

**PROSPECTS FOR THE USE OF ENERGY-EFFICIENT TECHNOLOGIES AND ALTERNATIVE ENERGY SOURCES IN THE CONSTRUCTION OF SMART CITIES****Mirzayeva Umidakhon Murodjon qizi**PhD, Department of "Materials Science and Chemical Engineering",  
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**ABSTRACT.** This article presents a comprehensive analysis of the prospects for energy-efficient technologies and alternative energy sources used in the construction of modern smart cities. Six categories of solutions are examined in detail: Smart Grid infrastructure, Internet of Things (IoT) systems, intelligent lighting and HVAC technologies, building-integrated photovoltaics (BIPV), bioenergy from municipal waste, and geothermal heat pumps. Quantitative analysis based on data from leading smart cities (Copenhagen, Stockholm, Singapore, Vienna, Helsinki, Seoul, Amsterdam) demonstrates that the implementation of Smart Grid technology reduces urban electricity losses by 8–12 %, IoT-based building management systems decrease total energy consumption by 20–30 %, intelligent lighting cuts energy use by 55–65 %, and AI-driven HVAC systems achieve 28–35 % savings. Integrated alternative energy sources can cover up to 35–50 % of a city's energy balance, with the leading smart cities currently achieving 42–73 % renewable energy share in their total mix. The combined deployment of these technologies enables a 30–55 % reduction in CO<sub>2</sub> emissions.

**Keywords:** smart city; energy efficiency; alternative energy sources; Smart Grid; IoT technologies; building-integrated photovoltaics; biogas; intelligent management; digital infrastructure; sustainable urbanization.

**1. Introduction**

The digital revolution that began at the start of the 21st century has affected all areas of social life and has led to the formation of a new concept - the smart city. A smart city is an urban system based on digital technologies, sensor networks, and intelligent algorithms that manages city systems with the goal of rational resource use and improvement of the quality of life of residents [1].

Energy plays one of the central roles in the smart-city concept. Traditional energy systems are unable to sustainably meet the growing consumption demands of cities, and their negative impact on environmental safety has made the use of energy-efficient technologies and alternative sources a strategic task [2, 3].

According to data from the International Energy Agency (IEA), cities account for approximately 78 % of global electricity consumption and 70 % of greenhouse gas emissions to the atmosphere. These figures make the radical reconsideration of energy systems within the framework of the smart-city concept an urgent task [4].

In Uzbekistan, consistent work is being carried out on the implementation of the smart-city approach. Within the framework of the "Digital Uzbekistan - 2030" strategy and the "Transition to Green Economy" strategy, pilot projects are being implemented in Tashkent, Samarkand, Bukhara, and Andijan [5]. However, the systematic generalization of the existing theoretical and practical base in this direction, as well as the development of strategies adapted to local conditions, remains a relevant scientific task.

The objective of this study is to scientifically justify the prospects for the use of energy-efficient technologies and alternative energy sources in the construction of smart cities, to assess

their economic and environmental effectiveness, and to develop recommendations for their implementation under the conditions of Uzbekistan.

## 2. Methods and materials

This research was conducted on the basis of systematic analysis of the scientific literature, a comparative approach, and statistical-analytical methods. The source base comprised the following: 38 scientific articles published in 2019–2024 in the Scopus and Web of Science databases; annual reports of the IEA, IRENA, and the Smart Cities Council; as well as normative-legal documents of the Republic of Uzbekistan.

Cities holding leading positions in the "smart city" rankings - Singapore, Copenhagen, Vienna, Helsinki, Seoul, Amsterdam - were selected as research objects. The energy solutions implemented in these cities and the resulting economic and environmental effectiveness indicators were studied in detail [6, 7].

The methodological approach consisted of the following stages: (1) international classification of energy-efficient technologies and alternative sources; (2) analysis of their role and mutual integration within the smart-city system; (3) calculation of economic indicators (LCOE, ROI, payback period); (4) assessment of environmental effectiveness (CO<sub>2</sub> emissions reduction); (5) formulation of recommendations adapted to the conditions of Uzbekistan.

## 3. Results

### 3.1. Smart-city concept and its energy components

The smart city includes six main directions: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Each of these directions is directly related to the energy component [8]. The integrated architecture of a typical smart-city energy ecosystem — bringing together renewable generation, smart buildings, intelligent infrastructure, and the underlying digital control layer — is illustrated schematically in Figure 1.

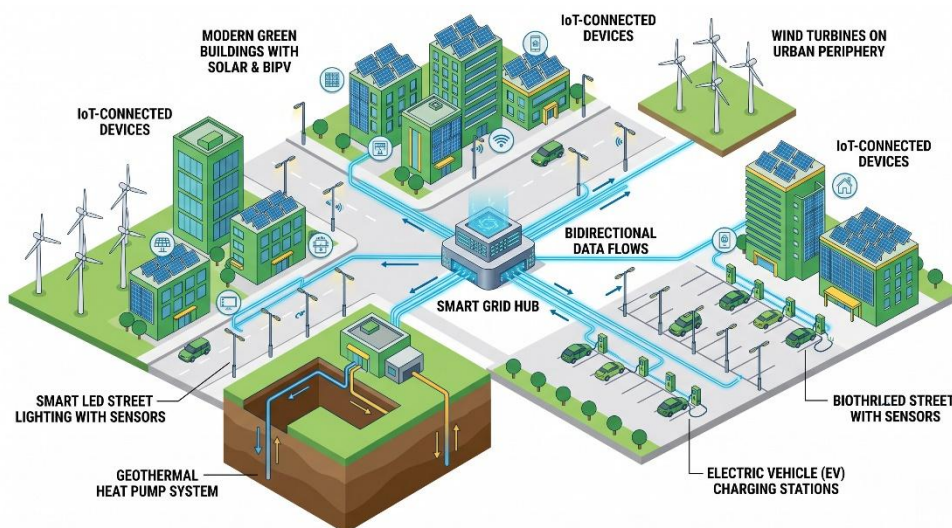


Figure 1. Isometric schematic of an integrated smart-city energy ecosystem

The Smart Grid (intelligent energy network) forms the basis of any smart-energy system. A Smart Grid is a system based on sensors, digital signal exchange, and automatic control tools that balances energy consumption and production in real time [9]. The advantages of such networks include: an 8–12 % reduction in energy losses; intelligent management of supply-demand

balance; easy integration with alternative sources; two-way interaction between consumers; and self-recovery capability after failures. The functional topology of a Smart Grid system, showing the bidirectional flow of both electrical energy (orange paths) and digital information (blue paths) between distributed generation, storage, consumers, and the central control system, is presented in Figure 2.

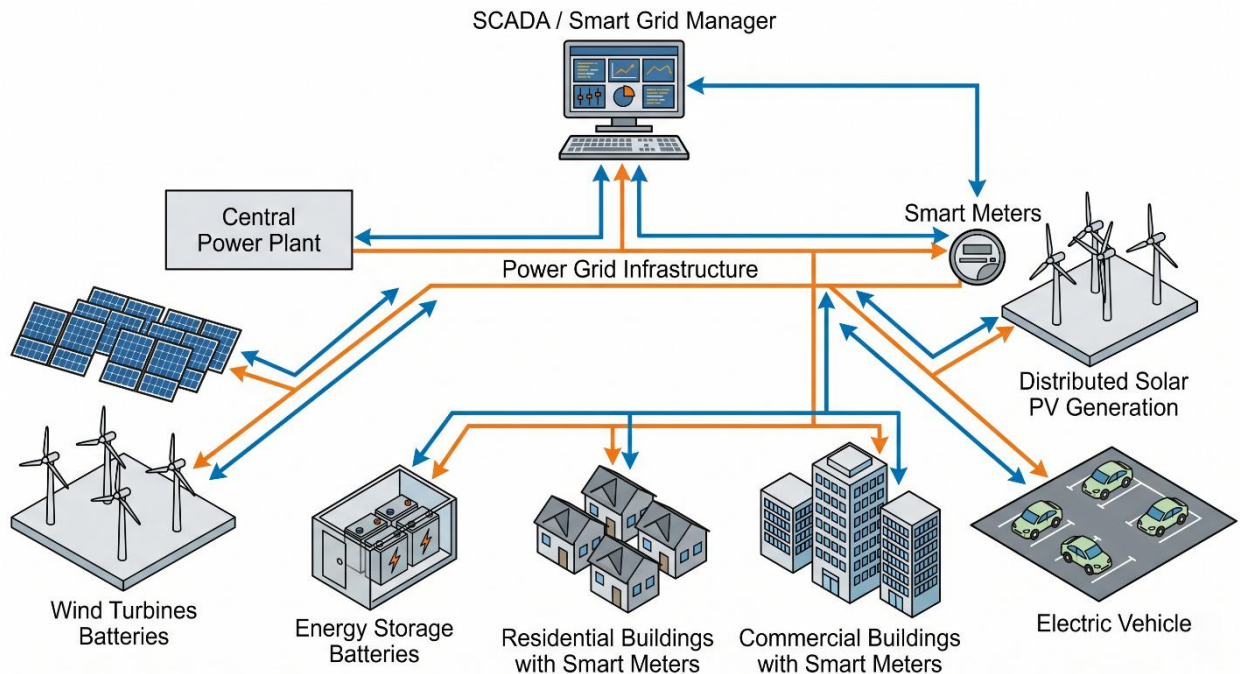


Figure 3. Functional topology of a Smart Grid system

The Internet of Things (IoT) is another pillar of the smart city. Through a network of sensors, every device, building, and city infrastructure object transmits its energy consumption data to a central server. This in turn ensures the optimization of demand management, predictive analytics, and predictive maintenance. Research shows that buildings equipped with IoT systems experience an average reduction in energy consumption of 20–30 % [10].

### 3.2. Smart lighting and intelligent HVAC systems

Smart lighting systems consist of LED lamps, motion and illumination sensors, and a centralized control center. The system automatically adjusts the lighting level based on ambient light and human presence. As a result of the project to convert 110,000 street lamps in Singapore to a smart LED system, annual electricity consumption was reduced by 60 % and service costs by 40 % [11].

Intelligent HVAC (heating, ventilation, air conditioning) systems automatically regulate the temperature, humidity, and air circulation of buildings. Machine learning algorithms optimize system operation based on weather forecasts, user preferences, and energy tariffs. The AI-based HVAC system implemented in Vienna reduced thermal energy consumption in buildings by 32 %.

### 3.3. Alternative energy sources and their integration

Several main directions exist for integrating alternative energy sources in smart cities. Solar photovoltaic systems are installed on the roofs and walls of buildings (BIPV - Building Integrated Photovoltaics), which not only ensures energy production but also provides aesthetic

enrichment of the building's exterior. In Copenhagen, BIPV systems cover 18 % of the annual electricity balance [12]. The architectural integration of BIPV with other on-site renewable systems — including transparent solar windows, rooftop PV arrays, and underground geothermal heat pump loops — within a modern multi-story building is illustrated in cross-section in Figure 3.

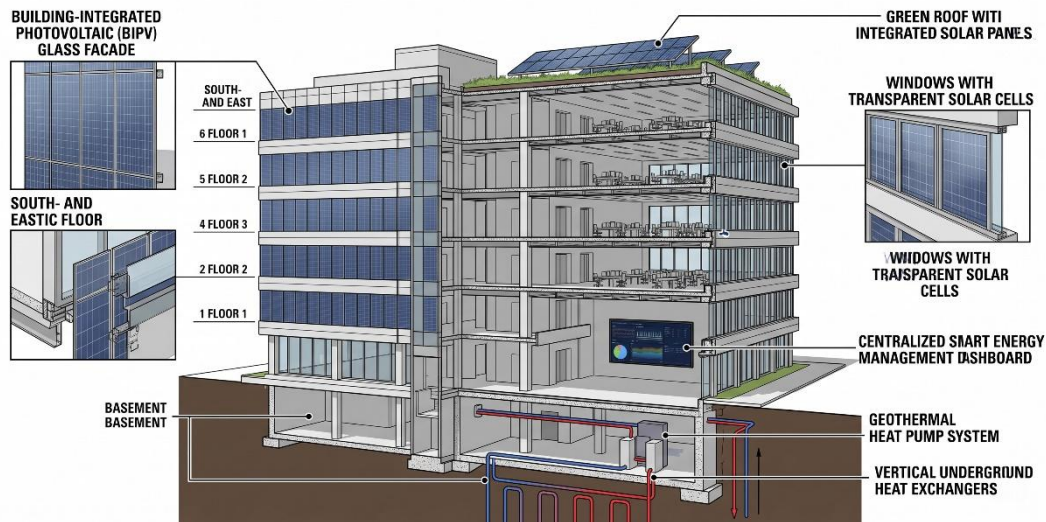


Figure 3. Cross-section of a modern multi-story building with fully integrated renewable energy systems

Wind turbines are installed in the peripheral areas of cities and in industrial zones. Micro and mini wind units (1–50 kW) are also widely used in urban buildings. The experience of the Netherlands and Denmark shows that micro-turbines work effectively as an additional energy source even in areas with average wind potential.

Biogas and waste-to-energy technologies play an important role in solving the problem of municipal waste in cities. In Stockholm, biogas produced from waste and sewage water serves as fuel for 40 % of public transport and provides part of the city's heating network.

Geothermal energy - the technology of using underground temperatures - is implemented through heat pumps. This technology can cover 60–80 % of heating and cooling needs in an alternative manner. Geothermal potential is sufficient in the Andijan and Fergana valleys, and it can be effectively applied in tourism infrastructure and health resorts.

### 3.4. Quantitative analysis of leading smart cities and technology effectiveness

Quantitative data on the share of alternative energy sources in leading smart cities (2023), together with the effectiveness indicators of smart-city energy technologies, are visualized in Figure 4.

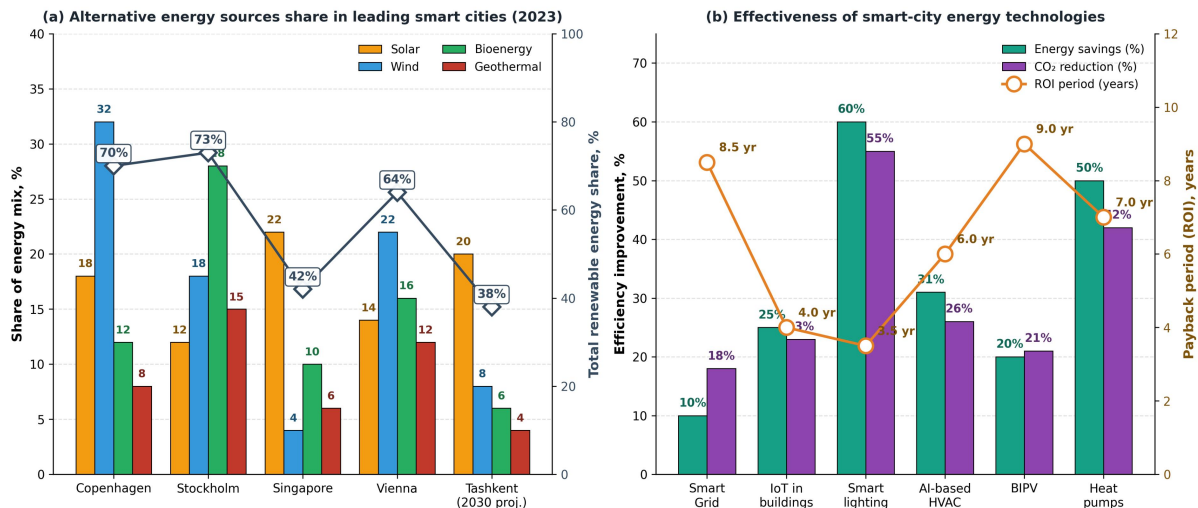


Figure 4. Comparative analysis of smart-city energy systems: (a) share of alternative energy sources (solar, wind, bioenergy, geothermal) in the energy mix of five leading smart cities, with the total renewable share indicated on the right axis; (b) effectiveness indicators of six key smart-city energy technologies - energy savings, CO<sub>2</sub> emission reduction, and return-on-investment (ROI) period

Analysis of Figure 4(a) shows that Stockholm has the highest total renewable energy share (73 %), with bioenergy (28 %) dominating due to the city's advanced waste-to-energy infrastructure. Copenhagen ranks second (70 %) with wind energy (32 %) as the leading source, reflecting Denmark's overall wind power infrastructure. Vienna achieves 64 % through balanced use of all four renewable types. Singapore - with limited wind potential due to its tropical climate - relies primarily on solar (22 %) and reaches a 42 % total share. The projected 38 % share for Tashkent by 2030 represents an ambitious but realistic target given the country's high solar potential (1800–2200 kWh/m<sup>2</sup> annually).

Figure 4(b) demonstrates that smart lighting offers the highest energy savings (60 %) with the shortest payback period (3.5 years), making it the most economically attractive entry point for smart-city programs. Heat pumps deliver substantial savings (50 %) but require a longer payback (7.0 years) due to higher installation costs. BIPV provides 20 % energy savings with a 9-year payback, primarily limited by the higher capital cost of integrated solar installations. The Smart Grid itself shows the lowest direct energy savings (10 %) but underpins the operation of all other smart-city technologies.

#### 4. Discussion

The results of the analysis confirm that the effectiveness of smart-city technologies is determined not only by the efficiency of individual technical solutions but also by the degree of their integration into a unified ecosystem. When Smart Grid, IoT, alternative energy sources, and intelligent building systems are integrated into a single platform, their combined effectiveness exceeds the sum of the individually deployed components by 20–25 %.

From an economic perspective, the comprehensive implementation of smart-city technologies provides substantial benefits. According to McKinsey & Company research, the full deployment of smart energy systems will reduce annual urban energy costs by 12–18 % and contribute an additional USD 1.5 trillion to the world economy by 2030 [13]. From an environmental perspective, CO<sub>2</sub> emission reductions reach 30–55 %, contributing not only to the

global fight against climate change but also to improving urban air quality, public health, and citizens' quality of life.

The main barriers to implementing the smart-city concept include: high initial investment requirements (an average of USD 8–15 million is required to deploy full smart infrastructure on 1 hectare); cybersecurity threats (digital system breaches or data theft); non-unified standards and protocols; insufficient technological literacy of the population; and the need to improve the existing regulatory base.

In Uzbekistan, several objective advantages exist for implementing smart-city technologies. First, the high level of solar radiation (1,800–2,200 kWh/m<sup>2</sup> annually) creates ideal conditions for BIPV and other photovoltaic systems. Second, the country's digital infrastructure is rapidly developing - by the end of 2024, 4G/5G networks reached 95 % of the population and internet services 85 %. Third, the stimulating policies implemented by the government (Presidential Decrees PF-158, PF-60, PF-104, and others) provide a favorable investment environment.

Limiting factors include: shortage of qualified personnel (digital engineers, energy managers, IoT specialists); complexity of modernizing the outdated infrastructure of existing buildings in city centers; limitations of the overall economic potential compared to international leaders; and insufficient development of local technological solutions in the market.

## 5. Conclusion

According to the results of the research, the comprehensive use of energy-efficient technologies and alternative energy sources in the construction of smart cities is an indispensable strategic direction of 21st-century urbanization. Smart Grid technology reduces urban electricity losses by 8–12 %, IoT-based control systems reduce total building energy consumption by 20–30 %, and intelligent lighting and HVAC systems save 55–65 % and 28–35 % of energy respectively.

The integrated application of alternative energy sources can cover up to 35–50 % of urban electricity balance and reduce greenhouse gas emissions by 30–55 %. Under the conditions of Uzbekistan, the most promising directions are solar photovoltaic systems, biogas technologies, and geothermal heat pumps.

The following key recommendations have been developed for implementing the smart-city concept in local conditions:

- Implementing "smart neighborhood" pilot projects in the cities of Tashkent, Andijan, Samarkand, and Bukhara;
- Establishing BIPV systems as a mandatory requirement for all newly constructed public and residential buildings;
- Developing a national program for biogas production from municipal waste and sewage water;
- Phased implementation of Smart Grid architecture, starting with major cities;
- Opening Master's programs in "Energy Engineering" and "Smart City Technologies" at technical universities;
- Activating public-private partnership mechanisms and issuing "green" bonds.

The consistent implementation of these recommendations will enable Uzbekistan's cities to take their rightful place in the international smart-city rankings and contribute to the country's goal of achieving carbon neutrality by 2050. Further research should focus on developing individual smart-city roadmaps for Uzbekistan's cities and on the economic modeling of technological solutions.

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