A Sensor Network for Existing Residential Buildings Indoor Environment Quality and Energy Consumption Assessment and Monitoring: Lessons Learnt from a Field Experiment

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Abstract: Enhancing residential buildings energy efficiency has become a critical goal to take up current challenges of human comfort, urbanization growth and the consequent energy consumption increase. In a context of integrated smart infrastructures, sensor networks offer a relevant solution to support building energy consumption monitoring, operation and prediction. The amount of accessible data with such networks also opens new prospects to better consider key parameters such as human behaviour and to lead to more efficient energy retrofit of existing buildings. However, sensor networks planning and implementation in general, and in existing buildings in particular, is a particularly complex task facing many challenges and affecting the performances of such a promising solution. In the present paper, we report on a field experiment of a sensor network deployment involving more than 250 sensors in three collective residential buildings in Paris region for the evaluation of a deep energy retrofit. More specifically, we describe the whole process of the sensor network design and roll-out and highlight the main critical aspects in such complex process. We also provide a feedback after several months of the sensor network operation and preliminary analysis of collected data. Reported results path the way for an efficient and optimized design and deployment of sensor networks for energy and indoor environment quality monitoring in existing buildings.

1 INTRODUCTION

Residential buildings are one of the major energy consumers and greenhouse gas (GHG) emitters, with 38.1% of the final energy consumption and 36% of the GHG emissions in Europe (ADEME, 2015). Efforts have been made to reduce the impact of residential buildings on energy consumption with various codes, standards and thermal regulation mandatory compliance for designs of new buildings (ASHRAE, 2013; HARMONIE, 2017). However, given the slow turnover of the building stock in European countries, the effect of these regulations is limited (INSEE, 2017). Hence, existing building retrofit turns into a priority (ADEME, 2018). On the other hand, ambitious massive smart sensor networks plans (European Commission, 2019; European Parliament & European Council, 2009; French Ministry of Ecological and Sustainable Transition, 2016) have been launched in recent years to enhance buildings energy efficiency.

On the other hand, sensor networks have been largely deployed in buildings for energy monitoring and operation (Fan, Xiao, Li, & Wang, 2018) or building energy consumption forecasting (Bourdeau, Zhai, Nefzaoui, Guo, & Chatellier, 2019; Jain, Smith, Culligan, & Taylor, 2014). Studies have used sensors to highlight and characterize the link between energy efficiency and inhabitants' behaviour (Li & Lim, 2013; Pisello & Asdrubali, 2014), identified as one of the main source of energy performance gaps (de Wilde, 2014). Data collection solutions have also been proposed to supervise building energy retrofits (Calì, Osterhage, Streblow, & Müller, 2016; CSTB, 2016; Jankovic, 2019). However, instrumentation solutions deployment is a complex task, facing many challenges and difficulties. Thus, it directly impacts on the quality of the analyses and the efficiency of related energy savings measures (Calì et al., 2016; Jankovic, 2019; Pisello & Asdrubali, 2014).

In this context, we present lessons learnd from a case study of a sensor network deployed in three existing collective residential buildings in France. The

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instrumentation takes part in a larger project that aims to study the impact of deep energy retrofit measures on the studied building energy consumption.

The present paper is organized as follows: we present the project case study in Section 2, then, we describe details of the instrumentation solution in Section 3. A feedback on the main critical points for sensor networks implementation in existing buildings is proposed in Section 4. Finally, Section 5 presents lessons learned from preliminary analysis of data collected after several months of operation of this experimental sensor network.

2 PRESENTATION OF THE CASE STUDY

In the present research project, a group of three existing social residential buildings – 63 apartments over a 4,600 m² living area – is considered for field experimentation. Buildings were built in 1974 in Paris (France) eastern suburb. Shared areas of the three buildings and a 10-apartment sample are selected for a three-year instrumentation period, starting in March 2019. The ten apartments comprise surfaces from 50 to 75 m² distributed in the three studied buildings, on different floors and with different orientations. Apartment case studies have one to two occupants of various ages, professional occupation and living habits.

Case studies only had minor retrofit actions. They are now planned to undergo deep energy retrofit measures over an eighteen-month period in 2020-2021. Retrofit measures will be implemented on occupied site with tenants living in their apartments during the whole retrofit period.

3 INSTRUMENTATION METHODOLOGY

3.1 Instrumentation Plan

3.1.1 Purpose of the Instrumentation

The sensor network deployed aims to provide a multi-scale and multi-targets wireless monitoring solution. It focuses on data collection at both building- and apartment-scale for energy consumption, outdoor and indoor conditions, and inhabitants' comfort and behaviour. The installed sensor network needs to be as non-intrusive as possible. This is essential to ensure that the participants' comfort and living habits remain undisturbed to prevent any bias in the experiment.

The instrumentation solution described in the present paper is the first step of a larger study. Data collected through the sensor network should further serve three consecutive purposes (Figure 1). First, data analysis should highlight behavioural patterns and energy drivers. Results should be used to obtain a calibrated energy model of the buildings prior to retrofit actions to predict their impact on buildings energy behaviour and latter identify performance gaps through a comparison with post-retrofit operation data.

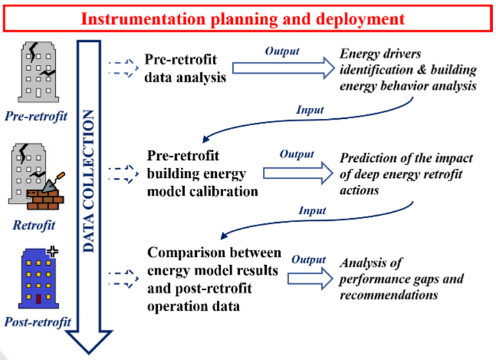

Figure 1: Description of the main steps of the research project starting with instrumentation planning and deployment.

3.1.2 Sensor Characteristics and Deployment

The sensors selection and deployment are performed in two different phases, to set a total number of 259 sensors and connected objects (Table 1). The first deployment phase covers shared areas and entire building level. Although it involves only 10% of the total number of sensors for 35% of the total cost. In this phase, sensors provision, installation and data communication are entirely managed by a hired contractor. Four categories of measurements are targeted:

- overall and detailed electricity demand in shared areas is monitored on the main electricity meters and switchboards. A one-minute measurement time-step is used to capture small electric events such as for timed lighting and lifts usage;
- building-scale thermal energy consumption is obtained using ultrasound thermal energy meters with a five-minute time-step (Figure 2);
- occupancy is assessed using infrared presence detection sensors positioned at the main entrance door of the three buildings;
- combined indoor temperature and humidity sensors are positioned on three floors of each building – ground floor, middle and last floor. Since variations of indoor temperature and humidity are not expected to abruptly change over time, hourly measurement time-step is set;

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- a weather station is positioned on a nearby university building to monitor local air temperature, humidity, wind speed, wind direction, rainfall and solar irradiation at 5-minute time-step.

This first instrumentation step is now fully operational, except for the weather station which is currently being installed.

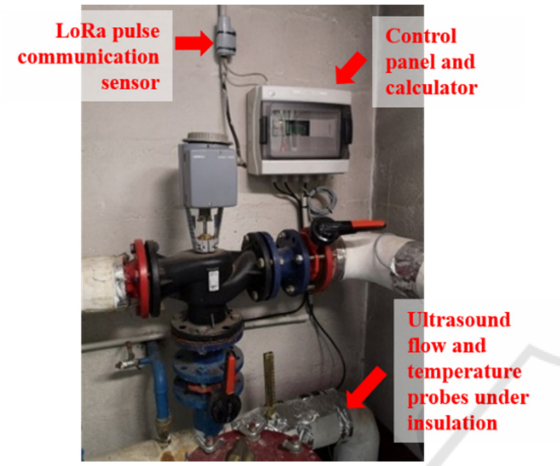

Figure 2: Installation example of a thermal energy meter for heating energy demand monitoring (right).

The second part of the sensors focuses on the characterization of apartments (aside from building-scale monitoring of domestic hot water consumption delayed to this second phase). This second deployment phase should start in November 2019. Categories of measurements are:

- electric power demand from the main electric meter and switchboard, and smart-plugs to monitor all the main appliances of the instrumented apartments (one-minute time-step);
- hot water consumption assessed using contact-temperature sensors on hot water pipes (one-minute time-step) and completed with data from already-installed remote reading volumetric water meters;
- heating energy consumption is deduced in a similar way using contact-temperature sensors installed on heaters (hourly time-step);
- natural gas consumption, only used for cooking, is monitored with sensors installed on apartments gas meter (one-minute time-step);
- indoor conditions and comfort should be captured using contact-temperature sensors on exterior walls of the apartments and a sensor combining indoor temperature, humidity, luminosity, CO_2 and presence measurements (hourly time-step);
- occupants' behaviours should mainly be characterized through occupation data and using sensors for window opening-closing detection.

As for building-scale measurements, the choice of time-steps is driven by the events sensors are targeting and the purpose of data analyses. For electricity, hot water and gas consumption, usages may only last a few minutes. Therefore, the smaller time-step the better. Regarding, heating energy consumption and indoor environment, they are more likely to change on an hourly basis. Finally, window-opening detection is event-driven while occupation detection is linked to indoor environment monitoring time-step.

3.1.3 Communication Network and Online Data Collection

Data communication for the present sensor network is entirely wireless (Figure 3). Several, communication protocols are available such as Modbus (The Modbus Organization, 2019), Sigfox (Sigfox, 2019) or LoRaWan. The latter is currently the most common for applications such as the one presented in this paper (Augustin et al., 2016) and most sensors available on the French market use LoRa technology. Indeed, LoRa is fit for IoT projects and wireless sensor networks deployed in smart buildings and smart cities contexts (Centenaro, Vangelista, Zanella, & Zorzi, 2016; Pasolini et al., 2018). It is relatively easy to implement, it provides information on the sensor status and it allows long-range data transmission even in areas with difficult access. LoRa technology is also energy-effective as it relies on radio waves with low communication rate and then low energy consumption. Several implementation strategies have been selected for the two presented instrumentation phases. The first phase uses an operated LoRa network with two gateways installed onsite. Onsite LoRa communication tests led to the conclusion that a single gateway would be sufficient. However, a second one is installed in case of reliability. Only the electricity consumption-dedicated sensors use a GPRS network because of their acquisition time-step and the limitations of operated LoRa network in terms of bandwidth usage (Electronic Communications Committee, 2019).

The second phase is processed differently and separated into three sub-phases. As for shared areas, energy monitoring is entirely managed by a contractor. Other sensors are provided and configured by a different service company and installed onsite by the research group in charge of the project.

Table 1: Characteristics summary of the deployed sensors.

Sensor	Number at building scale (per building)	Number per apartment	Total number	Acquisition time-step	Communication protocol
Indoor temperature & humidity	3	/	9	Hourly	Operated LoRa
Presence	1	/	3	Hourly	Operated LoRa
Combined indoor temperature, humidity, luminosity, presence & CO_2 level	/	1	10	Hourly	Private LoRa
Exterior walls surface temperatures	/	2-5	32	Hourly	Private LoRa
Window opening detection	/	3-5	38	Event-driven	Private LoRa
Gas consumption	/	0-1	4	One-minute	Private LoRa
Electricity demand – main electric meter	2-3	1	17	One-minute	GPRS
Electricity demand – switchboard	0-1	1	11	One-minute	GPRS
Electricity demand – smartplugs	/	5-9	67	One-minute	Private LoRa
Heating energy demand – thermal energy meter & pulse sensor	1 + 1	/	3 + 3	Five-minute	Operated LoRa
Heating energy demand – radiators	/	3-5	36	Hourly	Private LoRa
Domestic hot water energy demand – thermal energy meter & pulse sensor	1 + 1	/	3 + 3	One-minute	Private LoRa
Domestic hot water energy demand – apartments	/	2	20	One-minute	Private LoRa

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Finally, a ten-sensor sample (those combining measurement of indoor temperature, humidity, luminosity, presence and CO_2 level for apartments) is entirely set up and installed by the research group. The used LoRa network is configured as private network to bypass bandwidth usage constraints related to data acquisition time-step.

For all sensors, collected data are retrieved on three FTP servers: a first server used by the contractor for managing part of the instrumentation solution, a second sensor for equipment installed by the research group and a third server dedicated to data retrieved from the weather station. The final format provides collected raw data with one csv file for each day and for each sensor. Information include the sensor identification and location, the type of measurements, the timestamp, the measured values and the units.

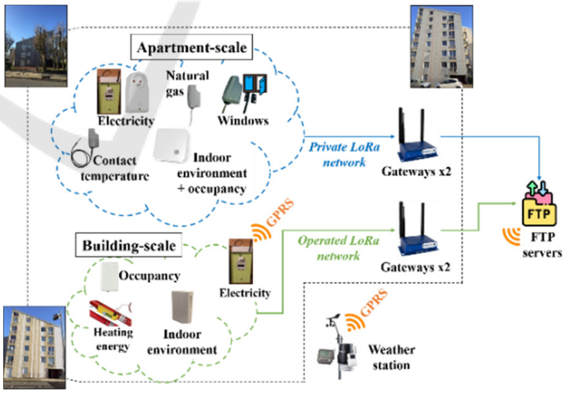

Figure 3: Simplified diagram of the wireless sensor network.

3.2 Instrumentation Management Process

Instrumentation overall management has a crucial impact on the success of the instrumentation and on the whole project. In the present study, it can be divided into six different stages over an estimated timespan of one year and four months (started in October 2018 and expected to end in January 2020).

First is the accurate definition of the instrumentation specifications to meet the needs of the project. In parallel, a review of service providers offering adapted solutions is performed and apartments are recruited to participate to the instrumentation study. Once specifications are organized in a clear framework, they are submitted to identified contractors. Several rounds of discussions allow modifications on the specifications. It aims to adapt to the reality of the market and for service providers to refine their offer to meet the needs of the project to the best of their capabilities. It also helps select the most relevant contractors. In the present case thirty-three service providers were contacted and two contractors were finally selected.

Once a contract is signed, sensors are ordered, delivered and installed under the supervision of the research group. Finally, when the sensor network is functional, data quality is checked. It ensures that all sensors are properly measuring and transmitting data, that there are no missing information or other issues and that the proper data format is displayed for future applications.

4 IDENTIFTICATION OF CRITICAL POINTS FOR SENSOR NETWORK IMPLEMENTATION

The planning and deployment of the proposed instrumentation solution has highlighted several critical aspects in sensor network implementation. These critical points arose from various issues encountered during the instrumentation process. These can be grouped into four categories with i) onsite installation conditions and environment, ii) characteristics and purpose of instrumentation, iii) service provider and iv) project tracking and management.

4.1 Onsite Installation Conditions and Environment

Characteristics of the experimentation site have a significant impact on the feasibility of a monitoring project. As a first step, it is crucial to identify the equipment and installations. Equipment conditions are important, as for security reasons some may not be monitored. Indeed, over the selected ten-apartment sample, seven electrical switchboards could not be equipped because of their obsolescence and should be replaced for the experimentation. Sensor connectivity must also be considered for sensors placement and to choose the relevant number of gateways necessary since metal stairs and doors disrupt radio waves and then data transmission. Finally, the installation environment should be documented. For instance, several sensors do not use batteries but need a main power supply – thermal energy meters for instance. In the buildings, such electrical installations were not adapted or even not existing where they were needed. Thus, additional costly actions were necessary to prepare the installation site.

The present instrumentation solution is also specific because all buildings remain occupied during the sensor network deployment and the whole experimentation. Then, the sensor network must be as non-intrusive as possible. However, non-intrusive sensors imply higher costs due to specific technologies. For instance, it applies with ultrasound thermal energy meters and with all electricity-related meters that need to be small, easy movable and without heavy installation work on the existing equipment.

Also, as the project mostly relies on collected data from apartments and occupants' behavior, it is necessary to recruit participants. Then, recruitment is a crucial step for the success of the research project, but is particularly time-consuming, requiring several rounds of presentations and visits (general presentation, door-to-door visits, phone calls and individual meetings). In the project, up to three months were necessary to recruit ten households. Moreover, it is crucial that inhabitants find clear benefits in their participation. In this case it was proposed for inhabitants to have access to all collected personal data and summary analysis results for their households. Finally, as most collected data are personal data, a specific attention should be given to related regulations and mandatory administrative actions (French Ministry of Economy, 2019).

4.2 Characteristics and Purpose of the Instrumentation Solution

The introduced sensor network serves for a research project with specific needs. Therefore, it differs from usual commercial monitoring studies because it aims to investigate situations and details that would usually not be considered. More specifically, there are a wide range of acquisition time-steps (from one minute to one hour) and a large variety of sensors and measurements as presented in Table 1.

Consequently, such a complex instrumentation solution faces several challenges. For instance, sensors are designed and manufactured for standardized usage conditions depending on the environment of installation and usually with hourly acquisition time-step. Their internal memory stores up to one day of data (24 measurements) communicated once a day. Then using sub-hourly acquisition time-steps requires more frequent data communication which is energy intensive and significantly reduces the expected battery lifetime. However, sensors such as for gas consumption metering (Zone-atex.fr, 2019) or used outdoor or in damp and dusty environments are airtight and cannot be opened once installed. This prevents the battery to be replaced and induces a costly replacement of the whole sensor instead.

Sensor technologies and measurement characteristics (especially the acquisition time-step) also have an impact on the design of the sensor network. There is first the choice between the different existing communication protocols with different characteristics, advantages and constraints. LoRa is the prominent solution on the market and was selected in the present case study but it presents drawbacks. For instance, operated LoRa networks restrict bandwidth usage. Then having a one-minute time-step on large amounts of sensors is hardly possible. Private LoRa networks offer a bypass solution since they are locally set networks dedicated to one specific sensor network. However, they are more complicated to implement. Other solutions such as GPRS used for some specific sensors also raise different issues related to wireless monitoring technologies and electro-sensitivity.

4.3 Service Providers and Contractors

Through this study, service providers have been hired to provide an instrumentation solution adapted to the goals of the research project. On the French IoT market, there are many different contractors. However, they do not all provide the same delivery. Most commercial proposals focus on sensor provision but do not include set up and installation. Therefore, such contractors must partner with other companies to match the needs of a project. This often leads to many communication issues and delays. Furthermore, when a contract is established, many terms must be carefully checked to ensure a smooth project process, and more particularly: i) responsibilities and guarantees about the sensors/network and about the potential provision and installation delays, ii) maintenance details and conditions when included, and iii) what is done by the contractor with collected data during and after the contract validity.

It is also necessary to ensure the service quality and expertise of contractors. Indeed, there is a significant difference between common “plug and play” sensors – such as for temperature or humidity sensors – and energy metering. The latter requires very specific knowledge on the technologies, installation procedures and data acquisition checking. Many contractors do not have such equipment and need to partner with other manufacturers. This lack of expertise often leads to many future issues with sensor calibration or equipment failures.

Finally, the budget management requires a detailed investigation. Indeed, there can be several unexpected expenditure items that can significantly increase the total instrumentation budget: include miscellaneous accessories, connectivity subscriptions, details of all-inclusive maintenance contracts, installation and setup, or site visits. A budget summary from the ten complete commercial proposals received is presented in Figure 4.

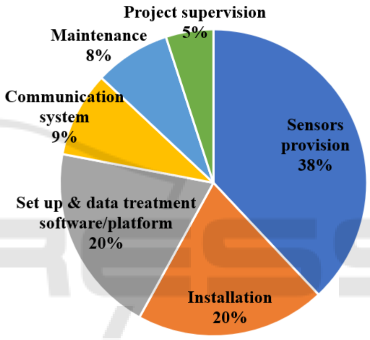

Figure 4: Budget summary for the presented sensor network.

4.4 Project Management

The overall project management, comprising supervision on the three previous subsections, is the key to a smooth sensor network deployment and optimal valorisation. Regarding the instrumentation, a detailed and precise tracking is mandatory to identify every sensor with sensor type, measurements, communication protocol, installation date and location.

Adapted and controlled communication is essential within the research group to prevent any loss of information and miscommunication. It also must be ensured with other actors and particularly with building occupants. Indeed, it is recommended to avoid any over-soliciting with inhabitants for obvious privacy reasons. Finally, as the present research project is a multi-disciplinary study combining several research teams, an optimal coordination is needed.

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5 PRELIMINARY DATA ANALYSIS FROM THE FIRST INSTRUMENTATION PHASE

The first instrumentation phase focusing on building common areas is fully operational. Thus, a statistical data analysis is performed on an observation window from 2019/02/19 to 2019/10/06 to highlight issues in collected data. Twenty sensors are considered including data for temperature & humidity (9 sensors), passage counting (3 sensors), thermal energy (3 meters) and electric power demand monitoring (5 sensors).

The main highlighted issue relates to missing datapoints. Over the given observation period, 92.7% of the expected datapoints are collected. Figure 5 compares the evolution of the expected number of measurements (blue curve) and of the effective collection results (orange curve). The percentage of acquired data over time is presented on the green curve.

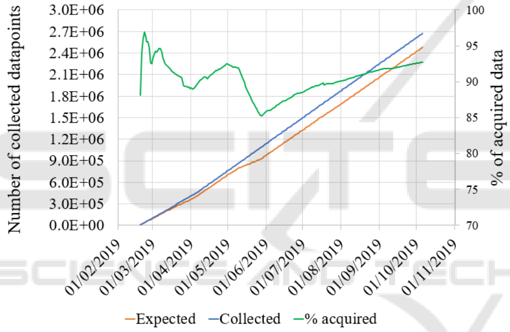

Figure 5: Evolution of collected datapoints (orange) compared to expected collected datapoints (blue) and percentage of acquired data (green) from 2019/02/19 to 2019/10/06.

The major gap is due to a 17-day-long sensor malfunction in May 2019 for the electrical switchboard monitoring. Electricity demand data collection is therefore the category with the least collected datapoints (on Figure 6: 92.0% of the optimal target), followed by thermal energy monitoring (94% of data collected). Indoor environment and passage counting account for more than 99% of collected data. However, large amounts of missing energy datapoints should also be transposed to time-scale analysis. Indeed, electric sensors provide one-minute time-step information. Hence, over a 230-day observation period, it would be equivalent to a loss of less than 19 days of data concentrated on a specific period for one specific sensor.

Other observed outliers are abnormal and additional measurements. Abnormal values are only found for energy demand monitoring, with overly high measurements or zero-values. They respectively represent 0.06% and 6.8% of total. Zero-values are almost exclusively related to electrical switchboard monitoring (99.9% of abnormal measures).

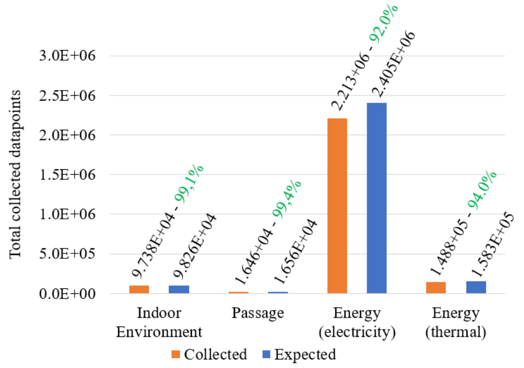

Figure 6: Comparison of collected datapoints (orange) compared to expected collected datapoints (blue) for the different monitoring categories.

6 CONCLUSIONS AND FUTURE WORK

This paper presents the planning, deployment and supervision of a sensor network for existing residential buildings monitoring. The proposed solution is a multi-scale sensor network covering thermal and electrical energy consumption, indoor environment and comfort, inhabitants' behaviour and weather conditions, at various timescales.

The instrumentation solution has been entirely planned and divided into two implementation phases. The first phase focuses on the monitoring of building shared areas and is operational. The second phase considers a similar approach on a ten-apartment sample and will be deployed starting from November 2019. Details of both phases are presented with a description of sensor characteristics, communication networks and overall project management.

A feedback on the first phase of the sensor network implementation is provided. It shows the obstacles and challenges when implementing large sensor networks with a wide diversity of measurements in existing old buildings. It highlights several critical points to be considered for similar future applications. These critical aspects are grouped in four categories with onsite installation conditions and environment, characteristics and purpose of the instrumentation solution, service provider and contractors and project management. A preliminary statistical analysis of

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collected data is also provided. It highlights the main encountered issues in data collection.

In future works, data analysis will be extended to measurements to the second instrumentation phase data. Moreover, in order to ensure long-term measurement accuracy and to prevent future avoidable data loss and highlighted data collection issues, a long-term calibration study will be conducted. Finally, collected data will be integrated in building energy models to characterize the buildings behaviours and investigate potential issues in building energy management.

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