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Incorporating Citizen Science to Enhance Public Awareness in Smart Cities: The Case Study of Balaguer

Luisa F. Cabeza [1,*], Mercè Teixidó [2,*], Francesco Guarino [3], Roberta Rincione [3], Manel Díaz [2], Rosa M. Gil [2], Maurizio Cellura [3] and Carles Mateu [1]

1 GREiA Research Group, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain; carles.mateu@udl.cat
2 GRIHO Research Group, University of Lleida, Jaume II 69, 25001 Lleida, Spain; manel.diazllobet@udl.cat (M.D.); rosamaria.gil@udl.cat (R.M.G.)
3 Department of Engineering, University of Palermo, Viale delle Scienze Edificio 9, 90145 Palermo, Italy; francesco.guarino@unipa.it (F.G.); roberta.rincione@unipa.it (R.R.); maurizio.cellura@unipa.it (M.C.)
* Correspondence: luisaf.cabeza@udl.cat (L.F.C.); merce.teixido@udl.cat (M.T.)

Featured Application: Our study introduces an innovative application through the deployment of the Totem Outdoor DELUX interactive kiosk, complemented by a user-friendly web application. This dual-component system is not solely a cutting-edge piece of smart furniture centered on hardware; it also encompasses a specially designed web application to engage the citizens of Balaguer. Together, they form a comprehensive infrastructure aimed at enhancing environmental awareness and promoting civic participation. This kiosk is a dynamic platform for displaying real-time data from sensors across the city, facilitating interactive questionnaires, and providing essential information about the city and town hall. The application of this technology directly contributes to several Sustainable Development Goals (SDGs) by fostering public awareness and participation in critical issues such as climate action, health and well-being, gender equality, innovation in infrastructure, and reducing inequalities. Specifically, the interactive totem allows for the collection and analysis of data regarding citizens' perceptions of their living conditions, environmental impact, and social inequalities. This practical application of our work exemplifies how technological innovation can be leveraged to enhance civic engagement, support sustainable development, and foster a more informed and participatory urban community.

Abstract: The concept of a smart city is becoming increasingly popular to improve citizens' quality of life. Institutions are also committed to enhancing the sustainability of cities by implementing the Sustainable Development Goals (SDGs). This paper presents a Balaguer case study investigating energy demand monitoring, decreasing energy demand, and citizen acceptance in a municipality district. The study collected data from three sources: (1) quantitative data coming from on-site sensors; (2) quantitative data from a simulation of the area; and (3) qualitative data from questionnaires developed with a totem located in the city center. This study shows the importance of citizen science in contributing towards the increased awareness of energy demand, renewable energy, and climate change. But it also shows how citizen science can improve research quality involving the municipality authorities. This study also was instrumental in contributing to the increase in awareness among municipality authorities and capacity building on the topic. This activity may also contribute towards the implementation of actions to reduce the energy demand in public buildings and helping them in deploying policies to decrease energy demand in buildings, increase the use of renewable energy, and increase awareness among citizens. The government will use the information gathered to develop policies for citizen improvement.

Keywords: smart city; building energy simulation; citizen science; public awareness; SDG; e-government

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1. Introduction

The construction sector stands out as a significant contributor to global energy consumption and anthropogenic carbon impacts. Efforts aimed at enhancing energy efficiency and curbing carbon emissions, formulated on both global and continental scales, can be interpreted as endeavors to mitigate the repercussions climate change could cause. Currently, the prevailing trend increasingly highlights more frequent and severe extreme events, coupled with a significant overall increase in monitored variables linked to global warming. In this context, attention in the construction sector is shifting from a narrow focus on individual buildings' energy efficiency to a broader exploration by research and policy entities at the neighborhood level, clusters of buildings, and cities [1]. Various initiatives, including the EU 100 Climate Neutral and Smart Cities program, the European Bauhaus initiative, and legislation addressing energy communities, underscore this shift toward a more comprehensive approach to decarbonizing the entire building energy infrastructure [2].

This transition aims to address the intricate aspects of building interactions, energy flexibility, grid integration, and load balancing [3]. Additionally, the urban scale facilitates a focus on critical elements such as urban planning and stakeholder involvement throughout the entire lifecycle of a neighborhood [4]. This broader perspective strives for an interdisciplinary and holistic approach to the design and management of neighborhoods and cities. Positive Energy Districts (PEDs), smart neighborhoods scaling up to smart cities and aiming towards the EU mission of Carbon neutral cities are the core tools chosen at the continental and international level to enhance the quality of life in European cities, contribute to COP climate targets, and bolster European leadership as a global model [5]. Smart cities solutions and positive energy districts will need to play a pivotal role in steering urban areas toward a low-carbon future, intending to partially cover the energy needs of nearby areas and foster the development of truly climate-neutral cities. This process involves deploying renewable energy systems within urban and regional energy frameworks, achieving high energy efficiency levels across systems and grids, implementing energy flexibility solutions, utilizing advanced materials, adopting smart energy grids, and emphasizing district-level self-consumption of renewable energy systems. Initiatives like PED JPI Urban Europe, IEA EBC Annex 83—Positive Energy Districts [6], EERA/Smart grids [7], and PED EU NET Cost Action [8] collectively strive to establish PEDs as integral components in the current building sector landscape. However, numerous challenges accompany these concepts, including the technical feasibility of achieving a positive balance in specific urban areas, the imperative for capacity-building among stakeholders, societal challenges, the enhancement of regulatory frameworks, the need for replication potential assessment, and the development of tailored business models for these specific technical solutions.

According to the most widely accepted definition [9], Positive Energy Districts are defined as "energy-efficient and energy-flexible urban areas or groups of connected buildings which produce net zero greenhouse gas emissions and actively manage an annual local or regional surplus production of renewable energy. They require integration of different systems and infrastructures and interaction between buildings, the users and the regional energy, mobility, and ICT systems, while securing the energy supply and a good life for all in line with social, economic and environmental sustainability" [10]. The concept is thus inherently not limited to a mere mathematical balance between energy use and generation and will require deeper integration with sustainability applications as well as the social sphere [11].

This initiative is designed to leverage technology as a bridge between citizens and their local government, fostering an environment of mutual trust and engagement. By integrating citizens directly into the data collection and policy-shaping process, we ensure that local governance is responsive and attuned to the community's needs and perspectives. This endeavor is not only about enhancing the quality of life through smart city innovations, but also about reinforcing the social contract by demonstrating a genuine commitment to considering citizen input. Accordingly, this aligns with and actively contributes to the Sustainable Development Goals, promoting well-being and ensuring inclusive participation in all facets of urban life. Gathering information from citizens in a smart city is essential for institutions to understand what measures to take to enhance the quality of life of its residents. Various methods can obtain this information, including observation, interviews, bibliographic study, IoT, public cameras, websites, etc. Lately, totems have been frequently used, to offer online bureaucratic services to the public to simplify and speed up procedures [12]. However, concerns about protecting citizens' data are significant, focusing on potential exploitation within the framework of neoliberal ideologies [13]. Recently, the term "smart street furniture" has been used to describe interactive equipment [14]. Interactive kiosks find practical applications in various sectors such as transportation systems [15], tourism [16], healthcare [17], and enhancing societal value [18].

In the case study of Balaguer, citizen data was collected through questionnaires displayed on a smart street furniture device known as a totem, a device installed at the town hall entrance in the city's most central square. The totem allowed a two-way communication channel between citizens and the city governmental institutions. This information is crucial for developing effective social policies, fostering trust in institutions [19–22], and meeting the needs of citizens.

Our study leverages a multifaceted approach that integrates quantitative data analyses—derived from on-site sensors and simulations—with qualitative insights from citizen science activities. The quantitative analyses provide the empirical evidence needed to understand energy demand patterns, while the citizen science component enriches this data with human insights, making the research outcomes more holistic and actionable. This interconnected approach ensures that policy interventions are not only data-driven but also aligned with citizen perceptions and behaviors, enhancing the likelihood of successful implementation and positive outcomes regarding sustainability and quality of life improvements.

2. Methods

2.1. Methodology

This study employed a mixed-method approach using qualitative and quantitative data to investigate energy-demand monitoring and the energy-demand decrease and citizen acceptance in a district of a municipality. The study used three levels of data gathering: (1) quantitative data coming from on-site sensors; (2) quantitative data coming from simulation of the area, and (3) qualitative data coming from questionnaires developed with a totem located in the city center.

2.2. Case Study

The case study investigated is in Balaguer, a city with approximately 15,000 residents in the province of Lleida, Catalonia, Spain. Figure 1 provides an aerial view of the district case study.

The entire district spans about 8825 m^2 and comprises various public buildings with diverse functions. From an energy standpoint, all these structures stand to benefit from efficiency measures due to common issues such as insufficient insulation, predominantly single-pane windows, and the prevalence of low-efficiency energy systems and lighting.

Figure 2 reports some pictures of the main facades of the buildings and some brief descriptions of the buildings within the district which are as follows:

- Angel Guimerà Public School (1800 m^2): Primarily operational during the day with limited afternoon occupancy and a month of inactivity in August. Envelope materials include solid brick and plaster, with single-glazed windows. Gas heating is utilized, and cooling is provided by single split systems in most areas, with some zones remaining unconditioned.
- Xalet Montiu (461.44 m^2): A historic building showcasing modernist architecture, operating mainly from 9:00 am to 8:00 pm. Envelope features solid brick and plaster, along with single-glazed windows. Various split air conditioner systems complement radiator-based heating, with cooling based on split single systems.

- Educative Service of La Noguera (1093 m^2): Mainly active during the day with limited afternoon occupancy and a month of inactivity in August. Envelope comprises solid brick and plaster, with double-glazed windows. Gas burner and radiators facilitate heating, while multi-split air systems are employed for cooling.
- Museum of La Noguera (1496 m^2): The building operates at different hours during the week. Envelope materials include brick, polystyrene, clay, plaster, and double-glazed windows. Gas is used for heating, and air systems distribute it, with chiller-based cooling systems of low efficiency.
- Library Margarida de Montferrat (3975 m^2): It operates with variable schedules during the week. Envelope features brick and plaster, along with double-glazed windows. Heating relies on radiators gas-based, while split air conditioning systems provide cooling for the entire area of the building.

Figure 1. Aerial view of the district.

Figure 2. (**A**) Anguel Guimerà Public School, (**B**) Museum of La Noguera, (**C**) Xalet Montiu, (**D**) Educative Service of La Noguera, and (**E**) Library Margarida de Montferrat.

2.3. Monitoring of Public Buildings

One key aspect of any research that involves either modeling, machine learning, big data, and so on, is the availability of data: a sufficient amount of data and adequate data quality are required for statistical, machine learning, and simulation models to be accurate. Within this project, one of the lines of work was the design of a method to monitor several data points from the buildings involved on the project. The requirements for the design were as follows:

1. It has to involve small form factor sensors (they should be aesthetically unpleasant and bulky, as they are placed in public places).
2. Data from the sensors have to be collected wirelessly (for the same reasons as 1).
3. As one of the goals was to enable citizen science and participation (a future endeavor), sensors and components should be cheap, and, if possible, COTS (Components Off The Shelf).
4. All protocols and software, wherever possible, should be open source and based on standards (to ease replication).

From these requirements, the sensoring architecture thus resulted in using the widely available COTS sensoring from Xiaomi/Aqara (China), Raspberry PI SBCs, from Raspberry Foundation (UK), as collecting nodes, and MQTT/InfluxDB/Grafana as transport, collection and graphing, respectively. An overview of the used architecture is shown in Figure 3.

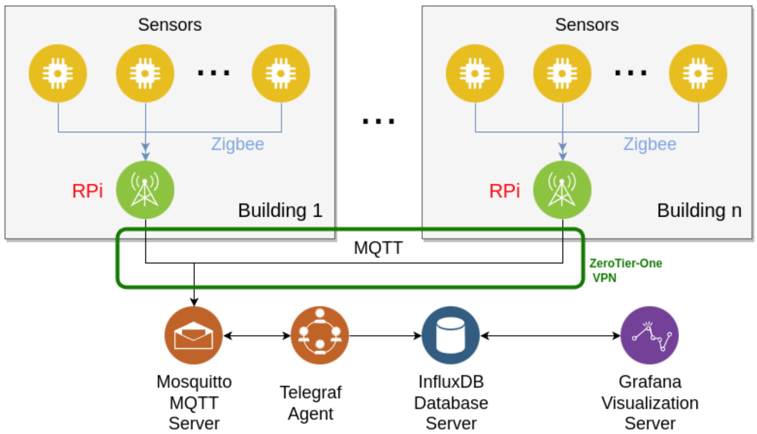


Figure 3. Overview of the used architecture for buildings monitoring and data collection and storage.

2.4. Modelling and Simulation of the District

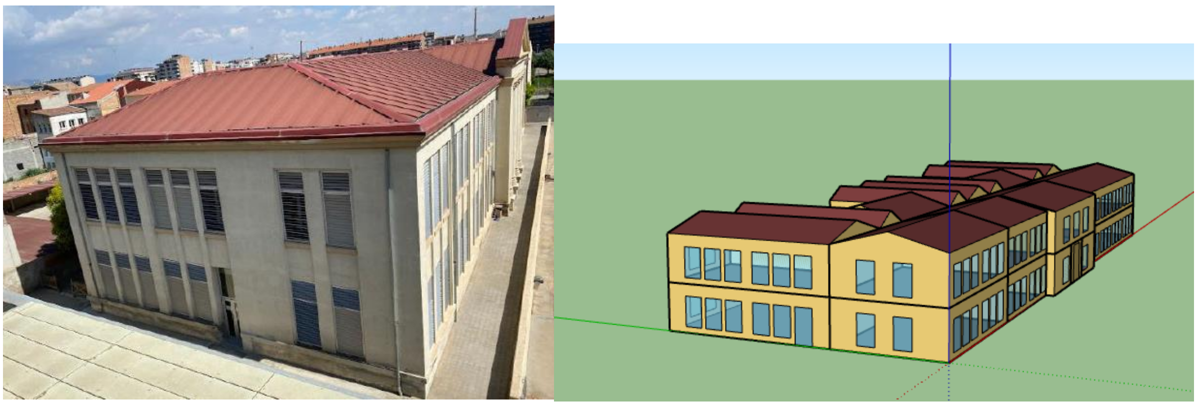
The simulation section of the study includes some further methodological stages:

i. On-site investigation of the district: multiple visits to the buildings were conducted between 2020 and 2022. Comprehensive data, including details about the building envelope, energy systems, occupancy levels, internal loads, lighting and equipment, and energy bill usage, were systematically gathered.
ii. District energy modeling and model calibration: This phase was executed within the Energy Plus modelling and simulation environment. All relevant data obtained during the on-site investigations were input into the models. A calibration procedure was executed, focusing on refining the accuracy of key variables that carried uncertainty.
iii. Towards the level of Positive Energy District, renovation, and energy efficiency measures: several solutions for enhancing energy efficiency and energy generation were introduced and implemented in the calibrated model. The subsequent calculation involved assessing the impact of these modifications on the overall energy consumption and verifying the achievement of the definition of the Positive Energy District.

The buildings models were developed in accordance with the available modelling information to mirror the existing district geometry. Screenshots in Figure 4 depict the models alongside the actual structures. The model geometry was developed using the Sketchup environment. Further information regarding the thermal performances of the building, either assumed based on the available information or computed as reported in Table 1, also reported the thermal transmittance, (U-value), defined as the rate of transfer of heat (in watts) through one square meter of a structure divided by the difference in temperature across the structure, expressed in W/(m²·K).

Table 1. Building energy performance parameters and assumptions.

Parameter	Angel Guimera Public School	Museum of La Noguera	Xalet Montiu	Educative Service of La Noguera	Library Margarida de Montferrat
Area m^2	1800	1496	461	1093	3975
U Exterior fenestration average (W/m^2K)	5.80	2.72	5.80	2.72	2.72
Average solar heat gain coefficient (−)	0.80	0.65	0.80	0.65	0.65
U Opaque exterior wall average ($W/m^2 \cdot K$)	1.2	0.3	1.2	1.2	1.5
U Opaque exterior floor ($W/m^2 \cdot K$)	3.7	3.7	3.7	0.5	3.7
U Opaque exterior roof ($W/m^2 \cdot K$)	5.1	1.7	2.3	0.7	0.8
Occupant	241	157	10	36	381
Lights (W/m^2)	9	7–20	9	10	10
Electric equipment (W/m^2)	0–14	0–3	0–10	0–7	3–5



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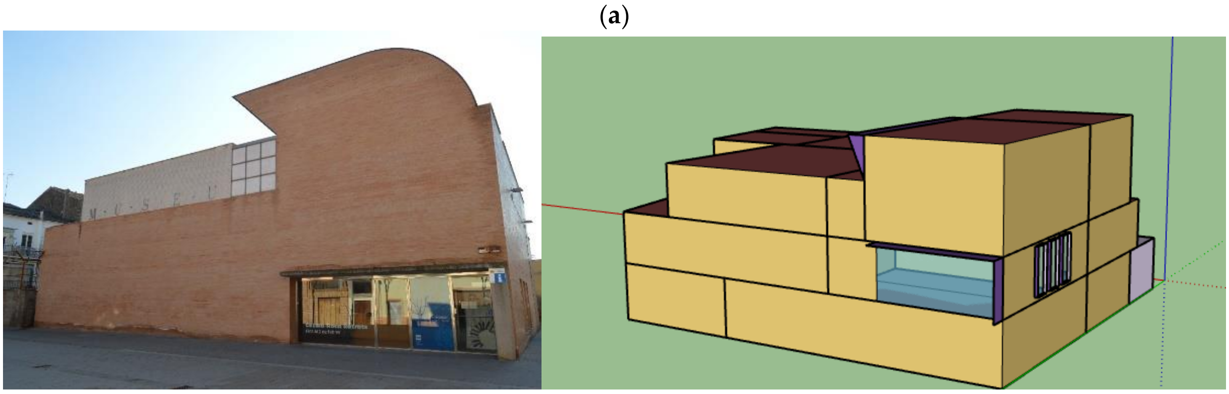
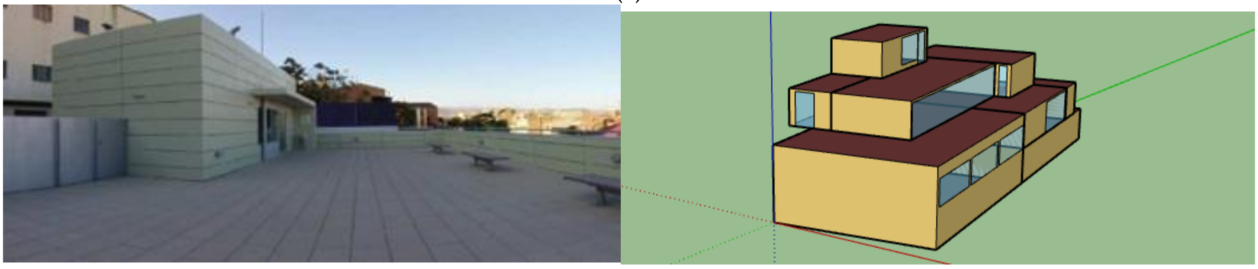


(**b**)

Figure 4. *Cont.*

(**c**)



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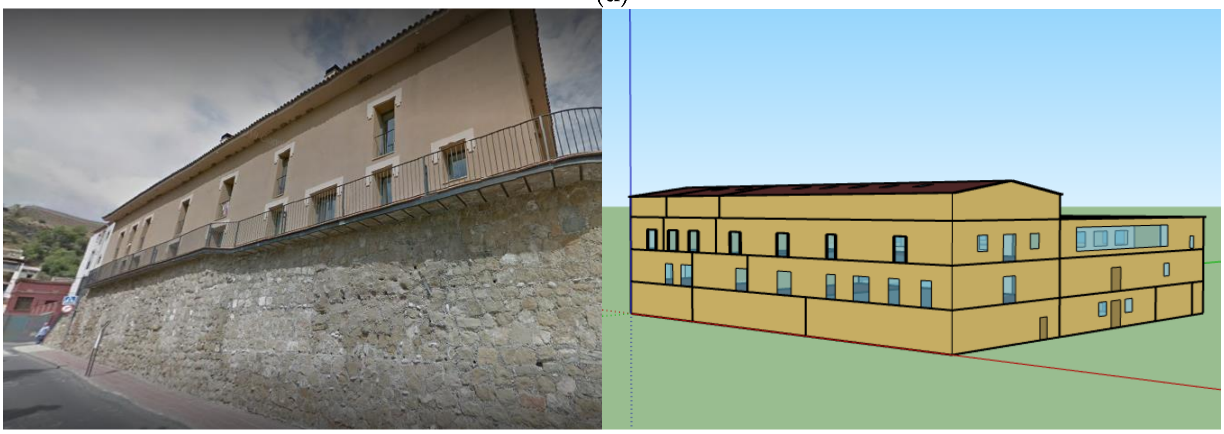


(**e**)

Figure 4. (**a**) Anguel Guimerà Public School, (**b**) Museum of La Noguera, (**c**) Xalet Montiu, (**d**) Educative Service of La Noguera, and (**e**) Library Margarida de Montferrat.

The building energy simulation was performed utilizing non-steady state calculations within the Energy Plus environment. The computation of air temperature and heat flows employed the heat balance method. Internal loads, encompassing lighting, occupancy, and appliances, were determined based on data acquired during the on-site investigation. Additionally, details on energy system usage, schedules, and occupancy information were derived from on-site surveys. The modeling of energy systems adopts a simplified approach, treating them as thermal ideal loads, and uses fixed efficiencies for the various components of the energy systems. A validation procedure was performed to compare baseline energy use (3 years energy bills for electricity and gas) with the actual models, in order check their reliability with a monthly base for validation for both electricity and gas energy consumption which is aimed at guaranteeing a lower than 10% error with this timestep.

Once the existing district was modelled and validated, renovation and renewable energy solutions were designed, modelled, and simulated in an energy plus environment to investigate the potential of the district to be a positive energy. The district renovation simulation incorporates the modelling and simulation of several technical solutions:

- External wall insulation coating (polystyrene): applied to buildings including Xalet Montiu, Servei Educatiu de la Noguera, Àngel Guimerà Public School, and Biblioteca Margarida de Montferrat.
- Roof external insulation coating (polystyrene): implemented in Xalet Montiu, Servei Educatiu de la Noguera, Àngel Guimerà Public School, and Biblioteca Margarida de Montferrat.
- Window substitution: windows with a thermal transmittance up to 1.6 $W/m^2 \cdot K$ and a Solar Heat Gain Coefficient (SHGC) of 0.6 are introduced to Àngel Guimerà Public School and Xalet Montiu.
- Replacement of lighting bulbs and heating/cooling generators: commercially available, state-of-the-art heat pumps (air or water-based) with Coefficient of Performance (COP) and an Energy Efficiency Ratio (EER) greater than 4.5 are implemented.
- Photovoltaic generation systems installation: deployed on surfaces facing south, south-east, and south-west, as well as on on-site close surfaces, such as parking areas. The planned total installation is 104 kW, covering a total area of 528 m^2, as detailed in Table 2.

Table 2. Generation of all roof-installed PV systems within the district.

	PV Power [kW]
Xalet Montiu	8.75
Àngel Guimerà Public School	26.6
Educative Service of La Noguera	6.3
Library Margarida de Montferrat	11.5
Museum of La Noguera	21
PV installation A	58
PV installation B	30.8

- Utilization of a 250-kWh storage system in scenario, reflecting the concept of structuring an energy community with peer-to-peer energy flow connections across the entire district.

The performance of the district in terms of the potential positive energy district was investigated according to the following equation:

$$B = \sum_{i=1}^{n} E_i * W_i - \sum_{i=1}^{n} C_i * W_i \quad (1)$$

where B refers to the PED balance results; i refers to the generic energy carrier being used within the district area; E_i is the energy generated on-site by means of renewable energy sources; C_i is the energy use on-site per energy carrier; and W_i is a weighting/conversion factor (e.g., from final energy to primary energy/carbon equivalent) [23]. An explicative view of all the other PV generation solutions planned in close-by buildings is in Figure 5.

The effect of the battery is quantified via the use of the Load Cover Factor [24] (Equation (2)), and is defined as the percentage of the electrical demand covered by on-site electricity generation. In periods with no on-site generation, the load cover factor value is zero, while the highest values are reached when there is a coincidence between the profile shape of electricity load and self-generation.

$$fload = \frac{\int_{\tau_1}^{\tau_2} min[g(t) - S(t) - \zeta(t), l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt} \quad (2)$$

where *g(t)* refers to on-site electricity generation (kW); *S(t)* refers to storage (kW); *f(t)* represents energy losses (kW); and *l(t)* is the energy load (kW).

Figure 5. Further PV installations planned.

2.5. Questionnaires

The approach of the questionnaires followed a four-phase methodology (Figure 6). The first phase involves designing a survey to gather necessary data. After conducting our study, we identified an interactive kiosk as the most suitable Smart Street Furniture to display information gathered by different humidity and temperature sensors throughout the city. In the second phase, we implemented a citizen data collection system with a web application focusing on Human–Computer Interaction and User Experience to encourage massive citizen participation. This web application allows citizens and visitors to access the survey designed for this study. The third phase involves placing the interactive kiosk in the town hall, a central location for Balaguer. The survey aims to collect responses from citizens and visitors to analyze the information gathered. Finally, in the fourth phase, we analyze all the collected data, discuss it, and draw conclusions. In the fourth phase, the government analyzes the data collected and adjusts their actions to align with the citizens' needs. City councils seek citizen feedback on aspects of city life for more attractive, useful, and closer projects. In this way, they help to enhance citizens' trust in their government institutions. Figure 6 provides a graphical illustration of the entire process.

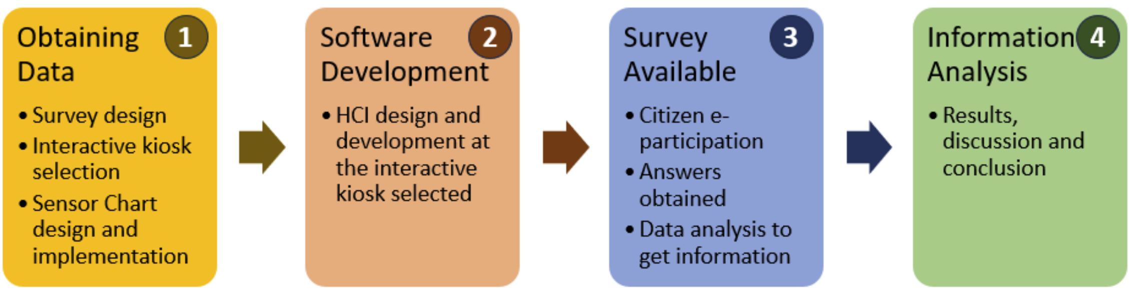


Figure 6. Four-phase methodology diagram.

As part of the infrastructure to complete questionnaires, an interactive kiosk named Totem Outdoor DELUX, ins-digital (Madrid, Spain), with a 65″ 2500 cd screen is provided (Figure 7). It runs on an Intel I3 CPU and Windows 10 Pro 64-bit operating system. This kiosk displays three types of data: information about the sensors installed in various Balaguer buildings, details required to complete the questionnaires, and static information about Balaguer city and town hall.

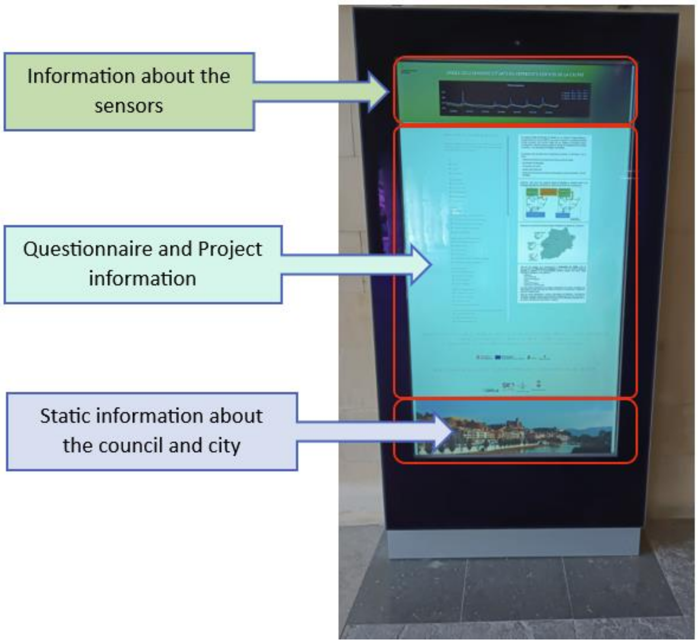


Figure 7. Balaguer interactive kiosk displaying the system implemented.

All this information is displayed on a web page. For this purpose, the interactive totem connects to two servers. The first is a web server with HTML5, CSS3 and PHP 8.1 code, which manages the data obtained from citizens in a relational database. The second is a Grafana server (V9.0.2), which collects data from the different sensors in relevant buildings in Balaguer and generates pre-designed graphics. The Grafana server then sends this information to the digital totem for display in real-time.

The questionnaires given to citizens included questions about their general information (age and gender), their life in Balaguer (origin, length of stay, neighborhood of residence, and preferred neighborhood), their opinions about the city, their perception of the atmospheric temperature, and their emotions generated by the weather. The questionnaires were designed using Nielsen's heuristic rules [25]. They were displayed in the central left part of the device screen to make it easier for citizens to interact with the system. The questionnaires were presented as a challenge under the question "How Balaguerian are you?" to motivate citizens to participate. At the end of the participation, the system displayed statistics that compared the individual answers of each citizen with the accumulated answers of all the participating citizens.

The objective of collecting and analyzing the questionnaire data was to interpret social data and their relationship with the following SDGs:

- SDG3: Good health and well-being: citizens should be aware of the temperature in public buildings, as it serves as an example of the temperature that should be maintained in private homes.
- SDG5: Gender Equality: the study results have been analyzed from the perspective of the participants' gender.
- SDG9: Industry, innovation, and infrastructure: the totem pole installed on the city hall's door is an innovative public infrastructure for the city.

- SDG10: Reduce inequalities: to reduce inequality, citizens can provide input on which neighborhoods need revitalization.
- SDG13: Climate action: analysis of wind chill's impact on women, men, and intersex people raises awareness of climate change.

3. Implementation Details

From the requirements already stated, we proceeded to implement the designed architecture, shown in Figure 3.

The details of each of the elements of this architecture and the reasons why they were selected are as follows:

- Aqara/Xiaomi Zigbee Sensors. We wished to have standard off-the-shelf components wherever it was possible, to lower the cost of possible replications of that setup, especially for citizen science. Zigbee is a wireless transmission protocol designed for IoT (Internet of Things) data transmission, and is becoming, due to its reliability, low power requirements, area coverage, and low price, the de facto standard for home sensoring. There are several manufacturers of Zigbee based devices, and one of such, Xiaomi/Aqara, has a wide selection of products, is affordable, and is aesthetically pleasant enough so they will not stand out once installed in place.
- Raspberry PI (RPi3). For the data collection nodes, we require a small form factor computer, which is affordable and easy to acquire. One such device is the RaspberryPi (Raspberry Pi Foundation, UK). For the deployment for this work, we used RaspberryPi 4/2 GB of RAM, the state-of-the-art SBC at the moment. Other models (RaspberryPi 5, or RaspberryPi Zero 2W) could be used, as they fulfill the requirements of RAM/CPU for the task they have to perform. These RaspberryPi will require this additional hardware and software:
  - CC2531 USB-2-Zigbee: Any USB to Zigbee device will operate. For our project we used one based on a Texas Instrument CC2531 (with a price tag around 10EUR each), with a modified firmware from the Zigbee2MQTT project.
  - Zigbee2MQTT: Zigbee2MQTT is a software system that, using a USB 2 Zigbee dongle, receives Zigbee messages from a network of sensors and relays them using MQTT to a MQTT broker. This software is running on a Docker container on the RPi3 for better isolation and more reliability.
- ZeroTier-One VPN. For increased security, the connections between the RPi3 nodes and the central MQTT broker are routed through a secure VPN (Virtual Private Network) using ZeroTier-One service.
- Mosquitto MQTT Server. All MQTT messages with the sensor data are transmitted from the RPi3 via the local building internet (through a VPN) to a Mosquitto MQTT Server that acts as the MQTT broker.
- Telegraf Agent. A Telegraf agent is running continuously subscribed to the MQTT broker and rerouting (and format translating) all messages to the InfluxDB database server.
- InfluxDB Database. Data is stored on an InfluxDB instance. As data coming from sensors is a time-series data stream, InfluxDB is one of the best choices for storing that data.
- Grafana Visualization Server. We are running a Grafana instance that, as it has the InfluxDB instance as a data source, allows us to visualize the collected data, as seen in Figure 8. The Grafana instance also provides the graphs that will be visualized as part of the display of the totem.

As can be seen from the detailed description we choose all elements of the architecture, both hardware and software, to be as standard, cheap, and affordable as possible, with the focus on having an easily reproducible setup. An example of the results obtained is presented in Figure 8.

After some months of operating with this architecture, we can see, on the hardware side, that:

- The sensors by Xiaomi/Aqara, priced around 5 EUR each, have enough precision for this kind of study: temperature can be between −20 °C and +50 °C, with a ±0.3 °C error; humidity can be 0–100% RH (non-condensing), ±3%, and, for those with atmospheric pressure, it can be between 30 kPa and 110 kPa, ±0.12 kPa. Their battery, a CR2032 cell, lasts around two years. And the chosen communications protocol, Zigbee, has a longer range than WiFi or Bluetooth and lower power consumption.
- The RPi is a robust SBC, and the latest models (Zero 2W) are widely available with a price tag floating around 20 EUR.
- The required Zigbee USB dongles have become, thanks to the expansion of domotic hardware by big brands (IKEA and Lidl amongst them), widely available, with prices between 10 EUR and 30 EUR (depending on antennas, range, brand, etc.).

On the software side:

- The combination of MQTT for messaging, InfluxDB for data storage, and Grafana as a visualization platform, has proven reliable and robust. No wonder this combination is becoming the powerhouse behind many home automation and sensoring projects.

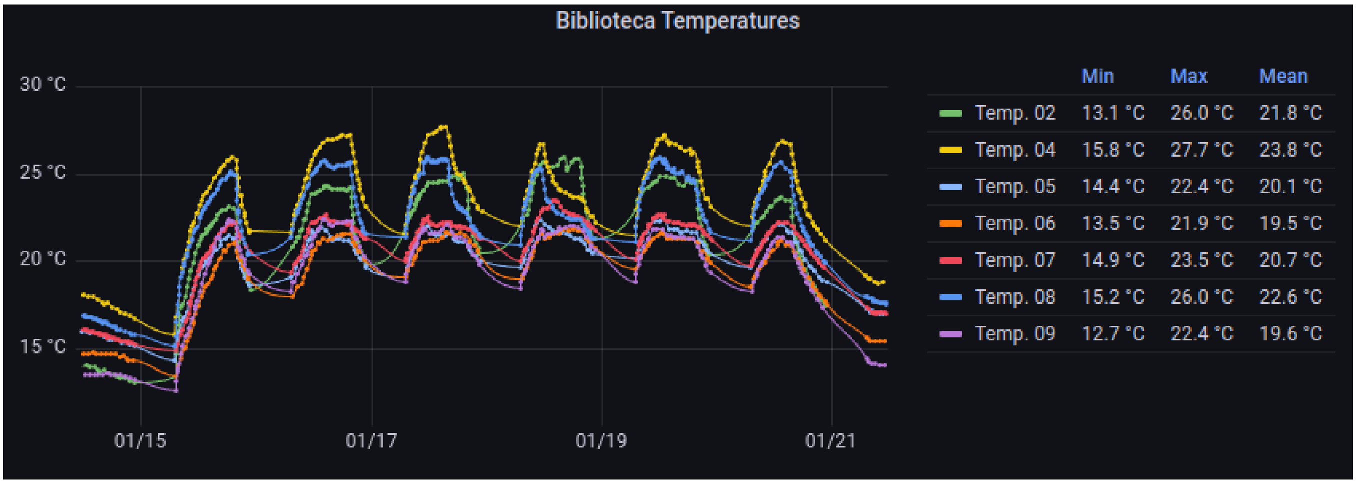


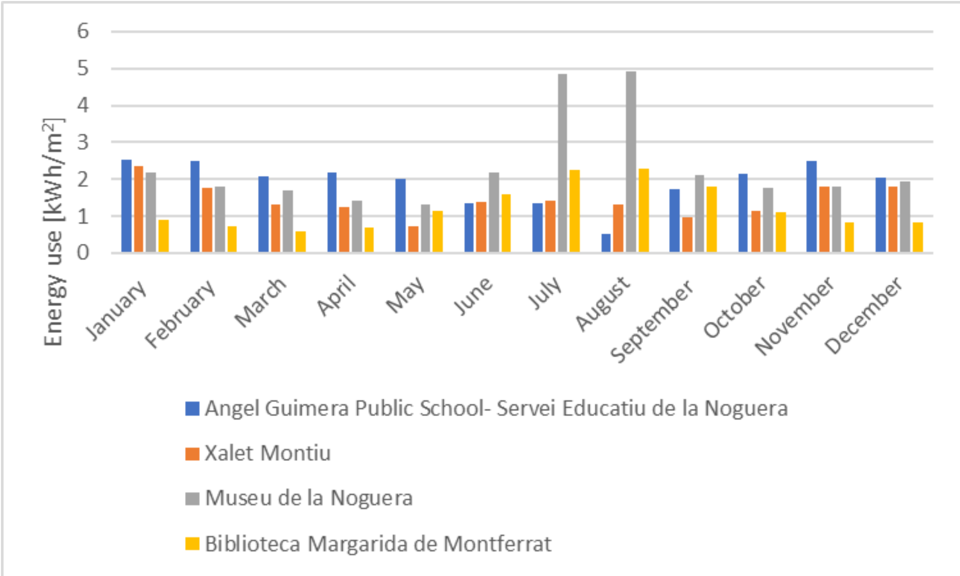
Figure 8. Example of the data obtained in the library.

4. Results and Discussion

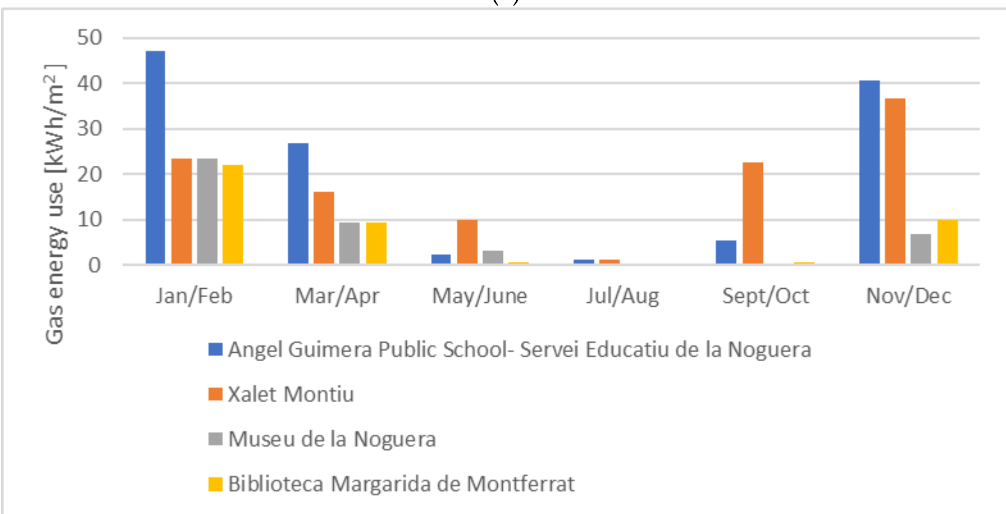
Given the results after several months of monitoring, it is clear that this architecture could easily be expanded to encompass a more ambitious citizen science project where citizens can easily deploy at home nodes for data collection with a low and affordable cost. Moreover, due to the low cost per citizen (under 100 EUR for a complete setup with 5+ sensors), if funding or sponsorship is available, such solutions could surely add several data collection points for a smart monitored city.

The outcomes derived from the methodological steps detailed for simulations earlier are presented below. Figure 9 succinctly presents the monitored data, offering insights across the entire district. The information includes detailed breakdowns of electricity and gas consumption at the individual building level. Table 3 describes the total consumption for each building, divided into thermal and electrical consumption. Figure 8 instead shows the main results achieved for district energy use within the district, respectively, including electricity and gas, based on the total computed in Table 3.

The electricity and gas expenditure over a two-year time span were averaged to facilitate a meaningful comparison with simulation data. The deviation between monitored and simulated results on a monthly base is presented in Figure 10. The results for the entire simulation year were then aligned with the corresponding billing periods for each building in the district. The annual deviation consistently falls below ±10%, confirming the soundness of the modeling and simulation efforts. The results for energy generation according to all the assumptions described in the methodology section are reported in Table 4. Table 5 instead shows the results of energy consumption due to renovation at the district level.



(**a**)

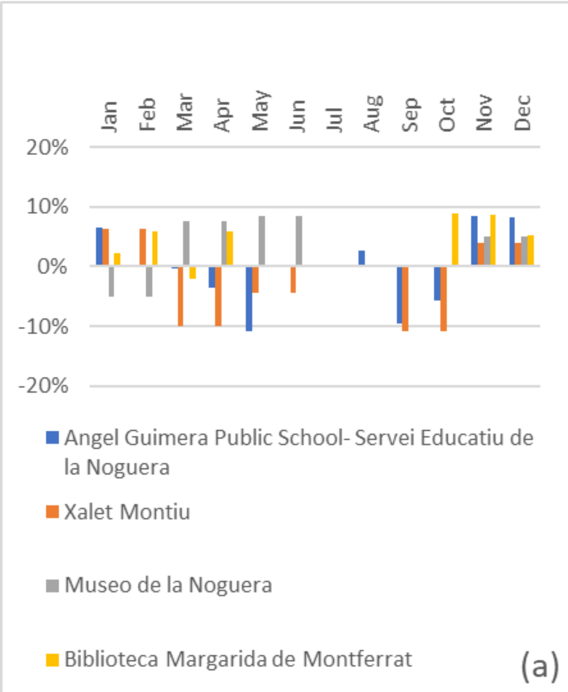


(**b**)

Figure 9. (**a**) District electricity use (average monthly), and (**b**) district gas use (average monthly).

Table 3. Thermal and electricity consumption.

Consumption	Xalet Montiu	Àngel Guimerà Public School	Biblioteca Margarida de Montferrat	Museu de la Noguera
Electricity and cooling consumption [kWh]	8202	64,596	55,114	40,940
Gas consumption [kWh]	50,282	367,853	175,482	64,700



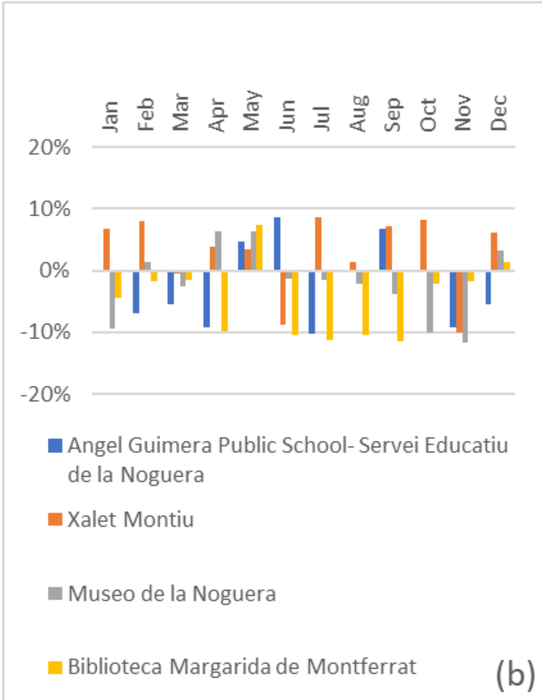


Figure 10. (**a**) Final error analysis in the electricity, and (**b**) gas consumptions for each building.

Table 4. Electricity generation per PV plant installed.

Building	PV Area [m^2]	Generation [kWh/y]
Xalet Montiu	50	11,540
Àngel Guimerà Public School	170	37,760
Servei Educatiu de la Noguera	74	8729
Biblioteca Margarida de Montferrat	73	16,647
Museu de la Noguera	234	29,212
PV installation A	769	79,661
PV installation B	352	40,605

Table 5. Pre- and post-renovation electricity and gas use.

Month	Electricity		Gas	
	Renovation	Existing District	Renovation	Existing District
Jan	33,624	15,137	0	270,208
Feb	28,501	13,531	0	
Mar	20,343	11,522	0	135,898
Apr	18,422	11,723	0	
May	13,371	12,565	0	18,954
Jun	9628	14,036	0	
Jul	14,168	20,721	0	3,918
Aug	14,333	18,583	0	
Sep	11,547	15,810	0	28,539
Oct	12,855	13,729	0	
Nov	18,620	14,022	0	184,459
Dec	24,119	12,987	0	

The electrification strategy implemented in the district, despite leading to an overall electricity usage increase of approximately 25% compared to the current system, has effectively eliminated gas expenses related to domestic hot water and heating. Additionally, this strategy ensures a substantial enhancement in building performance, notably reflected in discernibly lower electricity requirements during the summer months, attributable to reduced cooling needs. Figure 11 describes the primary energy balance as described in Equation (1) and further clarifies the aims of the electrification strategy pursued [26]. It describes the energy balance between energy use at the district level and the renewable energy solutions described in Table 2, the existing district highlights severe deficiencies across the year while the renovated one allowed to meet a positive energy balance across the year. In terms of overall generation and consumption of the renovated district, Figure 12 illustrates the monthly trends for electricity generation and consumption.

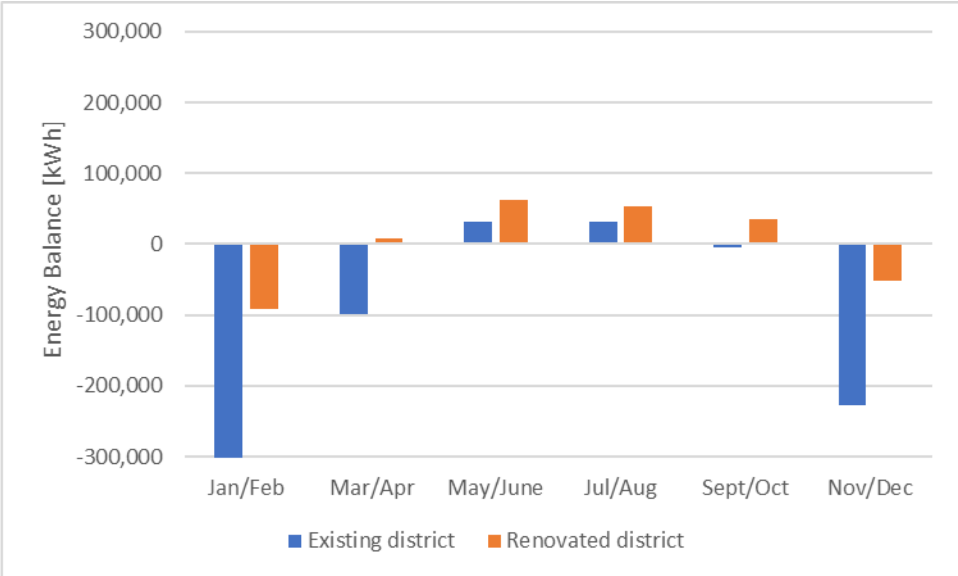


Figure 11. Primary energy balance.

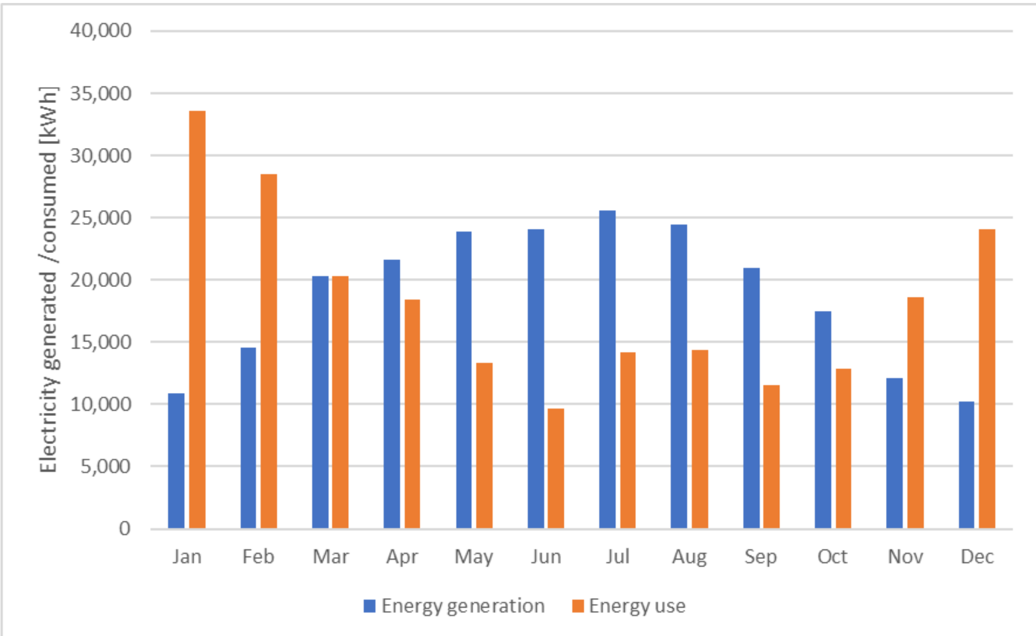


Figure 12. Electricity use and generation for the overall Balaguer district.

Although the overall generation is higher than consumption (overall generation is equal to 226,090.13 kWh, while consumptions amount to 219,532.04 kWh) during the year examined, it is worth mentioning that some deficits are traced for the winter months causing a significant import from the grid which is counterbalanced by a net export during summer.

Figure 13 describes the impact of the battery on the interaction of the district with the energy grid. The graph reports hours of the day on the x-axis and all 365 days of the year on the y-axis thus showing all hours of the year. The impact of the battery is clearly highlighted during days 50–300, whereas the load cover factor is nearly constant at one during most hours in the day throughout the year, thus theoretically allowing the smart district to become nearly independent from the grid during this timeframe. The average yearly load cover factor is improved from the existing district to the renovated one from 41% to around 80%.

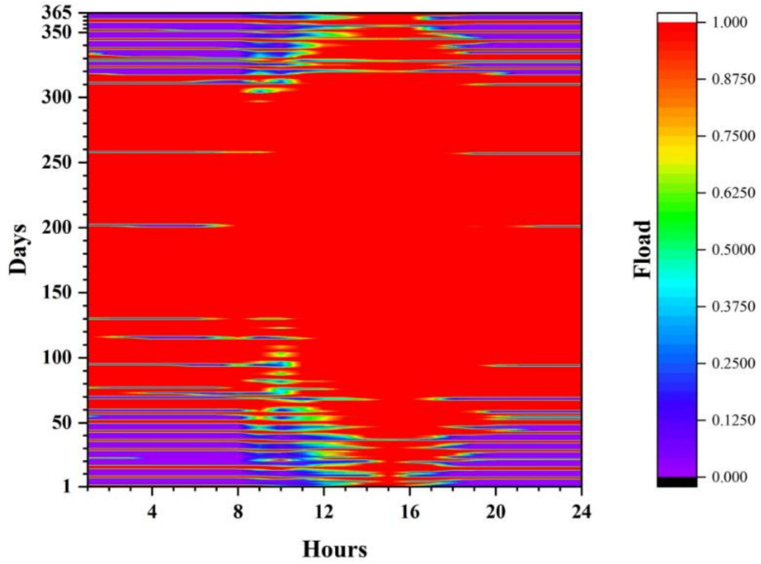


Figure 13. Load cover factor at the district level.

On the other hand, citizen response was positive, with 148 surveys collected between July and November 2022, resulting in 2528 answered questions.

To achieve gender equality, as outlined in SDG 5, we have analyzed the data from a gender perspective and presented the information in the graphs in a disaggregated manner. Figure 14 illustrates the distribution of citizen participation by gender and age. Notably, the age groups of 41 to 60 years and 21 to 40 years have the highest number of participants. It is important to note that in all age groups, except those aged 15 to 20 and over 60, men represent more than 50% of the participants.

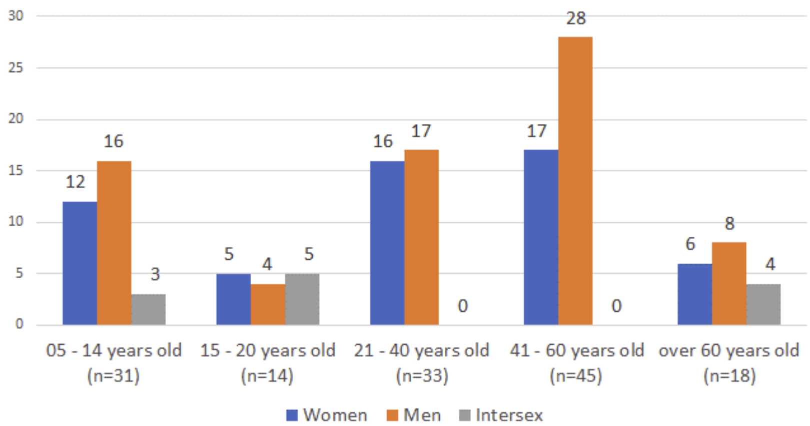


Figure 14. Breakdown of citizen engagement by gender and age group from surveys collected between July and November 2022.

To tackle inequalities per SDG 10, which focuses on reducing inequality within and between countries; the City Council of Balaguer has taken a step forward by allowing the residents to express their preferences for the neighborhoods where they would like to live. This approach aims to prioritize city actions and identify areas that require revitalization. Figure 15 illustrates the respondents' preferences for residential areas. It is worth noting that the neighborhoods of "Eixample" and "Casc Antic" have received more favorable results, while fewer respondents have expressed a desire to reside in the "Secà" area.

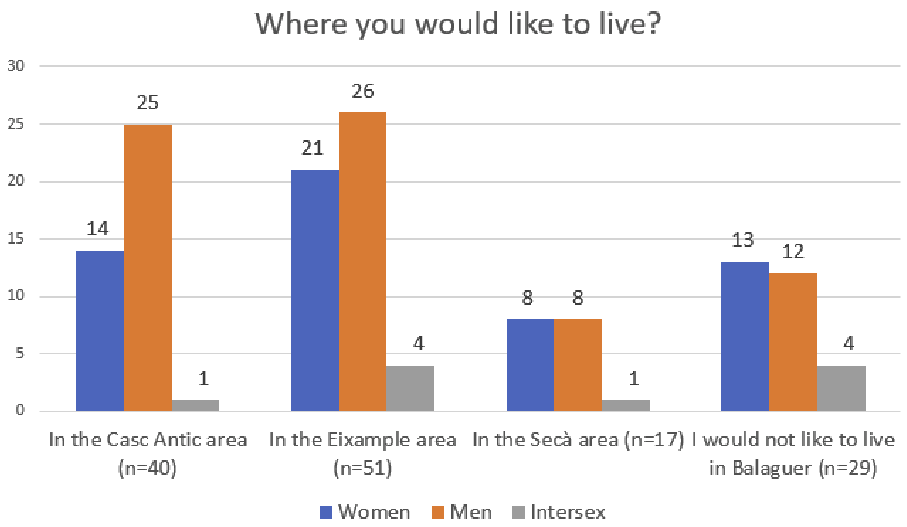


Figure 15. Respondents' preferences for residential areas from surveys collected between July and November 2022.

As per SDG goal 13 (climate action), raising awareness about climate change involves more than just monitoring weather data. It is also important to consider how people, regardless of gender identity, perceive the weather. Figure 16 illustrates how the general public perceives wind chill. The objective is to provide the Balaguer city council with valuable information that can assist them in implementing measures to improve the well-being of citizens concerning the thermal sensation they perceive. WeatherSpark [27] has defined the temperature ranges using six distinct categories: 1-Very hot (34–30 °C), 2-Hot (29–25 °C), 3-Normal (24–19 °C), 4-Cool (18–14 °C), 5-Cold (13–7 °C), and 6-Very cold (below 7 °C). Figure 5 shows these temperature ranges by color bands. It should be noted that no responses were received from the "6-Very cold" category, so it was excluded from the analysis.

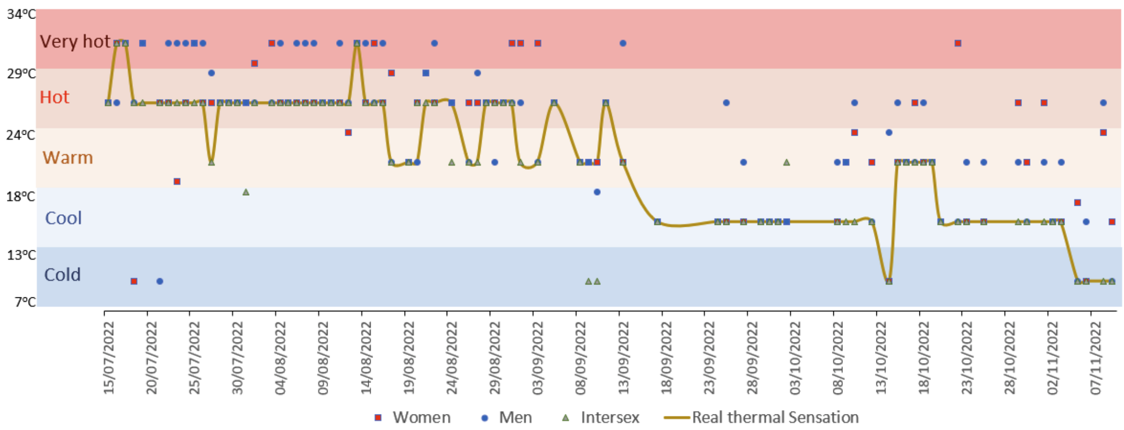


Figure 16. Comparison between real thermal sensation and perceived thermal sensation from surveys collected between July and November 2022.

As a part of the analysis, separate tables are created for different genders, such as female, male, and intersex. These tables compare the thermal sensation perceived by the respondents with the actual weather data. The deviations are calculated by comparing the average temperature range provided by two weather stations located in Balaguer and the nearest village (Ós de Balaguer) on the same date. For instance, if a respondent perceives a day as "Cold" (coded as 4) while the mean provided by the weather stations is "Cold" (coded as 2), the deviation for that day is −2 (Thermal sensation minus real temperature), indicating a lower perceived temperature. The resulting data show the thermal sensation deviation for each day and gender.

It is important to note that not all genders provide data every day. For days when no data was provided, it was assumed that there was no deviation from the real thermal sensation. The analysis shows that, in most cases, the deviation in perceived wind chill is minimal and falls within the upper or lower temperature range, as seen in the one-band row in Table 6. A deviation of three bands in the temperature range is considered an outlier, as shown in Table 6. Based on the results in Figure 15, respondents generally perceive temperatures to be higher than the real thermal sensation of the day.

Table 6. Deviation between the real thermal sensation and perceived thermal sensation by temperature bands (data expressed in days) from surveys collected between July and November 2022.

Deviation	No Deviation	2 Band	2 Band	2 Band
Women	14	17	8	3
Men	17	30	5	3
Intersex	1	3	3	0

Given the high impact of the Sustainable Development Goals driven by the United Nations, it is interesting to evaluate to which ones this study contributes:

- SDG3—Good health and well-being: decreasing GHG emissions and improving thermal comfort inside the buildings increased the population's health and its well-being.
- SDG4—Quality education: citizen science contributes to lifelong learning of the citizens involved in the actions.
- SDG5—Gender equality: The study results have been analyzed from the perspective of the participants' gender.
- SDG7—Affordable and clean energy: decreasing the energy demand of buildings decreases energy poverty; increasing the use of renewable energy contributes to having affordable, reliable, and sustainable energy.
- SDG9—Industry, innovation, and infrastructure: introducing innovation in public buildings and private households contributes to this SDG.
- SDG10—Reduce inequalities: decreasing energy demand and contributing to more affordable energy in buildings reduces inequalities between citizens.
- SDG11—Sustainable cities and communities: the study contributes to making cities and human settlements inclusive, safe, resilient, and sustainable.
- SDG12—Responsible consumption and production: an objective that also applies to energy.
- SDG13—Climate action: decreasing energy demand in buildings and introducing renewable energy production are clear actions towards climate change mitigation.
- SDG16—Peace, justice, and strong institutions: the involvement of municipality authorities in citizen science and energy-use optimization contributes to having stronger institutions.

5. Conclusions

Following the presentation of data within the totem increases awareness about energy demand and its consequences. Moreover, citizens' interaction with the totem showed increased interest in reducing energy demand in their households.

This study shows the importance of citizen science to increase awareness on topics such as energy demand, renewable energy, and climate change. But it also gives a clear example of how citizen science can improve the quality of research carried out. Even more interesting is the involvement of the municipality authorities. This study increased awareness among municipality authorities on the topic but also increased their knowledge; helping them implement actions to reduce the energy demand in public buildings and helping them in deploying policies to decrease energy demand in buildings, increase the use of renewable energy, and increase awareness among citizens. It is important to note that the proposed work aims to not only gather and analyze data, but also understand people's perceptions of significant aspects of the city, such as temperature sensations and perceptions of the citizens of Balaguer.

Our research explicitly demonstrates the role of citizen science in enhancing public awareness about key urban issues. The deployment of the Totem Outdoor DELUX interactive kiosk, alongside its accompanying web application, in the city center of Balaguer, established a comprehensive solution that transcends mere hardware. This system served as a physical and interactive platform for collecting and disseminating information directly from and to the citizens. At the same time, the web application provided an accessible digital interface for deeper engagement. Integrating the totem with the web application facilitated a multifaceted approach to citizen science—citizens could not only view real-time data on energy usage and participate in questionnaires physically but also engage with the content and contribute data digitally. This dual strategy emphasized the importance of a software-hardware symbiosis in enabling citizens to provide qualitative feedback on their perceptions and behaviors, ensuring a richer, more accessible data collection process. This dual flow of information is a quintessential example of citizen science, where the public participates in scientific research to achieve mutual learning experiences. Finally, this study highlights the effectiveness of our approach in fostering a more informed and participatory urban community, where citizen science acts as a catalyst for enhancing public awareness and influencing policy making. As part of future work, the city council will seek the citizens' opinions on the measures taken based on this study. In this way, citizens can provide feedback on whether the measures align with expectations, if progress is being made towards meeting SDGs, and if trust in government institutions has improved.

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