

Integrating Behavioral Economics and IoT for Energy Efficiency in Smart Cities: A Multi-case Study Approach

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Abstract. Urban areas play a vital role in global sustainability, especially regarding energy consumption. While smart city strategies emphasize technological innovation such as Internet of Things (IoT) and big data, behavioral factors also influence energy consumption. This paper aims to explore the integration of behavioral economics (namely nudging), with IoT-enabled systems to support energy efficiency within smart governance in urban areas. Using a qualitative case study methodology, three cases are analyzed: (1) the Renewable Energy Community of Magliano Alpi (Italy), (2) the NUDGE project (5 European Union countries), and (3) an IoT-driven behavioral intervention in municipal housing in Greenwich (United Kingdom). The findings show that combining real-time data with behavioral interventions enhances energy awareness and citizen participation in energy saving, which leads to increased energy efficiency. The paper links behavioral design, IoT infrastructure, and governance mechanisms, contributing to urban and regional planning.

Keywords: behavioral economics · nudging · Internet of Things · smart governance · sustainability

1 Introduction

The pace of urbanization in the 21st century has significantly increased the pressure on cities to address sustainability, improve energy efficiency, and manage resources more effectively, all while sustaining economic competitiveness and social cohesion. In response, the concept of smart cities has emerged as a notable shift in urban and regional planning, bringing together digital technologies, data-informed governance, and more participatory approaches to improve how cities function [9, 22]. Within this context, concepts such as smart governance and open governance emphasize transparency, active citizen involvement, and the purposeful use of open data and large-scale data infrastructures to support decision-making [15, 29, 49].

From a behavioral economics perspective, the assumption that individuals act as fully rational agents is increasingly subject to scrutiny. Empirical studies indicate that decision-making is frequently influenced by heuristics and cognitive biases, including

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status quo bias, loss aversion, and bounded rationality [23, 46]. In the context of energy consumption, these effects are reflected in a relatively low propensity to switch energy providers, a tendency to underinvest in energy-efficient technologies despite their potential long-term benefits, and the persistence of habitual patterns that may contribute to higher levels of energy use (overconsumption) [3, 4, 10].

To address these behavioral barriers, the concept of nudging, as introduced by Thaler and Sunstein [46], has gained attention as a policy approach that seeks to influence behavior by modifying the context in which decisions are made, without limiting individual choice. Various forms of nudges, including feedback mechanisms, social comparison, default settings, and framing techniques, have been examined in relation to energy consumption. Empirical research shows that such interventions can have measurable, albeit typically modest, effects. For example, social norm feedback has been associated with average reductions in household energy use of approximately 2–5% [2, 3], while real-time feedback appears to support increased awareness and behavioral change [12].

Building on these insights, integrating behavioral interventions with IoT technologies is an important development within smart city ecosystems. IoT devices—such as smart meters, sensors, and connected appliances—enable continuous collection of energy-use data, often at relatively high temporal and spatial resolutions, which, in turn, provides a basis for more data-informed nudging approaches, in which behavioral interventions can be tailored to individual users, promptly, and adapted to specific conditions [24].

In contrast to more traditional, static interventions (e.g., informational campaigns), IoT-enabled nudges can be adjusted dynamically in response to user behavior, environmental conditions, and broader system constraints. For example, real-time notifications can encourage users to change consumption to periods of high renewable energy production, thus aligning individual behavior with system efficiency goals. The above is consistent with emerging perspectives on adaptive and data-driven governance, including concepts such as smart governance, where urban systems are managed through continuous feedback loops and adaptive governance mechanisms [48, 51].

Despite growing interest in both behavioral interventions and smart technologies, there remains a gap in understanding how to systematically integrate these approaches into smart governance and urban planning strategies. In practice, many existing initiatives tend to emphasize either technological capabilities without sufficiently incorporating behavioral insights or, conversely, behavioral approaches without fully leveraging the potential of real-time data and connected infrastructure.

This paper addresses this gap by examining the combined use of behavioral economics (nudges) and IoT technologies in urban energy systems. It emphasizes the role of behavioral interventions in achieving sustainability, participation, and strategic urban development goals. The novelty of the contribution is threefold: (1) prior research has examined behavioral interventions and IoT-enabled energy systems largely in isolation; this paper brings an approach that links behavioral design, real-time data infrastructures, and governance arrangements. (2) The paper advances existing work on digital nudging by comparatively analyzing how different configurations of personalization, feedback, and social embedding influence behavioral outcomes across cases. (3) The paper extends current knowledge by incorporating governance and participation as a core analytical

dimension, thereby highlighting how institutional contexts influence the effectiveness and scalability of IoT-enabled behavioral interventions.

2 Theoretical Background

Evidence from CEE countries suggests that the effectiveness of smart energy interventions is strongly conditioned by institutional and market structures, including the role of policy support and innovation systems [20, 26]. The transition toward sustainable urban energy systems also calls for institutional innovation. In this context, smart governance frameworks emphasize participatory approaches, positioning citizens not only as consumers but also as active contributors, often described as "prosumers." The emergence of energy communities responds to this need by facilitating the collective production, sharing, and management of renewable energy resources. This perspective is broadly consistent with Ostrom's [35] theory of collective action, which highlights the roles of trust, shared norms, and institutional arrangements in the governance of common-pool resources.

Similarly, participatory digital platforms, e.g., IoT-based, enhance open governance and participation by providing citizens with access to real-time data and enabling co-creation, which supports both economic competitiveness through innovation and efficiency gains and social cohesion through more inclusive forms of participation [13].

From an urban and regional planning perspective, integrating behavioral economics with IoT technologies supports a complex approach to sustainability. Traditional urban planning, especially in the CEE, often focuses on infrastructure and regulatory frameworks, as well as on barriers to technology diffusion and adoption [27, 43]. In contrast, new approaches emphasize the interplay between physical systems, digital infrastructures, and human behavior [14].

The concept of digital nudging (nudges delivered through digital interfaces) extends behavioral interventions into everyday life, embedding them within urban planning [50]. When combined with IoT, these interventions influence behavior at the point of decision-making, highlighting the potential for interventions that are not only scalable and relatively cost-effective but also capable of addressing both environmental sustainability objectives and, potentially, aspects of social equity. Although recent studies explore IoT-enabled nudging architectures [30] and smart meter feedback interventions [40], these contributions tend to focus primarily on technological performance or behavioral outcomes, with limited attention to cross-case comparison and governance contexts.

The integration of behavioral economics and IoT within smart city governance can be conceptualized as a multi-layered system. In such a system, technological infrastructures enable behavioral interventions, which are, in turn, embedded within broader governance and planning. The framework presented in Table 1 captures the relationships among the technological, behavioral, and institutional dimensions of the system.

The presented framework builds on previous research that combines behavioral economics [11, 46], IoT-enabled systems [21, 54], and smart governance theory [31, 32]. It reflects a socio-technical perspective on urban sustainability [18], where technological infrastructures, behavioral mechanisms, and institutional arrangements interact.

While the above-mentioned studies are from different European contexts, the findings are particularly relevant for Central and Eastern European (CEE) countries, where

Table 1. Conceptual framework

Dimension	Studies	Components	Function	Expected Outcomes
Behavioral Design	[1, 11, 41, 45]	Nudges (feedback, social norms, prompts, defaults)	Influence individual decision-making	Reduced energy consumption, habit change
IoT & Data Layer	[3, 5, 21, 33, 52, 54]	Smart meters, sensors, platforms, apps	Real-time monitoring and data analytics	Increased awareness, personalization
Governance Layer	[8, 25, 32, 42]	Public institutions, policies, participation	Enable coordination and trust	Higher engagement, collective action
Urban Planning Context	[18, 29, 37, 39]	Sustainability strategies, infrastructure	Integration into spatial and policy planning	Long-term resilience and efficiency

Source: own based on the authors

a combination of legacy infrastructure, lower levels of digitalization, and evolving governance capacities shapes energy transitions. In these contexts, cost-effective, scalable approaches such as IoT-enabled behavioral interventions may offer a pragmatic pathway to improving energy efficiency without requiring large-scale infrastructure investments.

3 Research Design

This study aims to examine how integrating behavioral economics (nudging) and IoT-based technologies can improve energy efficiency in urban areas, and to assess their role in smart governance through a comparative analysis of selected case studies.

To address this objective, we use a qualitative multiple-case study approach [53], which is well-suited to exploring complex, context-dependent phenomena such as the integration of behavioral interventions and IoT technologies in urban energy systems. The case study design allows for the identification of key patterns and mechanisms, as well as similarities and differences across cases. This approach allows for insights generalization.

Three cases: Renewable Energy Community in Magliano Alpi (Italy), NUDGE Project (interventions in 5 European Union countries) and IoT-driven behavioral intervention in municipal housing in Greenwich (United Kingdom), were selected using purposive sampling based on the following criteria:

- Integration of behavioral and technological interventions (nudges + IoT or digital systems).

- Relevance to smart city and governance frameworks.
- Empirical evidence of implementation and evaluation (i.e., the interventions are already implemented and have yielded some outcomes).
- Diversity of contexts (municipal and cross-national settings).

The cases were selected to ensure variation in (1) level of personalization, (2) governance model, and (3) scale of implementation, enabling theoretically informed comparison rather than just a description.

The analysis is based on secondary data obtained from project documentation, evaluation reports, and related case materials. These sources include information on intervention design and implementation, behavioral mechanisms and tools applied, technological infrastructures (e.g., IoT devices and digital platforms), and monitoring and evaluation results and reported outcomes. A structured template was used to ensure comparability across cases. This template was developed within the STICS (Smart Transformation and Innovation Consortium Slovakia) research project - a standardized coding template covering behavioral mechanisms, technological components, governance arrangements, and reported outcomes.

The cases are analyzed using a comparative framework (based on Table 1) and research questions (RQ):

1. Behavioral Design – focusing on type of nudges used (e.g., feedback, social norms, prompts), and degree of personalization and targeting.
   RQ1: How do behavioral mechanisms such as social norms, feedback, and prompts influence user engagement and energy-related decision-making?
2. Technological Infrastructure – dealing with the role of IoT devices (e.g., smart meters, sensors), data collection and processing capabilities, the design of user interfaces and digital platforms.
   RQ2: How do IoT-based systems (e.g., smart meters, sensors, digital platforms) enable real-time feedback and personalized nudging strategies?
3. Governance and Participation – analyzing the role of public institutions and other stakeholders (including citizen participation), institutional and policy arrangements.
   RQ3: What roles do public institutions, governance structures and citizens play in the adoption of IoT-enabled behavioral interventions?

4 Results and Discussion

4.1 Renewable Energy Community of Magliano Alpi (Italy)

The Renewable Energy Community (REC) in Magliano Alpi is one of the first community-based energy initiatives in Italy. It is a non-profit entity created in December 2020, based upon the open and voluntary participation of citizens, small and medium enterprises (SMEs) and the City of Magliano Alpi. Its strategic objective is to use energy as the catalyst of local sustainable development.

The intervention aims to transform citizens from passive consumers into active "prosumers," while addressing challenges such as energy dependency, rising costs of energy, and low citizen engagement in local energy systems. In small municipalities such as Magliano Alpi (2,230 inhabitants), these issues can have significant economic

and environmental impacts because local governments often have limited financial and infrastructural capacity to implement large-scale energy solutions independently [38].

The intervention combines physical energy infrastructure with renewable generation and local sharing mechanisms. In particular, solar photovoltaic panels were installed on selected local buildings, including municipal facilities and private rooftops, and an accompanying system was introduced to enable the distribution and sharing of locally generated electricity among community members.

In addition to the physical infrastructure, the REC incorporates behavioral and social design elements to influence how citizens engage with local energy systems. In this case, the collective behavioral approach relies on trust and social norms rather than individualized feedback or targeting. The following behavioral mechanisms were identified:

- Social norms and social proof: The municipality plays an active signaling role, framing participation as both expected and socially beneficial.
- Default-like structures: Citizens are invited to join an already working system, which reduces the complexity of the participation decision.
- Framing and identity cues: Participation is presented as contributing to environmental sustainability and broader community well-being.
- Reduction of participation barriers: Administrative and technical requirements are streamlined through municipal coordination.

Behavioral mechanisms build on status quo bias (by providing an established infrastructure, citizens are more likely to "opt in") and social visibility (shared infrastructure reinforces collective identity and commitment). In this case, behavioral change is driven by collective norms, trust, and institutional leadership.

After the first year, the project produced several results. Locally generated electricity was successfully shared among participating members, thereby increasing local self-consumption of renewable energy. In addition, the initiative was associated with higher participation in renewable energy activities, including a change toward more active prosumer behavior, strengthening the citizen participation and engagement. Average benefits for participants included approximately €94 per person per year from incentives and up to €340 per year when including tax incentives and savings from energy bills.

The estimated investment payback period is about 8.8 years [19]. The project became Italy's first renewable energy community and a model replicated by other municipalities. Overall, the intervention is considered successful, as it demonstrated the feasibility of citizen-led renewable energy systems.

4.2 NUDGE - NUDging Consumers Towards EnerGy Efficiency through Behavioral Science

The NUDGE project (2020–2023) was a large-scale EU initiative aimed at systematically testing behavioral interventions to improve energy efficiency across five countries. It combined IoT technologies, digital platforms, and behavioral science to deliver and evaluate multiple nudging strategies in real-world conditions [34].

All five pilots in NUDGE launched summer 2021 and their execution followed an identical three-phase time plan: pre-interventions phase, enabling the establishment

of a benchmark, or baseline, in terms of energy use and consumer behavior for the participating households in each pilot (June–November 2021), testing phase, including the actual testing of the planned interventions in each pilot (between December 2021 and May 2023, so as to provide for the execution of several (consecutive) interventions and their evaluation) and post-interventions phase, running between June and September 2023, the pilots kept on running in the absence of any intervention, to evaluate whether the consumers maintain an improved energy efficient behavior after nudges cease, thus gaining insights into the long-lasting impact of the NUDGE approach.

Interventions included an interdisciplinary project-based education on home energy consumption **for children in Belgium**, where children were educated on and understand the impact of everyday life decisions on home energy consumption, with the support of intergenerational learning among family members and a great replication potential by transferring lessons learned to parents, family and friends. Smart electricity meters were installed at the children's households (N = 55) and schools, with a dashboard to visualize the collected consumption data. The social comparison with the households of classmates was one of the nudging interventions.

The pilot study in Greece aimed at improving the efficiency of natural gas boilers used for residential space heating. A total of 102 participants from five Greek cities took part in this study. Each household was equipped with the DOMX (domestic automation) smart heating controller, which allowed for efficient control of legacy gas boilers. This device could modulate heating based on weather conditions and pre-set schedules, potentially leading to energy savings of up to 30% without compromising user comfort. The study tested three types of nudges: NUDGE 1, which provided historical information on gas usage and consumption; NUDGE 2, which facilitated the adoption of energy efficient heating settings (configuration of lower target room temperatures or activation of weather adaptive control) through just in time prompts; and NUDGE 3, which involved the delivery of personalized notifications to encourage the adoption of energy efficient settings.

In **Portugal**, a study involving 101 families with children aimed to reduce electricity consumption while ensuring comfortable and healthy living environments. The study involved a detailed survey of the buildings and the installation of smart meters and indoor air quality (IAQ) sensors in homes. These devices monitored electricity use, carbon dioxide levels, airborne particles, temperature, and humidity. An app was developed to deliver nudging interventions to participants. The first nudging intervention, which provided historical electricity usage data, did not significantly reduce electricity consumption but increased the motivation to save energy. The second intervention, allowing users to view IAQ data, notably increased both the intention to save energy and awareness of households' energy positioning. It also effectively reduced average CO2 levels, with many participants acknowledging the usefulness of the IAQ data in understanding air quality factors and expressing a greater motivation to save energy when IAQ considerations were included.

In **Germany**, 111 households with photovoltaic (PV) systems in the Rhine-Neckar metropolitan area were involved. Among these, 39 had electric vehicle charging stations that could be remotely controlled, forming the EV group. This pilot focused on encouraging energy-saving behaviors and increased self-consumption of energy in households

with electric vehicles (EVs). Two digital platforms were used to deliver nudges: a web portal for all participants to track home energy usage and the HERMINE charging app for the EV group. The nudging strategies included providing feedback, raising awareness about energy efficiency, and offering comparisons, suggestions, and controls. The nudges led to a reduction of household consumption between 4–5%, and they also increased the self-consumption, generally between 3–4%. The EV group showed a more significant response, with self-consumption rising by 10–12%, compared to the average increase of 2–3% among all participants.

The Croatian Pilot engaged 82 consumers with PV systems installed in their home and monitored their real-time data on both electricity consumption and production. A user-friendly smartphone app was developed for the pilot to expose participants to nudges, which aimed to cultivate empathy, enhance awareness of energy usage, and encourage energy efficiency goal setting. The outcomes of the pilot suggest that consumers were more susceptible to adapting their energy use in response to external factors, namely limitations imposed by the regulatory framework, and less because of the nudges.

Types of nudges used across these 5 pilots can be summarized as:

- Feedback: Historical and real-time energy consumption data.
- Social comparison: Benchmarking with similar households.
- Prompts and reminders: real-time notifications.
- Goal setting and gamification: Encouraging engagement through targets and challenges.
- Personalized recommendations.

Behavioral Mechanism can be seen in turning energy management into a "challenge" or "game" with social leaderboards. For example, in a German pilot participants received "just-in-time" push notifications on their smartphones when solar production is high (e.g., a sunny afternoon), encouraging them to start energy-intensive tasks like laundry or EV charging. This approach helped residents optimize EV charging specifically during peak solar hours, increasing self-consumption by up to 15%.

Observed behavioral outcomes:

- 4–5% reduction in energy consumption.
- Increased renewable self-consumption.
- Higher engagement with digital tools.

This project systematically tested behavioral nudges across 5 EU countries to increase energy efficiency and renewable self-consumption. Throughout the project, a total of 472 households were directly involved in these pilot trials. Municipalities have used gamification to increase the residents´ awareness of energy usage and/or the share of self-consumption from renewable sources like solar PV.

4.3 Greenwich IoT Behavioral Intervention

This behavioral intervention was developed to address increasing energy costs, inefficient household energy use, and low awareness among residents about their energy consumption [36]. Because many residents struggle to understand how energy is used in their homes, they often cannot identify where savings are possible. Inefficient energy

behaviors, such as leaving appliances on standby or running devices unnecessarily or limited knowledge about which devices consume the most electricity means that energy consumption is difficult to track and residents often lack feedback about how their behavior translates into energy costs.

The Greenwich intervention is a municipal pilot project (2022–2023) targeting social housing residents and their energy consumption. By combining the use of IoT with a behavior change approach, centered around nudges and other behavioral interventions, the project sought to aid residents in developing a greater understanding of energy use, associated costs and ways to reduce them, and connecting residents to one another to support shared learning and increase motivation/engagement [28].

Of council social housing residents, 40 participants were recruited. AI-powered Sense monitors were chosen for this project, since the monitors use AI and machine learning to identify different devices within the home, measuring and recording their energy usage in KwH (kilowatthour) and providing estimations for how much the devices cost to run. The device is linked to a smartphone app that is downloaded by residents, where they can:

- view real-time energy consumption,
- track trends over time,
- identify which appliances used the most electricity,
- set energy-saving goals.

In the Greenwich case, several types of nudging interventions were implemented as part of an IoT-enabled behavioral program. These included real-time feedback on energy consumption and associated costs, informational prompts and energy-saving tips, as well as social norm-based mechanisms facilitated through peer interaction and community groups. The goal-setting elements and behavioral challenges were incorporated into the intervention to encourage engagement over time.

From a perspective of behavioral economics, these interventions are based on salience (immediate feedback stresses out the how individual actions are related to the energy outcomes), and on habit disruption (increased awareness can interrupt routine or automatic patterns of energy use).

In terms of observed outcomes, the intervention was associated with an average reduction in electricity consumption of approximately 4%, with reductions reaching up to 20% in some households. Moreover, reported effects included increased awareness of energy use and higher levels of user engagement with the system.

Throughout the pilot project, residents generated a greater understanding of their energy use, specifically around individual devices. The trial continues, following further support from Greenwich Council to continue to work with residents and gather lessons learned. Residents are still taking part in the Energy Community WhatsApp group and receiving support as well as energy-saving tips and advice.

4.4 Summary of Main Findings

The following Table 2 summarizes the main findings following the structure of the three research questions.

Table 2. Comparative Analysis of Case Studies: Behavioral, Technological, and Governance Dimensions

Dimension	Key Aspect	Magliano Alpi (Italy)	NUDGE Project (EU)	Greenwich (UK)
Behavioral Design (RQ1)	Type of nudges	Social norms, moral framing, default-like participation, reduced friction	Feedback, social comparison, prompts, goal setting, gamification, personalization	Real-time feedback, prompts, social interaction, goal setting
	Behavioral mechanisms	Social proof, trust, status quo bias, collective identity	Salience, social comparison, commitment, learning effects	Salience, habit disruption, social norms, peer influence
	Personalization level	Low (collective, non-targeted)	High (segmented, data-driven, context-aware)	Moderate–high (household-level feedback, semi-tailored nudges)
	Effect on behavior	Increased participation, prosumer behavior, community engagement	4–5% energy reduction, increased self-consumption, higher engagement	Avg. 4% reduction (up to 20%), increased awareness and engagement
Technological Infrastructure (RQ2)	IoT components	Smart meters, PV systems, energy-sharing platform	Smart meters, sensors, heating controllers, apps, dashboards	AI energy monitors, smart plugs, sensors
	Data capabilities	Aggregated monitoring of production and consumption	High-resolution, multi-source data (energy, environment, behavior)	Appliance-level, real-time consumption data
	User interfaces	Limited user-facing interfaces (system-level focus)	Mobile apps and dashboards with interactive features	Mobile app + messaging platform (WhatsApp)
	Role in nudging	Indirect (supports system efficiency, not personalized nudges)	Core enabler of personalized, adaptive nudging	Direct feedback–action loop enabling behavioral change

(*continued*)

Table 2. (*continued*)

Dimension	Key Aspect	Magliano Alpi (Italy)	NUDGE Project (EU)	Greenwich (UK)
Governance & Participation (RQ3)	Governance model	Municipality-led, community-based energy governance	Multi-level, research-driven consortium	Municipality-led with private partners
	Stakeholders	Public sector, citizens, businesses, research institutions	EU institutions, research orgs, private companies, households	Public sector, tech providers, residents
	Citizen participation	High (active prosumers, co-creation)	Moderate (participants in pilot trials)	Moderate–high (active engagement in community groups)
	Policy integration	Strong (aligned with EU and national energy transition policies)	Strong (EU-level policy alignment and recommendations)	Moderate (linked to local sustainability and social policies)
	Key governance role	Build trust, enables collective action	Enables experimentation and scalability	Enables targeted intervention and inclusion
Overall Contribution	Strengths	Strong social cohesion and collective engagement	High scalability, personalization, and empirical validation	Strong behavioral impact through real-time feedback and engagement
	Limitations	Limited personalization and individual feedback	Less community-driven participation	Smaller scale, pilot-based implementation

The findings indicate that integrating behavioral economics with IoT technologies represents an effective approach for improving energy efficiency in smart city contexts. By combining real-time data with targeted nudges, cities can influence citizen behavior.

A cross-case comparison reveals several insights. First, the effectiveness of behavioral interventions appears strongly dependent on the level of personalization enabled by IoT systems. Cases in larger municipalities (NUDGE, Greenwich) demonstrate measurable reductions in individual energy consumption (individual approach), whereas smaller municipalities (Magliano Alpi) primarily influence participation and social engagement, building on local ties (collective approach). Another insight shows that governance structures shape not only implementation but also behavioral outcomes. Municipality-led and

community-embedded models (Magliano Alpi, Greenwich) show stronger trust-based engagement, while large-scale experimental settings (NUDGE) achieve greater standardization and scalability but somewhat weaker social cohesion. Finally, the interaction between behavioral mechanisms and technological infrastructure indicates that nudges are most effective when embedded in continuous feedback loops.

These findings imply that the effectiveness of IoT-enabled behavioral interventions is not determined solely by individual components, but by their use within broader socio-technical systems.

These findings are mostly consistent with existing research. Across the three cases, behavioral mechanisms—particularly feedback, social norms, and prompts—appear to play an important role in shaping energy consumption behavior, aligning with the behavioral economics literature, which portrays nudges as tools for influencing decision-making without restricting choice. In particular, systematic reviews indicate that real-time feedback can increase user awareness and responsiveness, especially when individuals can directly associate their actions with observable outcomes [40]. The influence of social norms, which is especially evident in the Magliano Alpi case, is also well documented in the literature [2, 7, 17, 47], which supports the finding that community-based interventions, where participation is visible and socially reinforced, may support collective behavioral change even in the absence of personalized feedback.

However, the case studies also show that nudges' effectiveness increases with personalization and contextualization, as demonstrated by the NUDGE project, consistent with recent IoT-based research that finds that personalized feedback, social comparison and goal setting influence actual energy-saving activities [30].

On the other hand, the literature also highlights that nudging alone may not be sufficient to bridge the intention–behavior gap fully [6, 44], which partially explains why interventions relying solely on digital nudges (without strong governance or social embedding) may yield limited or short-term effects.

Across all three cases, IoT technologies emerge as a key enabling layer that translates behavioral concepts into operational, real-time feedback systems [30]. As outlined in the conceptual framework (Table 1), IoT systems do not only function as data collection tools, but also support continuous feedback loops between user behavior, system data, and intervention design. Additionally, IoT and big data enable user segmentation and targeting, thereby further enhancing the precision and effectiveness of behavioral interventions [16].

Finally, the analysis highlights the importance of governance and participatory structures in shaping the effectiveness of IoT-enabled behavioral interventions - a dimension that is scarcely mentioned in technology-centered studies [40]. Overall, the findings support the argument that sustainable energy transitions in smart cities are more likely to be effective when approached through integrated socio-technical frameworks, rather than through isolated technological deployments or standalone behavioral interventions.

5 Conclusions

This paper aimed to examine how integrating behavioral economics (nudging) and IoT-based technologies can improve energy efficiency in urban areas, and to assess their role in smart governance through a comparative analysis of selected case studies.

The conceptual framework used in this study provides a basis for future research and policy design, emphasizing the need for interdisciplinary approaches that connect technology (technological dimension), smart governance (institutional dimension), and human behavior (behavioral mechanism dimension).

Based on the analysis, we can conclude several main findings. First, technological and behavioral dimensions must complement each other: IoT systems, on their own, do not necessarily lead to energy savings; rather, their effectiveness depends on how the generated data is translated into actions through behavioral interventions such as nudges. Following this finding, real-time feedback mechanisms appear to enhance salience and learning by making energy consumption more immediately observable and interpretable. Also, social dynamics play an important role in strengthening behavioral effects, as evidenced by the cases of Magliano Alpi and Greenwich, which indicate that community-based approaches can support higher levels of engagement than individually oriented interventions. Moreover, governance arrangements appear to influence implementation outcomes, particularly when municipal involvement and institutional trust support adoption and scalability. Finally, heterogeneity among users points to the potential importance of personalization, as illustrated by the NUDGE project, where tailored interventions are associated with more differentiated behavioral responses.

From an urban planning perspective, these findings support a shift toward integrated socio-technical systems in which infrastructure, data, and human behavior are co-designed.

These insights are especially interesting for CEE countries, where municipalities often face financial and institutional constraints in implementing large-scale smart city solutions. The integration of behavioral mechanisms with relatively low-cost IoT technologies offers a feasible and scalable policy pathway in such conditions.

The study's limitation is that it analyzes only secondary data, which limits the depth of behavioral insights and introduces bias in reporting. Additionally, the heterogeneity of case studies disables direct comparison. While the findings support analytical generalization, they should not be interpreted as statistically generalizable because the study is qualitative and case-based.

Future research could focus on long-term effects of such IoT-behavioral mechanism combined interventions, scalability across different urban contexts, and ethical considerations related to data use and digital nudging.

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