (LULC) patterns and spatial estimation of building energy consumption based on cadastral attributes and the building's energy. By integrating geospatial modelling and energy assessment within a unified GIS environment, the paper proposes a methodology for projecting the spatial consequences of urban expansion on long-term energy demand.

The study is guided by the following research questions (RQ):

RQ1: Which are the main areas of urban growth expected in Sofia by 2074, and which existing land-use types are most likely to be converted into built-up areas?

RQ2: What is the spatial distribution of building energy demand across different functional building categories, and how does it vary between urban cores and peripheral zones?

RQ3: How can an FBEA support digital twin modelling, climate impact and greenery assessment, and strategic urban energy planning?

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The atlas extends beyond a static representation of consumption patterns. Instead, it provides a scenario-based analytical platform that supports long-term decision-making on sustainable development, climate adaptation, and energy system optimisation. The projected values could be further integrated into semantically enriched 3D city models, enabling advanced simulations of energy supply strategies, urban heat island (UHI) dynamics, and climate-resilient planning pathways.

The paper is structured as follows. Sections 2 and 3 outline the related work and the methodology used. The experimental results and discussion are described in Section 4. A conclusion is given in Section 5.

2. Related work

Previous studies have investigated the relationship between urban expansion, LULC change, and building energy demand using urban models and scenario-based energy assessments (Hashem and Balakrishnan, 2015; Karimi and Sultana, 2024). However, evidence suggests that the relationship between urban form, density, and building energy use is highly context-dependent and varies across cities (Mostafavi et al., 2021). Consequently, findings derived from one urban setting cannot be readily generalised to others without accounting for differences in local characteristics, such as urban morphology, climate, building stock, and socioeconomic conditions (Mostafavi et al., 2021).

Recent European initiatives have also emphasised the value of high-resolution spatial energy mapping. For example, the EU Energy Atlas estimates energy demand at a 1 × 1 km resolution by integrating national energy balances with land-use, demographic, and economic data (Energy and Industry Geography Lab, 2026). Although the atlas provides spatial continental-scale energy assessments, its estimates remain uncertain because it does not capture building-specific characteristics or occupant behaviour. Moreover, the 1 × 1 km resolution could be insufficient for building- or street-level analyses, and future projections are inherently dependent on climate scenario assumptions.

The proposed framework serves as an initial step towards integrating future urban growth with spatial energy demand assessment. The present study proposes a high-resolution (250 x 250 m) FBEA that integrates projected LULC changes with spatial building energy demand at the city scale. Rather than developing a detailed building stock model, the FBEA employs a representative reference cell together with observed historical energy consumption trends to estimate future building energy demand in newly urbanised areas. This simplified framework was adopted because detailed historical spatial datasets on building energy consumption, building typologies, and traffic energy use are currently unavailable for Sofia.

3. Methodology

This study integrates LULC and building energy assessment to develop a long-term urban energy outlook for Sofia with a 2070s horizon. The future LULC simulation process builds on the findings of (Pavlov et al., 2025). While retaining the core modelling logic, the present study extends the framework by enhancing its outputs and applying it to a different study area. Historical LULC data from the Corine Land Cover (CLC) (2018) are harmonised, reclassified, and standardised to ensure spatial consistency. Past land-use dynamics are analysed using correlation analysis and area-change detection. Future LULC development is simulated using a hybrid Cellular Automata (CA)-Artificial Neural Network (ANN) approach.

Building energy consumption is calculated using 2024 cadastral data (Geoportal of Geodesy, Cartography and Cadastre Agency, 2025). The energy estimates are derived from more than 2,500 representative buildings using official Energy Performance Certificates (Sustainable Energy Development Agency, 2024). Building energy consumption in 2074 is projected based on trends observed between 2000 and 2020, assuming continued growth (European Commission, 2024; Odyssee-Mure, 2022). More detailed information is available in Section 3.5.

3.1 Study Area

This research focuses on Sofia, the capital of Bulgaria (Figure 1). Over the past two decades, the city has experienced continuous demographic growth, with the population approaching 1.3 million residents by 2024, representing roughly 20% of the national population (World Population Review, 2024). Sofia is located in the Sofia Valley, a geographically distinct basin that accommodates both intensive urban development and agricultural activities in its peripheral zones.

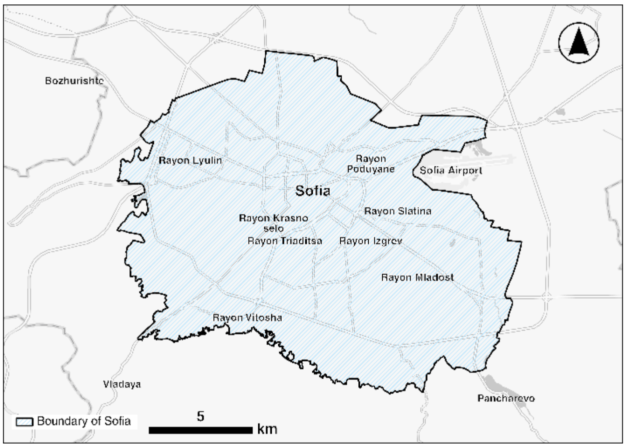

Figure 1. Study area.

The spatial heterogeneity of the study area, characterised by diverse land-use patterns, natural cover, elevation gradients, and uneven population distribution, provides a suitable setting for analysing long-term LULC dynamics and their implications.

In addition, the high concentration of residential, commercial, and public buildings makes Sofia a major centre of energy consumption, with building-related energy demand representing a significant share of the city's overall energy use. This combination of rapid urban growth, varied landscape structure, and substantial building energy consumption makes the region particularly appropriate for investigating the interaction between future land-use development and urban energy demand.

3.2 Data Collection

The study combines multi-temporal datasets with spatial predictors, including population density, road infrastructure, proximity to water, and topographic characteristics.

Historical land-use dynamics are primarily derived from CLC (1990–2018), provided as 100 m resolution raster data in EPSG:4326 and containing 48 thematic classes (Copernicus Land Monitoring Service, 2024a). Additional predictor variables are incorporated to support LULC transition modelling. Water

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bodies and wetness layers from Copernicus (100 m raster resolution, EPSG:4326) are used to derive proximity-to-water indicators (Copernicus Land Monitoring Service, 2024b). Population density data for 2018 are obtained from Google Earth Engine as 100 m raster data in EPSG:32634 (Schiavina M. et al., 2023). Road network information is sourced from TomTom Traffic Stats and classified into eight functional categories reflecting the transport hierarchy (TomTom, 2024). Topographic influence is represented using a 90 m resolution Digital Elevation Model (DEM), which serves as the basis for terrain analysis (Copernicus Land Monitoring Service, 2024b).

For the energy assessment, the study incorporates Sofia's 2024 cadastral database, which provides detailed information for 35 building types, including building footprints and the number of storeys (Geoportal of Geodesy, Cartography and Cadastre Agency, 2025). Based on these attributes, the GFA is calculated, and building types are consolidated into ten functional categories (residential, healthcare, cultural, administrative, hotels, services/restaurants, kindergartens, schools, universities, and sports facilities) to ensure consistency with the energy dataset.

Energy consumption estimates are derived from more than 2,500 representative buildings based on official Energy Performance Certificates (Sustainable Energy Development Agency, 2024). This integrated framework enables the spatial projection of future urban structure and associated building energy demand for the 2074 FBEA development.

3.3 Data preparation

Data preparation ensures that the datasets used are harmonised and of sufficient quality to feed into the simulation and analytical pipelines. Historical LULC data are first evaluated to identify classification inconsistencies, particularly within the CLC dataset. Detected inaccuracies are addressed during reclassification, and land-use categories are consolidated into five major classes: urban areas, cropland, forests, bare land, and water. Supporting predictor variables are transformed into spatial suitability layers. The road network is filtered to retain primary transport classes and converted into a raster-based proximity map. Water datasets are processed to isolate permanent water bodies and similarly transformed into proximity indicators. Population density data are incorporated in raster format without additional preprocessing. Elevation data are used to derive slope information, introducing terrain influence as an additional explanatory variable.

Finally, all raster layers are aligned to a common spatial extent and resolution (approximately 100 m) and reprojected to the WGS 84 / UTM Zone 34N coordinate system to ensure compatibility within the modelling framework.

Energy consumption data are derived from more than 2,500 representative buildings provided by (Sustainable Energy Development Agency, 2024). The estimation methodology follows established approaches previously developed within the framework of Sofia's energy atlas and related studies on semantic enrichment and urban building energy analysis (Koleva et al., 2024; Vitanova et al., 2023). In this study, a medium-energy consumption is used as the baseline for future analyses to facilitate the evaluation of climate change impacts (Vitanova et al., 2026).

3.4 Data analysis

This stage includes statistical and spatial analysis to better understand past land-use dynamics. After harmonising all datasets, the relationships among the predictive variables are correlated to identify potential interdependencies and their influence on LULC change patterns.

Long-term land-use dynamics are assessed using area-change analysis for the period 1990–2018, which provides the longest available consistent temporal coverage. Changes in the proportional extent of each of the five aggregated LULC classes are quantified, and transition matrices are generated to capture class-to-class conversions over time. The analysis is based on the CLC dataset, which provides extensive temporal coverage. Before simulating future land use, the model's predictive performance is validated.

Transition potential values generated by the ANN are used as input to the CA model to simulate a LULC map for the reference year (2018), which is then compared with the observed map. Model performance is assessed using overall accuracy and the Kappa coefficient, with thresholds set at >85% and >0.75, respectively. Spatial transition potentials (0–100) are also examined to interpret patterns of change likelihood and, if necessary, to refine model parameters. Simulations are performed in QGIS (QGIS Development Team, 2024) using the MOLUSCE plugin (NextGIS, 2024).

The CA algorithm is applied twice: first in the validation step and, if the validation results are satisfactory, to derive a simulation map of future LULC. The CA approach has been widely adopted in spatial modelling over the past two decades due to its ability to reproduce spatial diffusion processes, particularly when combined with remote sensing data (Ghosh et al., 2017). The algorithm simulates spatial transformations over time by utilising established transition rules and considering neighbourhood effects (Ghosh et al., 2017; Santé et al., 2010). The study area is a grid in which each cell's future state depends on its current state, the surrounding cells, and transition probabilities derived from historical data. The model updates the landscape through multiple iterations, capturing urban expansion, land conversions, and environmental shifts. A single iteration equals the time span between the LULC input years.

After LULC data processing, energy demand is assigned using a representative 250 × 250 m reference grid cell that reflects contemporary residential development patterns. The selected 250 m spatial resolution ensures consistency with the spatial requirements of planned urban climate simulations, facilitating its use in subsequent modelling applications. More information is provided in Section 4.1.

The building energy consumption within each grid cell is computed by aggregating contributions from individual building segments. Initially, buildings are spatially segmented using the GeoPandas *overlap operation* with the *intersection* method. For each resulting building segment within a grid cell, both the built-up area and the GFA are calculated.

Energy consumption at the segment level $E\ segment$ is derived using an energy coefficient a expressed as:

$$a = \frac{E\ building}{GFA\ building} \tag{1}$$

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where $E\ buildings$ denotes the total energy consumption of the building and $GFA\ building$ represents its GFA. The energy consumption assigned to each intersected building segment is then calculated as:

$$E\ segment = a \times GFA\ segment \quad (2)$$

where $GFA\ segment$ corresponds to the GFA of the building portion located within a given grid cell. Finally, energy consumption values are aggregated at the grid-cell level using the *groupby* function in Pandas, summing segment-level energy values to obtain total building energy consumption for each grid cell.

3.5 Development of the Future Building Energy Atlas (FBEA)

The FBEA is developed based on a framework for the year 2074, structured around two main components: (i) modelling of LULC and (ii) projection of long-term building energy demand.

First, the future land-use and land-cover (LULC) data were enhanced and applied to Sofia within its construction boundary (Figure 1). Within the boundary, 188 grid cells (each 250 × 250 m) are identified in which agricultural or green areas become urban land by 2074. For these cells, energy consumption in urban areas is estimated using a representative reference cell. This reference cell is in the Manastirski Livadi neighbourhood, one of the fastest-growing residential areas in Sofia. It was selected because it reflects recent intensive urban development, with newly built multi-family residential buildings and a typical medium-density urban structure. The selected cell has an average energy consumption of 11.6 Wh/m², which corresponds to the national residential average reported in previous studies (European Commission, 2024; Odyssee-Mure, 2022; Vitanova et al., 2025). The average building energy consumption calculated from this reference cell is then applied to all grid cells that are projected to undergo land-use change. In this way, the energy demand associated with future urban expansion in Sofia was estimated.

Second, a uniform increase in building energy consumption is applied to all grid cells in 2074, regardless of land-use change. This increase is based on historical trends observed between 2000 and 2020, during which building energy consumption grew by 2.75% in 2074 (European Commission, 2024; Odyssee-Mure, 2022). A key assumption for the energy estimate is that the growth rate will continue in the future. Under this hypothesis, energy consumption values for 2074 are calculated. Means the future case aligns with methodological consistency with observed historical data and is based on medium-energy consumption.

Note that, due to the lack of detailed historical datasets on building energy consumption by building typology and on traffic emissions, the model adopts a simplified approach based on historical trends. This ensures methodological consistency but does not account for variations in building types, demographic changes, or future energy efficiency improvements. These limitations are discussed in Section 5.2 and will be addressed in future work by incorporating land-use-specific energy demand, building typologies and climate scenarios.

4. Results and Discussion

This section introduces results on changes in LULC and building energy consumption for the present (2024) and future (2074) cases. Additionally, the climate-resilient and green mitigation strategies are considered based on the future expansion of Sofia City.

4.1 Land use change of Sofia City

Table 1 shows the statistical distribution of major land-use categories in Sofia for the present and future cases. The total study area remains constant at 209.0 km², allowing direct comparison of proportional changes over time.

Case	Urban (km²)	Forest (km²)	Cropland (km²)	Total (km²)
Present (2024)	155.9	16.7	36.4	209.0
Future (2074)	168.1	14.4	26.5	209.0

Table 1. LULC distribution inside Sofia for the present and future cases (km²).

The results indicate a clear expansion of urban land, increasing from 155.9 km² (74.6%) in the present to 168.1 km² (80.4%) in the future case. This growth occurs primarily at the expense of cropland and forest areas. Cropland decreases substantially from 36.4 km² (17.4%) to 26.5 km² (12.7%), while forest areas decline from 16.7 km² (7.9%) to 14.4 km² (6.9%).

These shifts reflect a continued urbanisation trend toward 2074, characterised by the conversion of agricultural and green areas into built-up land. The changes confirm the dominance of urban land use, with important implications for spatial planning, ecosystem services, and the intensification of future energy demand.

The results summarised in Table 1 are further illustrated in Figures 2 and 3. The comparison between the 2024 and 2074 LULC of Sofia shows a clear expansion of urban areas over the 50-year period. In 2024, urban land is concentrated in the city's central area, while the surrounding areas are dominated by cropland and mixed forest (Figure 2).

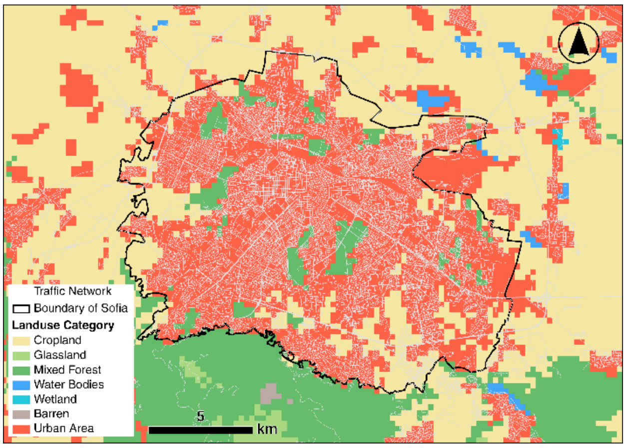

Figure 2. LULC in 2024 of Sofia City.

By 2074, urban land cover significantly increases and extends toward the peripheral zones, replacing parts of the agricultural land (Figure 3). At the same time, forested areas in the southern part of the region remain relatively stable, reflecting the preservation of mountainous and protected landscapes.

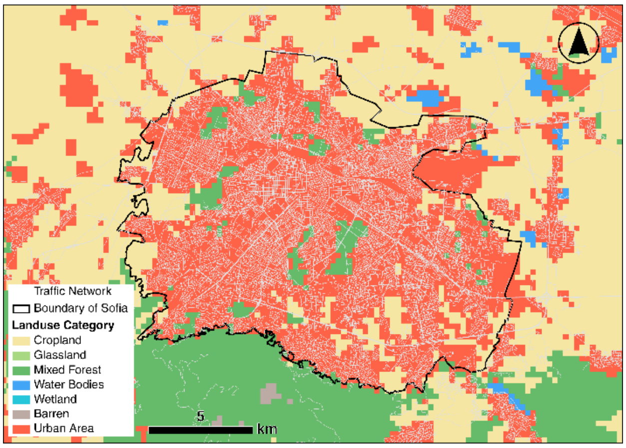

Figure 3. LULC in 2074 of Sofia City.

Overall, the results indicate substantial urban growth and spatial expansion of Sofia's built-up areas, potentially reflecting long-term urban growth pressures and land-transformation trends.

4.2 Statistical comparison of present and future energy conditions in Sofia City

Table 2 presents descriptive statistics of spatially distributed building energy consumption within Sofia for the present and future cases.

Note that in this study, a medium-energy consumption is used as the baseline, based on previous studies (Vitanova et al., 2026).

Statistic	**Present (2024),** W/m²	**Future (2074),** W/m²
Minimum	0.0	0.0
Maximum	35.2	115.8
Mean	2.3	8.2
Median	1.4	5.8

Table 2. Descriptive statistics of building energy consumption inside Sofia.

The results indicate a substantial increase in projected energy demand over the 50-year period. While minimum values remain at zero in both scenarios, reflecting non-built or very low-consumption grid cells, the maximum energy intensity rises from 35.2 W/m² in 2024 to 115.7 W/m² in 2074. Similarly, the mean value increases from 2.3 W/m² to 8.2 W/m², representing more than a threefold growth. The median shows a similar trend, rising from 1.4 W/m² to 5.8 W/m², suggesting that the increase is not limited to extreme values but also affects the overall spatial distribution.

These results reflect the combined impact of projected urban expansion and long-term growth in building energy consumption, resulting in intensified, spatially concentrated energy demand patterns within the city.

4.3 Present and future building energy atlas of Sofia City

In 2024 (Figure 4), building energy consumption is relatively low to moderate across most of the municipal territory (1–20 W/m2). Higher consumption values are primarily concentrated in the central urban core and several localised sub-centres, forming a clustered but spatially heterogeneous pattern (21–40 W/m²). Peripheral and mountainous areas display consistently low energy demand, reflecting lower building density and reduced anthropogenic activity. Overall, the spatial structure suggests a monocentric pattern with limited high-intensity hotspots.

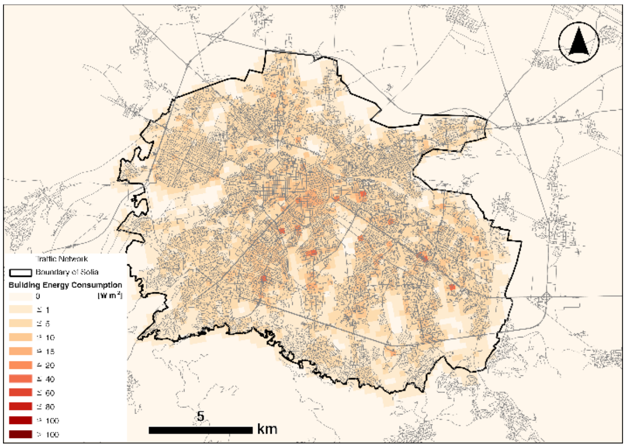

Figure 4. Present Building Energy Atlas (2024) of Sofia City.

The 2074 projection (Figure 5) indicates a clear intensification and spatial expansion of energy consumption across the urban territory (1–60 W/m^2). High-consumption zones become more pronounced and spatially extensive, particularly in the central area and along emerging development corridors (61–115 W/m^2). The number and magnitude of localised hotspots increase, suggesting both densification of existing built-up areas and outward urban expansion.

Compared with the present-day distribution, the future case shows greater spatial continuity in moderate-to-high energy consumption, indicating a shift toward a more polycentric, spatially integrated energy-demand structure.

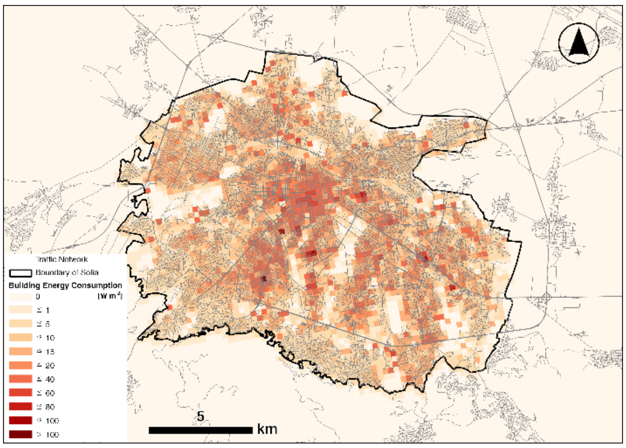

Figure 5. Future Building Energy Atlas (2074) of Sofia City.

Overall, the energy consumption changes reveal a substantial increase in building energy demand intensity and spatial coverage by 2074. The observed pattern reflects the combined effects of urban growth, increased building density, and potential changes in building typology and usage. The results suggest that future energy planning strategies will require spatially differentiated approaches, particularly in central and rapidly developing zones where demand intensification is most evident.

4.4 Urbanisation, energy demand growth, and environmental implications in Sofia

In rapidly urbanising cities, the expansion of built-up areas increases total energy consumption, particularly in the building sector, which accounts for a major share of global energy use (Hristov et al., 2026). Studies show that building density, urban form, and land-use patterns strongly influence building energy demand through factors such as solar exposure, ventilation, and urban microclimate conditions (Assenova et al., 2024; Shirinyan et al., 2025). According to the International Energy Agency, buildings account for nearly 30% of global final energy consumption, and urban growth, combined with increasing GFA, is a key driver of rising energy demand in cities (International Energy Agency, 2026). These findings indicate that the expansion of land use and building development in urban areas plays a critical role in increasing energy consumption and shaping urban residents' living conditions.

The findings are consistent with the FBEA results for Sofia, which indicate continued urban expansion and increasing building energy demand. Such land-use transformations may reduce vegetated surfaces and increase heat retention, potentially intensifying local UHI conditions and increasing the need for cooling energy in buildings (Skelhorn et al., 2016).

According to the FBEA results, the maximum values rise from 35.2 W/m² to approximately 115.8 W/m². Although the framework does not explicitly evaluate temperature changes or cooling loads, the substantial growth in energy demand and the spatial expansion of built-up areas suggest trends consistent with those observed in studies linking neighbourhood dynamics, UHI effects and increased cooling demand (Aghniaey and Lawrence, 2018; Subasinghe et al., 2022; Zhou and Chen, 2018).

Higher electricity demand often leads to increased emissions of pollutants, which contribute to smog formation, acid rain, and fine particulate pollution, which are associated with respiratory diseases, cardiovascular problems, and environmental damage (Abel et al., 2018). Exposure to such particles has been linked to cardiovascular diseases, respiratory illnesses, and premature mortality (Pope and Dockery, 2006). Among the most vulnerable groups are elderly people, children, and individuals with pre-existing health conditions, who have been shown to be particularly susceptible to these effects and to experience greater health risks following exposure to air pollutants (Sahu and Dutta, 2020). While the FBEA does not directly model pollutant emissions or health impacts, the projected increase in building energy demand and urban expansion indicates that similar environmental pressures could emerge if energy consumption continues to grow in Sofia.

Overall, the literature and the FBEA of Sofia highlight the strong interconnection among urban expansion, increasing building energy demand, and potential environmental and health impacts, emphasising the importance of integrating land-use planning and energy modelling to support sustainable urban development.

5. Conclusion and Future Work

This section presents the study's main conclusion, followed by its limitations and proposed future work.

5.1 Main Conclusions

This study developed an FBEA for Sofia by integrating land-use change and building energy demand within a GIS-based framework. The methodology combines historical LULC analysis, a hybrid ANN–CA model for predicting future land-use patterns and building energy estimation based on cadastral and energy-performance data.

The main results of the study can be summarised as follows:

- **Urban expansion:** Urban land within Sofia is projected to increase from 155.9 km² (74.6%) in 2024 to 168.1 km² (80.4%) in 2074, indicating continued urbanisation and outward spatial growth (RQ1).
- **Loss of agricultural and forest land**: The expansion of built-up areas occurs primarily at the expense of cropland and forest areas, with cropland decreasing from 36.4 km² to 26.5 km² and forest areas from 16.7 km² to 14.4 km² (RQ1).
- **Increase in building energy demand:** The future building energy consumption shows a significant rise, with the mean energy intensity increasing from 2.3 W/m² in 2024 to 8.2 W/m² in 2074, while the daily mean of maximum values increases from 35.2 W/m² to approximately 115 W/m² (RQ2). Note, this study uses a medium-energy consumption as the baseline for future analyses to facilitate the evaluation of climate change impacts
- **Spatial intensification of energy demand**: Future energy consumption patterns become more spatially extensive, with higher intensity zones emerging in central areas and along new urban development corridors (RQ2, RQ3).

5.2 Limitations and Future Work

Although the proposed framework integrates LULC simulation and spatial energy calculation into a unified FBEA, several limitations remain. The long-term projection toward 2074 is based on historical land-use transitions and assumes continuity of observed development patterns, which may not fully capture disruptive socio-economic, technological, or policy-driven changes. Assigning representative energy values to newly urbanised areas simplifies the range of possible building typologies and densities. In addition, the current assessment focuses primarily on operational building energy use and does not incorporate embodied energy, renewable generation potential, or detailed infrastructure constraints, traffic patterns, and electricity demand for charging e-vehicles, due to data limitations.

Future research should therefore expand the framework toward multi-scenario modelling, incorporating alternative urban development pathways, energy-efficiency trajectories, and climate change projections. Integrating the atlas with high-resolution climate datasets and semantically enriched 3D city models would enable advanced simulations of UHI dynamics, solar potential, retrofit strategies, and distributed energy systems within a digital twin environment. Further refinement at the building level, including socio-economic variables and energy supply network modelling, would enhance accuracy and policy relevance. Such developments would transform the FBEA into a comprehensive decision-support platform for climate-resilient and energy-aware urban planning.

Acknowledgements

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