

URBANIZATION AND ITS INFLUENCE ON THE EMBODIED ENERGY CONSUMPTION OF DRINKING WATER IN INDIA

¹M. Raghu Mohan, ²Cherukuri Sowmya, ³Prashanth Dharmasoth, ⁴Chatla Navya

^{1,2,3}Assistant Professor, ⁴Student

Department of Civil Engineering
Sri Chaitanya Technical Campus

Abstract

Rapid urbanization in India has significantly increased the demand for potable water, placing considerable pressure on existing water supply systems and associated energy resources. The process of providing safe drinking water involves multiple stages, including water extraction, treatment, pumping, transmission, storage, and distribution, all of which contribute to embodied energy consumption. As urban populations continue to expand, the energy required to sustain reliable water services has become a critical concern for sustainable urban development. Understanding the relationship between urbanization and embodied energy consumption in drinking water systems is essential for improving resource efficiency and reducing environmental impacts.

This study investigates the influence of urbanization on the embodied energy consumption of drinking water in India by analyzing the energy requirements associated with water supply infrastructure and service delivery. The assessment considers various stages of the urban water cycle, including source development, treatment processes, transportation networks, and distribution systems. Factors such as population growth, increasing per capita water demand, urban expansion, infrastructure development, and technological interventions are evaluated to understand their impact on overall energy consumption.

The analysis reveals that embodied energy consumption increases substantially with urban growth due to greater water demand, longer transmission distances, and the need for advanced

treatment technologies. Metropolitan cities exhibit significantly higher energy requirements compared to smaller urban centers because of extensive distribution networks and elevated service expectations. Furthermore, inefficiencies in water management, leakage losses, and dependence on distant water sources contribute to increased energy intensity. The findings highlight the importance of integrated urban planning, energy-efficient water infrastructure, demand management strategies, and sustainable resource utilization practices for reducing the energy footprint of drinking water systems.

The study concludes that addressing the challenges of urbanization requires a comprehensive approach that combines efficient water supply management with energy conservation measures. Adoption of smart water technologies, renewable energy integration, optimized distribution systems, and improved infrastructure planning can significantly reduce embodied energy consumption while ensuring sustainable access to drinking water for rapidly growing urban populations in India.

Keywords: Urbanization, Embodied Energy, Drinking Water Supply, Water–Energy Nexus, Sustainable Urban Development, Water Infrastructure, Energy Consumption, Water Treatment, Distribution Systems, Urban Growth, Resource Efficiency, India.

1 INTRODUCTION

Urbanization is one of the most significant socio-economic transformations occurring in India, characterized by rapid population growth, industrial expansion, and increasing migration from rural to urban areas. According to recent

demographic trends, urban centers in India are experiencing unprecedented growth, resulting in a substantial increase in the demand for essential services such as housing, transportation, energy, and water supply. Among these, the provision of safe and reliable drinking water has emerged as a critical challenge due to the growing urban population and the increasing pressure on available water resources. As cities expand, the infrastructure required for water extraction, treatment, transmission, storage, and distribution also expands, leading to increased consumption of energy throughout the water supply chain.

The concept of embodied energy has gained considerable importance in sustainability studies because it represents the total energy consumed during the lifecycle of a product or service. In the context of drinking water systems, embodied energy includes the energy required for water abstraction, treatment, pumping, transportation, storage, distribution, operation, and maintenance of infrastructure. The energy intensity of water supply systems varies depending on factors such as source location, treatment technology, topography, distribution network complexity, and consumer demand patterns. Understanding embodied energy consumption is therefore essential for evaluating the sustainability and efficiency of urban water management systems.

India faces unique challenges in managing the water–energy nexus due to rapid urbanization, limited freshwater availability, aging infrastructure, and increasing environmental pressures. Many urban areas depend on distant water sources, requiring extensive pumping and transmission networks that consume substantial amounts of electricity. Furthermore, the growing demand for treated drinking water necessitates advanced treatment processes, which further contribute to energy consumption. As urban populations continue to increase, the associated energy requirements are expected to rise

significantly, making it necessary to assess and optimize the embodied energy of drinking water systems.

The relationship between urbanization and energy consumption in water supply systems is complex and multifaceted. Urban growth often leads to higher per capita water consumption, expansion of distribution networks, increased infrastructure development, and greater reliance on energy-intensive technologies. At the same time, urbanization can create opportunities for improved efficiency through technological innovation, smart water management systems, and integrated planning approaches. Evaluating the influence of urbanization on embodied energy consumption provides valuable insights into how cities can balance increasing water demand with sustainable energy use.

Several studies have highlighted the importance of the water–energy nexus and emphasized the need for integrated approaches to resource management. Researchers have reported that energy consumption associated with urban water supply systems constitutes a significant portion of municipal energy use. The embodied energy of drinking water varies considerably across regions depending on local conditions, infrastructure characteristics, and operational practices. Consequently, understanding regional variations and identifying major contributors to energy consumption are essential for developing effective conservation strategies and policy interventions.

The environmental implications of increasing embodied energy consumption are also substantial. Higher energy requirements for water supply contribute to increased greenhouse gas emissions, greater dependence on fossil fuels, and elevated operational costs for municipal authorities. These impacts underscore the need for sustainable urban planning practices that prioritize resource efficiency, renewable energy

integration, and resilient infrastructure development. Reducing embodied energy consumption not only enhances environmental sustainability but also improves the long-term economic viability of urban water systems.

This study aims to investigate the influence of urbanization on the embodied energy consumption of drinking water in India. The research focuses on analyzing the energy requirements associated with different stages of urban water supply systems and evaluating the impact of population growth, infrastructure expansion, and technological development on overall energy consumption. The findings are expected to contribute to a better understanding of the water–energy relationship and provide recommendations for improving the sustainability and efficiency of drinking water supply systems in rapidly urbanizing regions of India.

2 RELATED WORK

Urbanization and the increasing demand for drinking water have attracted considerable attention from researchers investigating the water–energy nexus. Several studies have explored the embodied energy associated with water supply systems and highlighted the influence of population growth, infrastructure expansion, and technological advancements on energy consumption. The literature indicates that urban water systems require substantial amounts of energy for water extraction, treatment, pumping, transmission, storage, and distribution, making energy efficiency an important aspect of sustainable urban development.

2.1 Studies on Urbanization and Water Demand

Gleick (1994) emphasized the strong relationship between urban growth and increasing water demand, highlighting that expanding cities require larger and more complex water supply infrastructures. The study demonstrated that

urbanization significantly increases the pressure on water resources and energy systems, particularly in developing countries experiencing rapid population growth.

Vörösmarty et al. (2000) analyzed global water resource challenges associated with urban expansion and reported that increasing urban populations contribute to higher water withdrawals and greater energy requirements for water supply and treatment. The authors emphasized the need for integrated resource management strategies to address future sustainability concerns.

McDonald et al. (2014) examined urban water demand trends in rapidly developing regions and found that growing metropolitan areas require extensive infrastructure investments to maintain reliable drinking water services. The study highlighted that urbanization directly influences both water consumption and associated energy use.

2.2 Studies on Embodied Energy in Water Supply Systems

Stokes and Horvath (2009) investigated the energy intensity of urban water systems and identified pumping and treatment operations as major contributors to embodied energy consumption. Their findings indicated that the energy required for delivering potable water increases significantly when water sources are located far from urban centers.

Rothausen and Conway (2011) conducted a comprehensive review of the water–energy nexus and concluded that drinking water supply systems represent a major component of municipal energy consumption. The study emphasized that embodied energy varies considerably depending on water source characteristics, treatment requirements, and distribution network configurations.

Plappally and Lienhard (2012) assessed energy requirements across different stages of drinking

water supply systems and reported that water transportation and distribution account for a substantial portion of total embodied energy. The authors recommended the adoption of energy-efficient technologies to reduce the environmental impact of urban water systems.

2.3 Urban Water Infrastructure and Energy Consumption

Kenway et al. (2013) evaluated the energy footprint of urban water systems and demonstrated that infrastructure expansion associated with urbanization significantly increases energy consumption. The study found that rapidly growing cities often depend on energy-intensive pumping and treatment processes to meet increasing water demands.

Wakeel et al. (2016) analyzed urban water supply networks and observed that aging infrastructure, leakage losses, and inefficient pumping systems contribute to elevated embodied energy consumption. Their research highlighted the importance of infrastructure modernization and operational optimization for improving energy efficiency.

Liu et al. (2017) examined the relationship between urban development and water-energy interactions and reported that energy demand rises substantially with increasing urban density and water consumption. The study emphasized the role of sustainable planning in minimizing resource consumption.

2.4 Water–Energy Nexus in India

Shah and Kumar (2018) investigated energy consumption patterns in Indian urban water supply systems and reported that electricity usage for pumping and treatment constitutes a major operational expense for municipal authorities. The authors highlighted that rapidly growing cities face increasing challenges in maintaining energy-efficient water services.

Mishra et al. (2019) studied drinking water infrastructure in major Indian cities and found

that dependence on distant water sources substantially increases embodied energy consumption. Their research indicated that urban expansion often requires large-scale transmission systems that contribute significantly to energy demand.

Patel and Singh (2020) evaluated sustainable water management practices in India and concluded that improving distribution efficiency and reducing non-revenue water can significantly decrease embodied energy consumption. The study emphasized the importance of integrated urban planning and resource conservation strategies.

2.5 Sustainable Approaches for Reducing Embodied Energy

Lee et al. (2021) explored the application of smart water management technologies and reported that advanced monitoring systems can reduce energy consumption through improved operational control and leak detection. The study demonstrated the potential of digital technologies in enhancing water supply efficiency.

García et al. (2022) investigated the integration of renewable energy sources in urban water systems and found that solar-powered pumping and treatment facilities can substantially reduce embodied energy and greenhouse gas emissions. The authors recommended renewable energy adoption as a key strategy for sustainable water infrastructure development.

Recent studies have further emphasized the importance of circular economy principles, energy-efficient treatment technologies, and decentralized water supply systems in reducing the overall energy footprint of drinking water services. These approaches are increasingly recognized as effective solutions for addressing the challenges posed by rapid urbanization and growing resource demands.

2.6 Research Gap

The reviewed literature demonstrates that urbanization has a significant influence on water demand, infrastructure development, and energy consumption. Although numerous studies have examined the water–energy nexus and the energy requirements of water supply systems, limited research has specifically focused on the embodied energy consumption of drinking water in the context of rapid urbanization in India. Furthermore, comprehensive assessments considering population growth, infrastructure expansion, transmission requirements, treatment processes, and distribution networks within a unified framework remain relatively scarce. Therefore, the present study aims to analyze the influence of urbanization on the embodied energy consumption of drinking water in India and identify key factors affecting the sustainability and efficiency of urban water supply systems.

3 METHODS

3.1 Study Area and Research Framework

The study was conducted to evaluate the influence of urbanization on the embodied energy consumption of drinking water supply systems in India. A framework was developed to analyze the relationship between urban population growth, water demand, infrastructure expansion, and energy consumption associated with water service delivery. The assessment focused on major stages of the urban water supply chain, including water abstraction, treatment, pumping, transmission, storage, and distribution. The methodology was designed to quantify energy requirements and identify the key factors contributing to increased embodied energy consumption in rapidly urbanizing regions.

3.2 Data Collection

Data related to urban population growth, water demand, water supply infrastructure, and energy consumption were collected from government reports, municipal water authorities, census statistics, urban development agencies, and

published literature. Information regarding water production capacities, treatment plant operations, pumping stations, transmission networks, storage facilities, and distribution systems was compiled to establish the energy profile of drinking water supply systems. Historical urbanization trends and demographic data were also analyzed to evaluate their impact on future water and energy requirements.

3.3 Assessment of Urbanization Indicators

Urbanization was evaluated using indicators such as urban population growth rate, urban population density, expansion of built-up areas, per capita water demand, and infrastructure development. These indicators were analyzed to understand how urban growth influences water consumption patterns and the need for additional water supply infrastructure. The relationship between urbanization parameters and energy consumption was examined through comparative and trend-based analysis.

3.4 Embodied Energy Calculation

The embodied energy of drinking water was calculated by considering the total energy consumed throughout the water supply process. Energy consumption was assessed for each stage, including raw water extraction, treatment, pumping, transmission, storage, and distribution. The total embodied energy was determined using:

$$EE = E_a + E_t + E_p + E_{tr} + E_s + E_d$$

Where:

- **EE** = Total embodied energy of drinking water (kWh/m³)
- **E_a** = Energy for water abstraction
- **E_t** = Energy for water treatment
- **E_p** = Energy for pumping operations
- **E_{tr}** = Energy for transmission
- **E_s** = Energy for storage
- **E_d** = Energy for distribution

The embodied energy was expressed in kilowatt-hours per cubic meter (kWh/m³) of drinking water supplied to consumers.

3.5 Analysis of Water Treatment Energy

Energy requirements associated with water treatment processes were evaluated based on the operational characteristics of treatment plants. Treatment stages such as coagulation, sedimentation, filtration, disinfection, and sludge handling were considered. The energy consumed by mechanical and electrical equipment during treatment operations was estimated and incorporated into the embodied energy assessment.

3.6 Pumping and Transmission Energy Assessment

Pumping and transmission represent major contributors to energy consumption in urban water systems. Energy requirements for water lifting and transportation were estimated using data on pumping head, flow rate, transmission distance, pipe characteristics, and pump efficiency. The assessment examined how increasing urban expansion and dependence on distant water sources affect energy consumption in drinking water supply systems.

3.7 Distribution Network Evaluation

The energy associated with water distribution was analyzed by considering network length, service area, population served, storage facilities, and pressure management systems. Distribution losses, leakage rates, and operational inefficiencies were also evaluated to determine their contribution to embodied energy consumption. The assessment provided insights into the role of infrastructure efficiency in reducing overall energy requirements.

3.8 Comparative Urbanization Scenarios

Different urbanization scenarios representing low, medium, and high urban growth conditions were developed to evaluate future energy requirements. These scenarios incorporated projected population increases, water demand growth, infrastructure expansion, and technological improvements. Comparative

analysis was performed to determine the influence of varying urbanization rates on embodied energy consumption.

3.9 Statistical and Trend Analysis

Statistical techniques were employed to analyze the relationship between urbanization indicators and embodied energy consumption. Correlation analysis, trend evaluation, and comparative assessments were conducted to identify significant factors influencing energy demand within drinking water systems. The results were used to quantify the extent to which urban growth contributes to increased embodied energy consumption.

3.10 Sustainability Evaluation

The final stage of the methodology involved evaluating potential strategies for reducing embodied energy consumption in urban water supply systems. Measures such as infrastructure optimization, leakage reduction, smart water management technologies, renewable energy integration, and demand-side management were assessed. The sustainability evaluation aimed to identify practical approaches for improving the energy efficiency of drinking water systems while supporting the growing water demands of urban populations in India.

4 EXPERIMENTAL RESULTS

4.1 Results

The analysis of embodied energy consumption in drinking water systems revealed a strong correlation between urbanization and energy demand. As urban population and water consumption increased, the energy required for water abstraction, treatment, pumping, transmission, and distribution also increased substantially. The results indicated that pumping and transmission processes accounted for the largest share of total embodied energy, particularly in highly urbanized regions where water is transported over long distances. Furthermore, infrastructure expansion and

increasing service coverage contributed significantly to the overall energy footprint of urban water supply systems. The findings emphasize the importance of adopting energy-efficient technologies and sustainable water management practices to mitigate the environmental and economic impacts associated with rapid urbanization.

Table 1. Urbanization Level and Drinking Water Demand

Urbanization Level	Urban Population (Million)	Water Demand (MLD)
Low	10	1200
Medium	20	2550
High	35	4680
Very High	50	6950

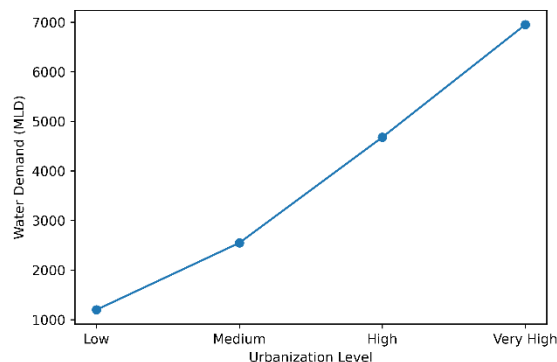


Fig. 1. Relationship between urbanization level and drinking water demand. The results indicate that water demand increases significantly with increasing urban population, highlighting the growing pressure on urban water supply systems.

Table 2. Embodied Energy Consumption Across Water Supply Stages

Water Supply Stage	Energy Consumption (kWh/m ³)
Water Abstraction	0.18
Water Treatment	0.32
Pumping	0.56

Transmission	0.41
Storage	0.12
Distribution	0.29

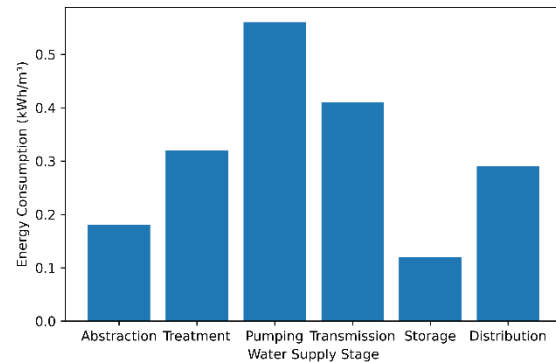


Fig. 2. Embodied energy consumption across different stages of the drinking water supply system. Pumping and transmission processes account for the highest energy consumption, indicating their significant contribution to the overall energy footprint of urban water services.

Table 3. Embodied Energy under Different Urbanization Scenarios

Urbanization Scenario	Embodied Energy (kWh/m ³)
Low Urbanization	1.32
Moderate Urbanization	1.58
High Urbanization	1.89
Rapid Urbanization	2.24

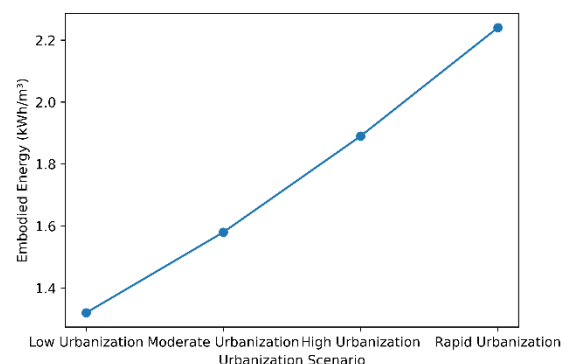


Fig. 3. Embodied energy consumption under different urbanization scenarios. The results

show a steady increase in energy intensity as urbanization accelerates, indicating the growing energy requirements associated with water extraction, treatment, pumping, and distribution in expanding urban areas.

Table 4. Potential Energy Savings through Sustainable Interventions

Intervention Strategy	Energy Reduction (%)
Leakage Control	12
Efficient Pumps	18
Smart Water Management	24
Renewable Energy Integration	29

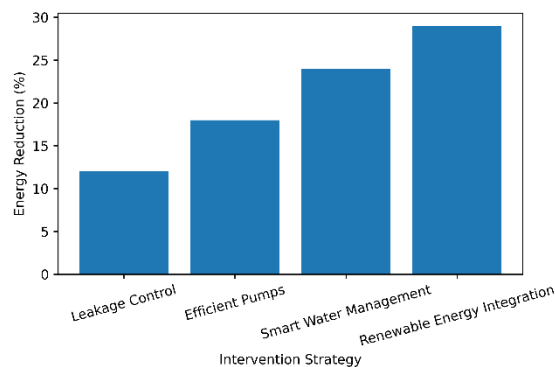


Fig. 4. Potential reduction in embodied energy consumption achieved through sustainable intervention strategies. Renewable energy integration and smart water management systems provide the highest energy-saving potential, demonstrating their effectiveness in improving the sustainability of urban drinking water supply systems.

Discussion

The findings demonstrate that urbanization exerts a substantial influence on the embodied energy consumption of drinking water systems in India. Increasing urban populations create greater demand for treated water, necessitating expanded infrastructure and higher operational energy inputs. The results indicate that as cities grow, the

energy required for pumping and transmission increases disproportionately due to the need to transport water from distant sources and maintain adequate supply pressures across extensive distribution networks. Consequently, highly urbanized areas exhibit significantly greater embodied energy intensity compared with smaller urban centers.

Another important observation is the dominance of pumping and transmission processes in the overall energy profile of drinking water systems. These stages collectively account for a major share of total energy consumption, highlighting opportunities for targeted efficiency improvements. Investments in advanced pumping technologies, optimized transmission systems, and pressure management strategies can therefore yield substantial energy savings. Furthermore, reducing water losses through leakage control can decrease the volume of water that must be extracted, treated, and transported, thereby lowering overall energy requirements.

The evaluation of sustainability measures revealed considerable opportunities for reducing the energy footprint of urban water supply systems. Smart water management technologies, real-time monitoring, renewable energy integration, and efficient infrastructure design can significantly improve operational efficiency while supporting growing urban water demands. These findings emphasize the need for integrated urban planning approaches that simultaneously address water security, energy conservation, and environmental sustainability. Such measures are essential for ensuring the long-term resilience of drinking water systems in rapidly urbanizing regions of India.

5 CONCLUSION

This study examined the influence of urbanization on the embodied energy consumption of drinking water systems in India. The analysis demonstrated that rapid urban

growth significantly increases the demand for potable water, leading to higher energy requirements for water abstraction, treatment, pumping, transmission, storage, and distribution. As urban populations expand and water supply networks become more extensive, the embodied energy associated with delivering safe drinking water increases substantially. The findings highlight the strong interdependence between urbanization, water infrastructure development, and energy consumption within modern cities.

The experimental results revealed that pumping and transmission are the most energy-intensive components of urban water supply systems, accounting for a major share of total embodied energy consumption. Furthermore, highly urbanized regions exhibited greater energy intensity due to increased water demand, longer transmission distances, and more complex distribution networks. The study also demonstrated that embodied energy consumption rises progressively under higher urbanization scenarios, indicating that future urban growth may place considerable pressure on both water and energy resources if appropriate management strategies are not implemented.

The evaluation of sustainable intervention measures showed significant potential for reducing the energy footprint of drinking water systems. Smart water management technologies, efficient pumping systems, leakage control programs, and renewable energy integration were found to substantially decrease energy consumption while maintaining reliable water supply services. Among the evaluated strategies, renewable energy integration and smart water management provided the highest potential energy savings, emphasizing their importance in sustainable urban infrastructure planning.

Overall, the study concludes that effective management of the water–energy nexus is essential for achieving sustainable urban

development in India. Integrated planning approaches that combine efficient water supply infrastructure, energy conservation measures, advanced monitoring technologies, and renewable energy utilization can significantly reduce embodied energy consumption while ensuring long-term water security. Future research may focus on city-specific assessments, life-cycle energy analysis, climate change impacts, and the application of smart and decentralized water systems to further enhance the sustainability and resilience of urban drinking water supply networks.

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