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AN AUTONOMOUS HUMAN-POWERED AMBIENT LIGHTING SYSTEM WITH INTEGRATED GRAVITY ENERGY STORAGE

In the rapidly evolving landscape of urban development, the quest for sustainability has catalyzed a transition toward smarter, more resilient city environments. This paper presents a comprehensive study of a novel autonomous lighting system that uniquely integrates human biomechanical energy harvesting with a gravity-based storage mechanism. Designed for seamless incorporation into the public spaces of Smart Cities, the system addresses the critical dual need for environmental responsibility and active community interaction. The proposed solution champions urban sustainability by operating entirely off-grid, utilizing a calibrated mass-based energy storage system that circumvents the ecological drawbacks of conventional photovoltaic panels and chemical batteries, such as intermittency, toxic waste generation, and limited lifecycles. Unlike traditional energy storage solutions that rely on lithium-ion or lead-acid technology, this mechanical approach offers a service life exceeding 20 years with minimal maintenance requirements. The technical core of the system comprises a manual lifting mechanism where a user raises a 25 kg mass to a height of 5 meters via a robust crank handle. The gravitational potential energy thus stored is converted back into electrical power during a slow, controlled descent regulated by a centrifugal brake and a high-ratio planetary gearbox (approx. 1:1000). This transmission setup drives a high-efficiency BLDC generator to power a low-voltage 0.5 W LED fixture. Theoretical feasibility analysis and experimental simulations demonstrate that a mere 15 seconds of manual effort can yield approximately 35 minutes of pleasant ambient illumination. Beyond its technical performance, the system serves as a «tangible energy» installation, providing a visceral educational experience that makes energy consumption physical and understandable. By directly involving citizens in the act of energy co-creation, the system promotes mindful consumption and enhances community engagement. In the context of urban resilience, particularly in regions facing energy instability or frequent blackouts, this human-powered installation offers a reliable, decentralized alternative for essential public lighting. The study validates that such "Active Infrastructure" not only provides functional benefits but also reshapes the relationship between residents and their urban environment, fostering a durable culture of sustainability within the Smart City paradigm.

Keywords: *Human-powered lighting, Gravity battery, Urban furniture, Citizen Engagement, Sustainable Technology, Smart City, Energy harvesting.*

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АВТОНОМНА СИСТЕМА ЛОКАЛЬНОГО ОСВІТЛЕННЯ НА БАЗІ М'ЯЗОВОЇ ЕНЕРГІЇ ЛЮДИНИ З ІНТЕГРОВАНИМ ГРАВІТАЦІЙНИМ НАКОПИЧУВАЧЕМ

У контексті стрімкого розвитку сучасного міського простору пошук шляхів сталого розвитку став каталізатором переходу до «розумніших» та більш стійких міських середовищ. У цій статті представлено комплексне дослідження інноваційної автономної системи освітлення, яка унікальним чином поєднує збір біомеханічної енергії людини з гравітаційним механізмом накопичення. Розроблене рішення призначене для безшовної інтеграції в громадські простори Smart City та вирішує критичну подвійну потребу в екологічній відповідальності та активній взаємодії з громадою. Запропонована система підтримує принципи сталого урбанізму і функціонує повністю автономно поза електромережею. Використання каліброваного масового накопичувача енергії дозволяє уникнути екологічних недоліків традиційних фотоелектричних панелей та хімічних акумуляторів, таких як переривчастість генерації, утворення токсичних відходів та обмежений життєвий цикл компонентів. На відміну від традиційних накопичувачів, що базуються на літій-іонних чи свинцево-кислотних технологіях, цей механічний підхід забезпечує термін експлуатації понад 20 років за мінімальних вимог до обслуговування. Технічне ядро системи базується на механізмі ручного підйому, де користувач піднімає вантаж масою 25 кг на висоту 5 метрів за допомогою посиленої корби. Накопичена потенційна енергія перетворюється на електричну під час повільного контрольованого спуску, що регулюється відцентровим гальмом та планетарним редуктором із високим передавальним числом (близько 1:1000). Ця конструкція приводить у дію високоефективний BLDC-генератор для живлення світлодіодного світильника потужністю 0,5 Вт. Аналіз технічної доцільності та моделювання демонструють, що лише 15 секунд ручних зусиль забезпечують приблизно 35 хвилин комфортного фонового освітлення. Окрім технічних показників, система виконує роль інсталяції «відчутної енергії», надаючи безпосередній освітній досвід, який робить процес споживання енергії фізично зрозумілим. Залучаючи громадян до генерації енергії власними фізичними зусиллями, *система стимулює усвідомлене споживання та посилює взаємодію в межах громади. В контексті міської стійкості, особливо для регіонів, що стикаються з енергетичною нестабільністю або частими відключеннями світла, ця установка пропонує надійну, децентралізовану альтернативу для критичного громадського освітлення. Дослідження підкреслює, що така «активна інфраструктура» не лише забезпечує функціональні переваги, але й трансформує відносини між мешканцями та міським середовищем, формуючи тривалу культуру сталого розвитку в межах парадигми «Розумного міста».*

Ключові слова: *освітлення за рахунок м'язової сили, гравітаційна батарея, вуличні меблі, залучення громадян, сталі технології, Розумне місто, збір енергії.*

Statement of the problem

The global trend towards urbanization has placed unprecedented pressure on city resources, necessitating a shift towards smarter, more sustainable development. The "Smart City" concept leverages technology to enhance quality of life and operational efficiency [1]. Central to this vision are public spaces that are safe, accessible, and interactive. However, the energy required for essential services like public lighting presents a challenge due to reliance on centralized grids or components with adverse lifecycles.

Conventional off-grid solutions often depend on solar panels and chemical batteries. Solar systems are limited by intermittency, geographical location, and space requirements. Chemical batteries pose environmental risks and disposal challenges throughout their limited 5–10 year lifespan [2]. Most importantly, these technologies create a passive relationship between citizens and the urban environment. This paper argues that a truly "smart" city requires active citizen engagement, transforming residents from passive consumers into active participants in sustainability [3].

The evolution of the "Smart City" paradigm has transitioned from purely techno-centric models (Smart City 1.0) to more integrated, citizen-oriented frameworks (Smart City 3.0). Modern urban innovations are characterized by the convergence of the Internet of Things (IoT), distributed energy resources (DER), and "Active Infrastructure". According to the multidimensional model proposed by Giffinger et al., a smart city encompasses six key dimensions: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance.

A critical innovation in the «Smart Environment» dimension is the development of decentralized energy harvesting systems. Unlike traditional infrastructure, which relies on unidirectional energy flow from central plants to consumers, innovative smart systems promote bidirectional «prosumerism» – where citizens contribute to energy generation. The concept of «Energy as a Service» (EaaS) and the integration of kinetic harvesting into urban furniture represent a shift toward "Tactical Urbanism". This approach utilizes low-cost, high-impact physical interventions to improve the quality of urban life.

Furthermore, innovations in smart cities are increasingly focusing on circular economy principles. This involves minimizing the lifecycle environmental impact of infrastructure by replacing high-maintenance electronic components (like chemical batteries) with durable mechanical alternatives. The integration of gravity energy storage into urban landscapes exemplifies this trend, offering a robust, long-term solution that maintains functionality without the ecological burden of rare-earth materials or toxic chemical recycling.

A prominent example of aesthetic and functional integration in smart environments is the «Solar Tree.» Solar trees are architectural installations that mimic the phyllotaxy of natural trees to optimize the placement of photovoltaic (PV) panels. These structures serve multiple purposes: providing shade, offering Wi-Fi hotspots, charging mobile devices, and supplying energy for ambient lighting. They represent a significant advancement in urban prosumerism by maximizing solar energy harvesting within a limited spatial footprint.

However, despite their visual appeal and multifunctionality, solar trees face several engineering challenges. Most current designs rely heavily on battery storage to bridge the gap between daytime generation and nocturnal usage. This dependency reintroduces the issues of chemical degradation, maintenance costs, and recycling difficulties. Furthermore, the efficiency of solar trees is significantly hampered in high-latitude regions or dense urban canyons with frequent overshadowing. Our proposed gravity-powered system complements the solar tree concept by offering a strictly mechanical, user-triggered alternative that is immune to weather intermittency and battery-related lifecycles, thereby enhancing the overall resilience of the smart city's micro-energy grid.

Analysis of remaining research and publications

Human-powered energy harvesting has transitioned from a niche concept to a viable micro-generation strategy. Projects like GravityLight demonstrated the potential of gravity-based systems for developing nations [4–6]. However, urban applications require higher durability and integration into existing infrastructure. Research by Vytyaz O., Wang R. and Rimpel A. on energy storage control efficiency emphasizes that optimized mechanical and electrical control systems can significantly improve the round-trip efficiency of kinetic energy storage installations [7–9].

As summarized, gravity systems circumvent the issues of Lithium-Ion batteries (degradation), Flywheels (self-discharge), and Pumped Hydro (scale). It uses durable, inert materials with a lifespan measured in decades, making it ideal for low-maintenance public installations [10].

Research Objective

The primary objective of this research is to design and theoretically validate an autonomous, human-powered ambient lighting system integrated with a gravity-based energy storage mechanism for smart city public spaces. Specifically, this study aims to: calculate the mechanical and electrical efficiency of a system utilizing a high-ratio planetary gearbox and a BLDC generator; determine the feasibility of achieving functional lighting durations through manageable manual input; compare the proposed solution with conventional solar-battery systems in terms of lifecycle, maintenance, and environmental impact; and explore the socio-educational potential of tangible energy harvesting in fostering active citizen engagement and promoting sustainable urban behaviors.

Presentation of the main research material

Materials and Methods. The proposed system consists of a structural column (integrated into urban furniture, such as a bench) approximately 5 meters in height. Inside this column, a calibrated mass is suspended on a high-tensile cable. The operational cycle begins with manual energy input, where a user employs a manual crank handle with a radius of $r = 0.2$ m to lift the internal mass. This physical action effectively converts biomechanical energy into gravitational potential energy stored within the elevated weight. Once the crank is released, the energy generation phase commences as the mass undergoes a slow, controlled descent. This downward movement drives a high-efficiency DC generator through a reduction planetary gearbox with a ratio of approximately 1:1000, converting low-speed mechanical motion into high-frequency electrical output. Finally, the resulting electricity directly powers a 0.5 W LED fixture, providing localized ambient illumination for the surrounding area without contributing to the broader issue of urban light pollution.

The technical architecture of the system is built upon a robust structural foundation consisting of a steel or concrete column, which houses an internal "elevator shaft" designed to guide the moving weight. The energy storage medium is a calibrated 25 kg solid block, chosen for its durability and consistent performance.

To regulate the discharge of energy, the transmission system utilizes a specialized gearbox equipped with a centrifugal brake that maintains a constant descent speed, ensuring stable power delivery. Safety is prioritized through the integration of a «safety break» mechanism and a secure protective enclosure for all moving parts, thereby preventing public injury and ensuring vandal-resistant operation in uncontrolled urban environments.

To ensure a manageable user experience, the torque τ required on the crank is calculated as follows:

$$\tau = m \cdot g \cdot r = 25 \cdot 9.81 \cdot 0.2 = 49.05 \text{ Nm}. \quad (1)$$

This torque level is well within the capabilities of an average adult.

Stored Potential Energy (E_p):

$$E_p = m \cdot g \cdot h = 25 \cdot 9.81 \cdot 5 = 1226.25 \text{ J}. \quad (2)$$

Electrical Energy Delivered (E_a):

$$E_a = E_p \cdot \eta = 1226.25 \cdot 0.85 = 1042.3 \text{ J}, \quad (3)$$

assuming system efficiency (η) of 85 % (mechanical and electrical losses).

Achievable Lighting Duration (t):

$$t = \frac{E_p}{P} = \frac{1042.3}{0.5} = 2085 \text{ seconds}. \quad (4)$$

The system defines a clear niche: creating localized, intimate atmospheres where high-power street lighting is not required (Table 1).

Table 1

Comparative characteristics of Gravity Storage vs. Solar-Battery Systems

Technical Feature	Gravity System	Solar-Battery System
Operational Lifespan	20+ years	3–7 years (battery limited)
Climatic Dependency	0 % Independent of irradiance	100 % Inefficient in winter/cloudy
User Interaction Type	Active (kinetic engagement)	Passive
Maintenance Requirements	Low Mechanical lubrication	High Battery replacement, cleaning
Environmental Footprint	Minimal Fully recyclable metals	High Hazardous chemical waste

The performance scales linearly with mass, allowing for design flexibility based on the intended site (Table 2).

Table 2

Scaling of potential energy and lighting duration (at h = 5 m, P = 0.5 W)

Mass (m), kg	Potential Energy (E_p), kJ	Electrical Energy (E_a), kJ	Duration (t), min
15	0.74	0.63	21
20	0.98	0.83	28
25	1.23	1.04	35

The graph (Fig. 1) demonstrates a strictly linear relationship between the input mass and potential energy storage. Utilizing a 25 kg mass with a 0.5W LED provides an optimal balance between human effort and functionality (35 min duration). Doubling the power load proportionally reduces the runtime, highlighting the necessity of high-efficiency components in kinetic micro-generation systems.

Possible applications include park seating areas, viewpoints, quiet urban zones, or trail markers. The system complements high-power lighting with a sustainable layer of human-scale illumination (Fig. 2).

Beyond functional merits, the system re-contextualizes energy consumption. In modern society, energy is often an abstract concept (kWh on a bill). The physical act of turning a crank provides a visceral lesson in the "cost" of energy. A user personally invests effort to produce a tangible outcome: half an hour of light. This experience fosters a deeper appreciation for energy conservation and transforms citizens from consumers into «co-creators» of their urban environment.

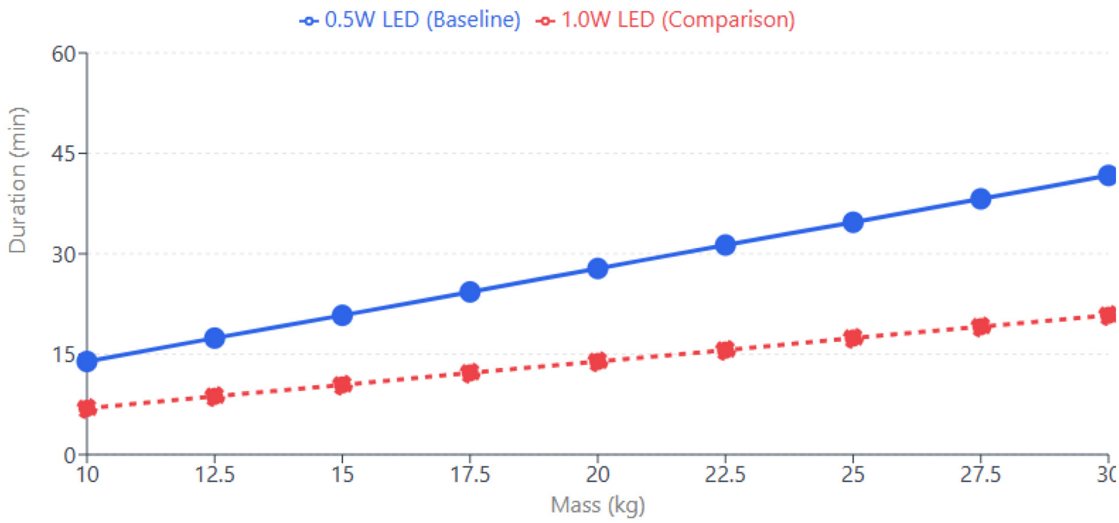

Fig. 1. Relationship between the input mass and potential energy storage

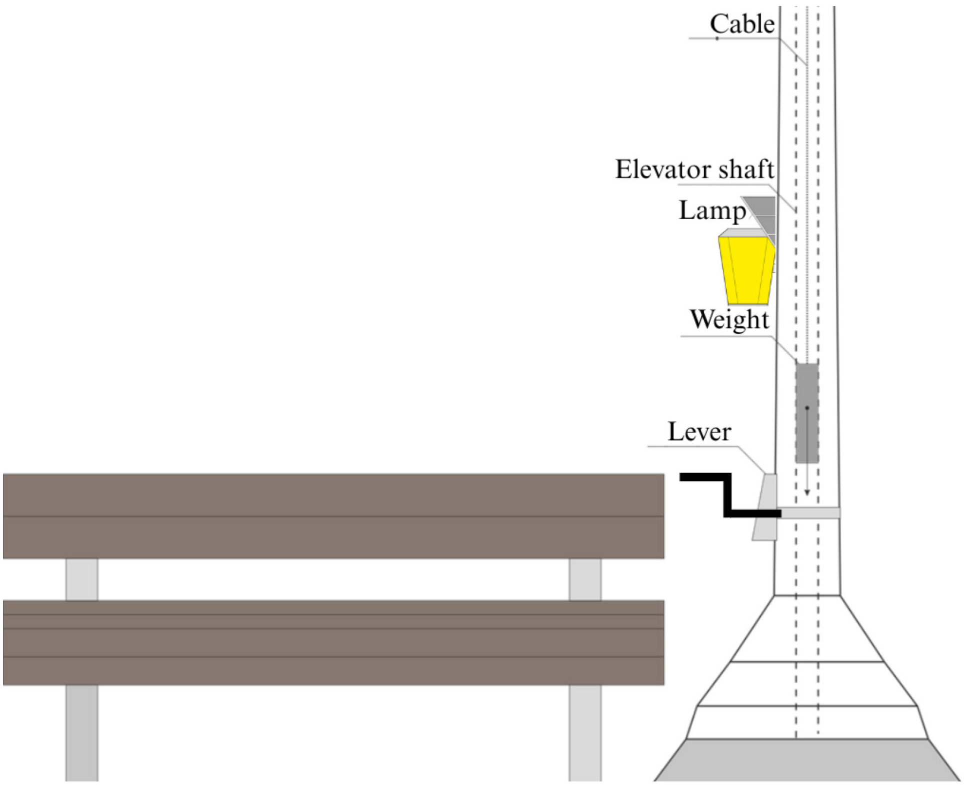

Fig. 2. Concept of an autonomous ambient lighting system with integrated gravity energy storage

Conclusions

This study successfully validates the feasibility of a human-powered gravity lighting system. Lifting a 25 kg mass to 5 meters provides 35 minutes of light, making it a practical solution for Smart City infrastructure. The system offers dual value: resilient off-grid lighting and an interactive educational tool.

Future work: evaluating the crank mechanism with different age groups, testing the gearbox under extreme temperature variations, designing a reinforced casing for permanent public installation, considering a small supercapacitor to bridge the energy gap during the manual lifting phase.

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