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PROJECT REPORT

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CELSIUS: an international project providing integrated, systematic, cost-effective large-scale IoT solutions for improving energy efficiency of medium- and large-sized buildings

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Abstract

Worldwide, buildings consume about 40 percent of the overall energy resources and contribute to an average of 30 percent of the global carbon emission. Hence, technologies for improving the energy efficiency of buildings play an essential role in the global fight against climate change. The CELSIUS project aims to improve the energy efficiency and indoor climate of medium to large sized commercial and public buildings by developing an integrated system solution that consists of (1) an IoT-enabled and cloud-based platform for monitoring and diagnostics of building energy performance and indoor climate quality, (2) a middleware software platform for cost-effective large-scale deployment of wireless sensors and gateways, and (3) an IoT network management platform for cost-efficient life-cycle maintenance of sensors and gateways. The integrated system solution will be deployed and demonstrated in a 6000 m^2 building in Aarhus, Denmark, and an 18,000 m^2 building in Kuala Lumpur, Malaysia. By choosing buildings located in different climate zones on different continents allows the developed system solution to be tested under realistic conditions for the international export market.

Keywords: IoT network, Energy efficiency, Building, Cloud platform, Building energy performance, Indoor climate

Introduction

Globally, building sectors consume 40 percent of the overall energy resources and contribute to an average of 30 percent of global carbon emissions (Amasyali and El-Gohary 2018). European Union (EU) countries utilise 32 percent of their energy to provide electricity for buildings (European Comission 2013; Billanes et al. 2017). Buildings, therefore, present large opportunities but also barriers for improving energy efficiency by advancing building intelligence (Ma and Jørgensen 2018; Ma et al. 2016). However, buildings do not exist in isolation, they are part of complex ecosystems where the primary uses of the buildings are more important than their energy use (Ma et al. 2019, 2017a). This is for instance the case for medium to large buildings like retail stores (Ma et al. 2017b) and hospitals (Billanes et al. 2018). The electricity demand across the Southeast Asia region, for example, is expected to double by 2040 (The ASEAN Post Team 2018; Qingnan Li 2016). Hence, there is an urgent need for a cost-effective IoTs (Internet of Things) -enabled and cloud-based solution that can help building owners to easily monitor and compare the energy performance with the indoor climate in their buildings (Ma et al. 2021).

In commercial buildings, the number of IoT devices often significantly exceeds the 1–200 number limit, as thousands of devices can be connected. In a standard solution, a lot of planning is needed to connect the devices to a specific gateway within range. This, combined with the dynamic range (people and furniture moved around), makes it of high value to have a system that automatically assigns each device to an appropriate gateway. However, current IoT technologies do not support cost-effective large-scale deployment of wireless sensors, as they are mainly based on the manual configuration of gateways and sensors. Hence, there is an urgent technical need for IoT solutions that can auto-configure and automate the maintenance of sensors and gateways for large-scale deployments.

Therefore, an international project—CELSIUS, is funded to serve the identified needs. CELSIUS project is a three-year (2021–2023) international project funded with a total budget of 1.65 million euros by the Danish Energy Technology Development and Demonstration (EUPD) program. The CELSIUS project aims to improve the energy efficiency and indoor climate of medium to large commercial and public buildings by developing an integrated system solution. The integrated system solution consists of:

1) an IoT-enabled and cloud-based platform for monitoring and diagnostics of building energy performance and indoor climate quality,
2) a middleware software platform for cost-effective large-scale deployment of wireless sensors and gateways, and
3) an IoT network management platform for cost-efficient life-cycle maintenance of sensors and gateways.

The integrated system solution will be deployed and demonstrated in a 6000 m2 building in Aarhus, Denmark, and an 18,000 m^2 building in Kuala Lumpur, Malaysia. Choosing buildings located in different climate zones on different continents allows the developed system solution to be tested under realistic conditions for the international export market.

Background

Managing building energy consumption and sustaining an ideal indoor climate require extensive monitoring and sensing mechanisms within the building compound and outdoor. This ensures that accurate information can be obtained on the overall energy consumption and indoor climate. The challenges in enabling IoT sensing technology in the building is the complexity of merging and networking incompatible sensing and IoT devices and data security (Dyess 2018). It also increases the complexity of controlling and managing large-scale IoT solutions, which become more decentralised, heterogenous, and more complex to configure manually. More significant challenges arise when we consider cloud-based solutions and optimal configuration of tunable settings in several devices, such as gateways or router boxes.

Faults in building energy systems are also a significant challenge. Fault can be defined as “an unpermitted deviation of at least one characteristic property of a variable from acceptable behaviour. Therefore, the fault is a state that may lead to a malfunction or failure of the system” according to Isermann (1997). Fault typically refers to a part of the building energy systems does not perform according to the expectation. Faults in building energy systems can cause energy waste and occupant discomfort.

The state-of-the-art

The State-of-the-Art (SoA) includes three aspects:

Large scale IoT sensor network deployment

The common methods for the large-scale IoT sensor network deployment in introduced in the literature are:

- MONICA IoT infrastructure for large-scale IoT pilot implementation (Meiling et al. 2018)
- Dynamic application infrastructure for heterogeneous IoT deployment (Michael et al. 2015)
- Sensor integration method with various wireless protocols into centralised gateways (Rajaram and Susanth 2017)

IoT sensor network management

The most common methods to address automatic configuration and self-management of IoT networks are:

- Middleware (Familiar et al. 2012)
- Software Defined Networking (Huang 2012)
- Semantics (Perera et al. 2013)
- Autonomic Computing (IBM Corporation 2005)

However, only the autonomic computing supports topology control, node registration, and heterogenous nodes (Ashraf and Habaebi 2015). Furthermore, several proposed frameworks can handle the complexity of automatic configuration, e.g., the Adaptive Collaborative Ubiquitous Systems (FACUS) framework and the FRAMESELF generic autonomic framework (Alaya and Monteil 2012).

Building energy performance monitoring and diagnostics

The classification of FDD studies can be either based on the approach used, or specific equipment under test (Woohyun and Katipamula 2018). Many methods have been developed over the years for fault detection and diagnosis (FDD) of buildings. However, they have not been integrated into the currently available building energy diagnostics tools. The existing available diagnostic tools, such as EcoStruxure Building Advisor from Schneider electric, have only integrated simple rule-based methods with minimal and generic diagnosis explanations. They also suffer from configuration issues. This compromises the performance of the tool. Diagnostic software that integrates more advanced methods and is scalable and adjustable will be a very competitive tool in the market.

Project aim and objectives

The SoA investigation shows that there are technological gaps in existing solutions:

- Tools to control and manage large-scale IoT solutions do not provide fully integration of different technologies.
- Most of the available technologies are based on manual and not automatic configuration.
- The existing available diagnostic tools have only integrated simple rule-based methods with limited and generic diagnosis explanations.
- Most of the available diagnostic technologies suffer from configuration issues
- Lack of large-scale IoT sensor network deployment experience.

The non-fully integrated and non-fully automatic technologies and solutions increase the cost and barriers for the monitoring, diagnosis and maintenance of energy management systems in buildings, especially medium- and large-sized buildings. Therefore, this project aims to develop a cost-effective IoT-enabled cloud-based solution for reducing the enormous amount of energy used for heating and cooling in medium to large-sized buildings worldwide. This project will achieve its goal by delivering:

- An IoT-enabled and cloud-based platform for monitoring and diagnostics of building energy performance and quality of indoor climate.
- A middleware software platform for cost-effective large-scale deployment of wireless sensors and gateways in medium to large-sized buildings.
- An IoT network management platform for cost-efficient life-cycle maintenance of sensors and gateways.

The project is organised into nine work packages (WPs), including five technical WPs for the software development and two WPs for the software test in a large-scale building environment:

- WP2 Automatic configuration of large-scale IoT networks aims to address the issues of automatic configuration and self-management of large-scale IoT networks, i.e., how to address the unpredictable changes of topology, load, task, and network physical and logical characteristics.

- WP3 Fleet management of large-scale IoT networks aims to address the development of a Cloud-based management solution for essential aspects of large-scale IoT networks, such as monitoring and maintenance of sensors, gateway backup systems and OTA fleet management.
- WP4 Cloud-based storage solution for sensor data addresses the development of a cloud solution for storing the data readings from indoor climate sensors, i.e., Temperature, Lux, Humidity, VOC, CO2 and PIR and windows opening sensors.
- WP5 Building performance dashboard aims to develop a building performance dashboard to show building energy performance (compared to its size and energy standard), actual energy consumption, energy production (in case the building has PV), individual room indoor climate measurements, and the building's CO2 emission footprint.
- WP6 Building energy performance diagnostics aim to address the development of methods and software algorithms for diagnostics of buildings' energy performance based on inputs from wireless sensors. The WP will focus on a scalable and adjustable approach combining Rules-Based Methods, Performance Indexing and statistics-based Fault Detection and Diagnosis (FDD). The approach will focus on the common faults and uses validated data from wireless sensors.
- WP7 Test Lab Tangen, Denmark, is to set up a test environment for testing the developed systems in the Elbek & Vejrup owned office building where Develco Products is located.
- WP8 IoT Living Lab at UNITEN Campus, Malaysia This work package involves the installation of IoT devices at three selected campus buildings in Universiti Tenaga Nasional (UNITEN), Putrajaya Campus, Malaysia. The total area size covered by the installation is 18,000 m2. Once the devices have been installed, sensor data from those buildings will be collected for several months before data analysis.

The correlations among the above technical WPs are shown in Fig. 1.

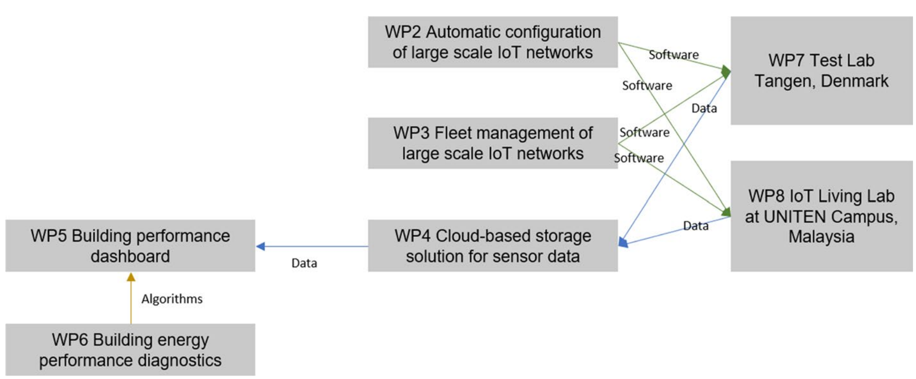

Fig. 1 Overview of work packages and their relationships

Project methodology

One of the project partners, Develco Products (DP), develops, produces, and supplies IoT solutions within smart home, smart energy, healthcare, and building management. DP products are based on a wide range of wireless technologies such as WiFi, Zigbee, Z-wave, and Bluetooth, including:

- Squid.link Gateway (hardware)—All-in-one solution for connecting IoT devices across models and wireless protocols. The gateway supports various communication protocols, including Zigbee, Z-Wave, WLAN, Wireless M-Bus, and Bluetooth Low Energy. The gateway hosts a programmable Linux-platform and is integrated with a wide variety of cloud solutions.
- Squid Smart App Wireless platform (software)—The Squid.link Gateway includes an application called Squid Smart App, which consists of a restful API, providing an interface between applications and the devices. Squid Smart App includes easy-to-read templates with predefined commands for the devices. This means that users will only have to configure the devices' settings, rules, and actions through the API or templates instead of programming an application.
- SmartAMM API—The application API can be accessed from applications running on the gateway and a hosted application running remotely. The remote access runs through a separate channel established between the gateway and the server. For easy access, a server middleware (SmartAMM server) is available through which you can debug the wireless communication with the development tool. The 3rd party application connects to the application API via a socket connection.

Based on DP's IoT solutions, this project aims to develop an integrated systematic IoT solutions, including:

ZigBee "Controller"

The ZigBee "Controller" can decide which gateway should accept a specific device. The following method is expected to be developed, tested and documented:

- A ZigBee device sends out a request to join a network.
- All ZigBee PAN Coordinators (ZPC) receiving the request, reports this to the "Controller".
- The Controller selects the ZPC with the best connection, by telling the selected ZPC to add the device address to the trust center and let it join.
- The device joins the ZPC, which gates data between the device and the Controller.
- The controller is one single point of contact for the entire network.

This controller is intended to be implemented in the next generation high-performance Squid.Link 2X gateway—eventually including an LTE modem for redundant data. The connected gateways can be implemented in the more cost-effective Squid. Link 2B. Communication between the gateways is done over IP via Ethernet (shown in Fig. 2).

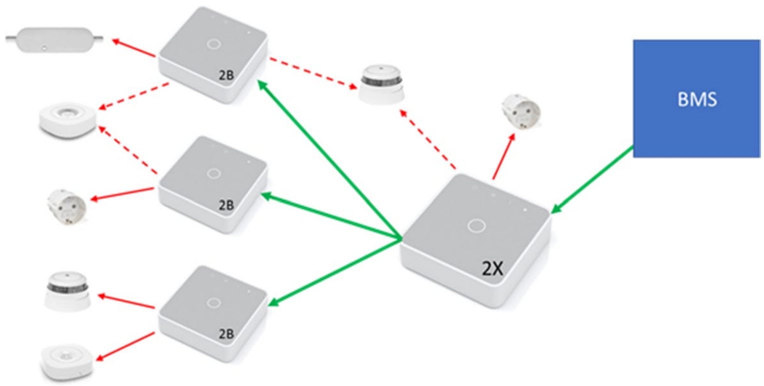

Fig. 2 Communication between gateways and devices

Cross-platform registering system

Develco Products offers an IoT gateway, including a ZigBee personal area network (PAN) Coordinator. The PAN coordinator is capable of monitoring/controlling up to 1-200 sensors, relays, lightbulbs and other IoT devices. When a ZigBee device is powered up, it will search for PAN coordinator, which will accept it to join the network. The PAN coordinator in a specific gateway is to be told if a particular device can join, which facilitates deployment and management of multi-gateway networks.

This automatic configuration of large-scale networks will be realised based on a cross-platform mobile application. This cross-platform mobile application for Android and iOS will be implemented, which serves as an entry point for registering sensors and creating the needed association to a physical context i.e., room, as shown in Fig. 3. This is done by scanning the QR codes of the sensors and the room. To reduce flexibility, the component's metadata is stored as an URL in the QR code that points to a database that can be altered. This provides flexibility because metadata can be changed in the database without changing the fixed QR codes.

Posting the scanned devices from the app to the room-API triggers the registering of the sensors. Afterwards the room-API begins configuring the pairing between the sensors and gateways associated with the room. The strongest connection is then determined by pairing every sensor to every gateway.

In pre-studies we have created methodising tests for the range between gateways and sensors to determine the quantity of gateways to cover a given infrastructure. ZigBee radio waves' strength decays very differently depending on the environment, making conclusions difficult. We're have also explored different pairing strategies between the devices, i.e., first come, first served or balancing the number of sensors in each room to optimise signal strength.

Fleet management of large-scale IoT networks

The Squid.Link gateway has a ZigBee trust center (TC) which decides whether to allow or disallow new devices into its network. The TC is usually the network coordinator but is also able to be a dedicated device. It is responsible for security roles such as Trust Manager, to authenticate devices that request to join the network, Network Manager, to maintain and distribute network keys. Configuration Manager, to enable end-to-end

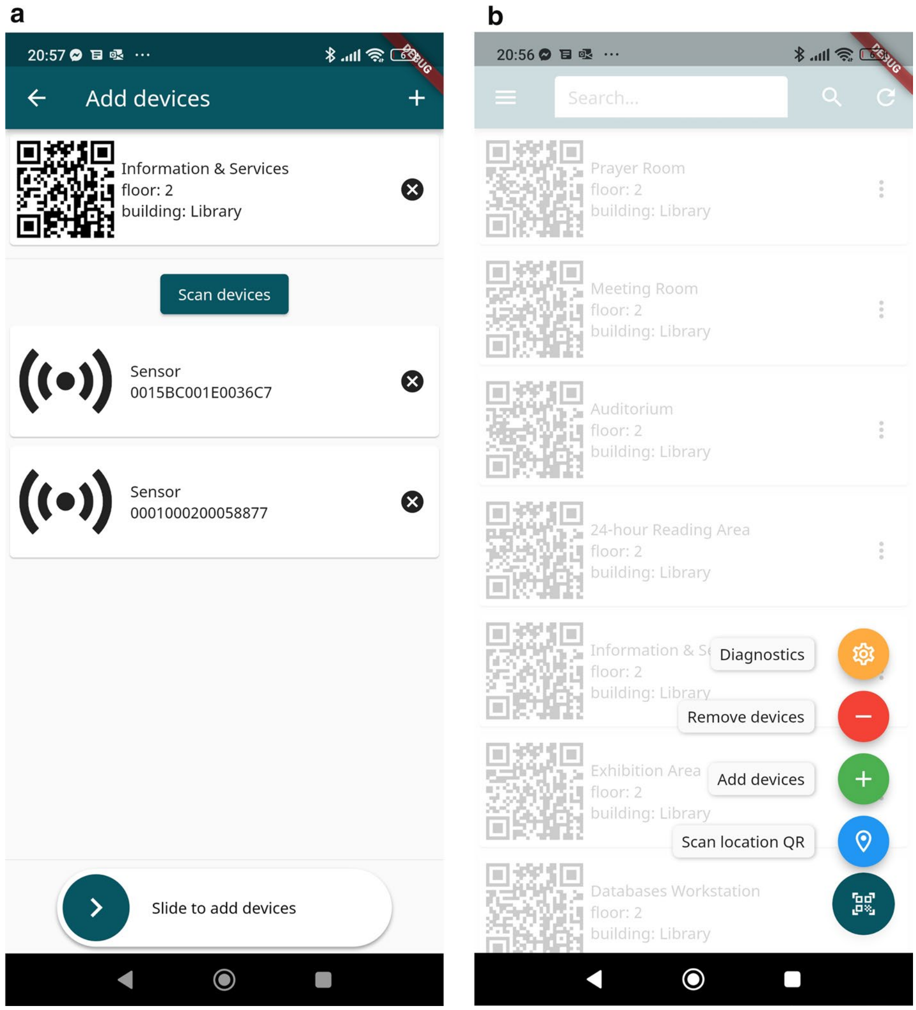

Fig. 3 Cross-platform registering system

security between devices. The data required to include the connected ZigBee device and sensors.

This project will develop an application that is a software infrastructure using data from connected sensors and devices that also runs on the gateway. Data from TC and applications can be backed up and restored in case of failures to maintain a solid IoT network environment without untimely network outages and the disrupted network connectivity and data loss they cause. The fleet management software module will be implemented on the Squid.Link 2 × gateway to primarily facilitate:

- Backup and restoration of TC data.
- Backup and restoration of application data.

Building energy performance diagnostics software

This project will develop a software solution for diagnostics building energy performance based on inputs from the proposed IoT solutions. The tool uses a scalable and

Fig. 4 IoT Test Lab Tangen in Denmark

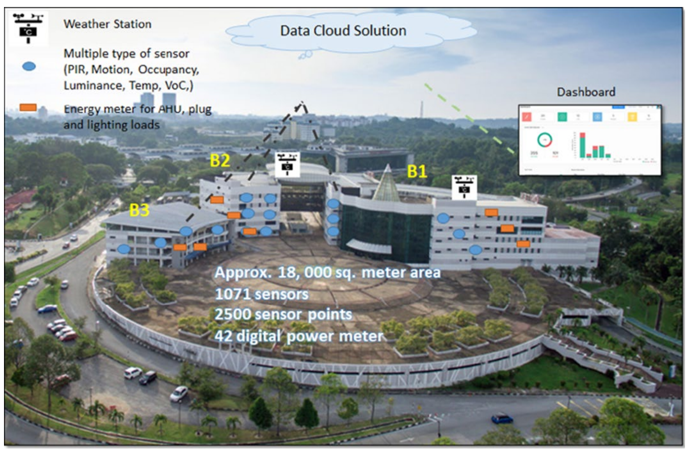

Fig. 5 IoT Living Lab at UNITEN Campus in Malaysia

adjustable approach combining Rules-Based Methods, Performance Indexing and statistics-based FDD. The tool will focus on the common faults and uses validated data from IoT devices.

Two IoT test labs

Headquarter building of Elbek & Vejrup and Develco Products

Elbek & Vejrup and Develco Products' headquarters is in Aarhus, Denmark (as shown in Fig. 4). The building complex covers an area of approximately 6000 square meters, distributed over three floors. The building was constructed in 2018 and is an energy class 2010.

Three connected buildings at campus University Tenaga Nasional (UNITEN) in Kuala Lumpur

To address the lack of experience in large-scale IoT sensor network deployment, a study has been designed where IoT capabilities are retrofitted into a building complex consisting of three connected buildings at UNITEN campus in Kuala Lumpur. The selection was carried out by considering the complex's wide function variations. Three buildings

Table 1 Malaysian building complex description

Building ID	No. of floors	Total Size (m^2)	Function
B1	6	Approx. 6632	Resource centre, exam hall, auditorium, staff offices, 24-h study area
B2	6	Approx. 3160	Classroom, laboratory, staff offices
B3	3	Approx. 2004	Staff offices, shop, café, classrooms

Table 2 Details on the sensing devices to be utilised in the project

Item	Details	No. of units
Gateway	Intermediary point between multiple sensors and servers	74
Sensors	Comprised of lighting, humidity, volatile organic component (VOC), motion (PIR), door/window and CO_2	1071
Digital power meter	To collect electricity data	42
Weather station	To collect outdoor temperature as well as air and wind conditions	2

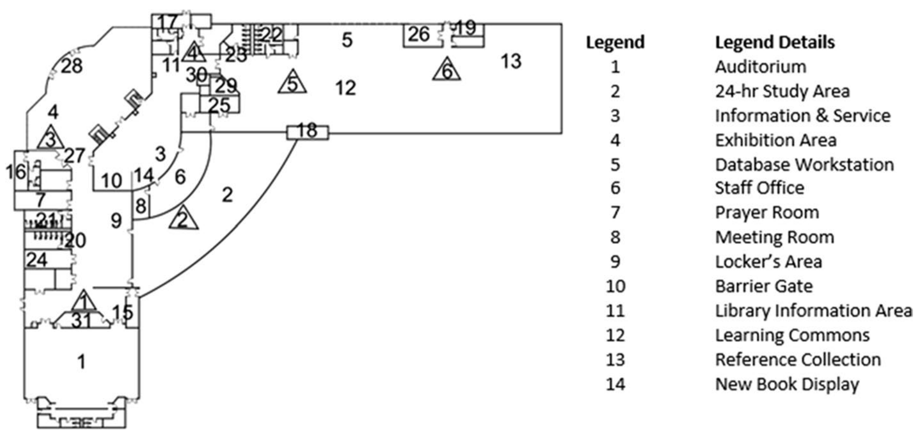

Fig. 6 Sample of building layout and gateway positioning

within the complex covers an area of approximately 18,000 square meters, as shown in Fig. 5. The buildings in the complex are 20 years old and are interconnected, with two buildings (B1 and B2) comprised of six floors while one building (B3) consists of three floors, as shown in Table 1. Table 2 summarises the number of sensors, gateway and digital meters to be utilised in this project.

There is no centralised, automated control of electricity consumption in the buildings. Instead, timers switch the lighting and cooling systems on and off at a specified time. So far, the buildings' electricity consumption within the complex is captured based on the manual meter reading from the main switchboard.

Figure 6 shows the sample of the second-floor layout for building B1. The numbers in the layout represent the areas, while the numbers in the triangles represent the proposed gateway positioning. In the IoT setting, the gateway acts as an intermediate tool to collect data from the installed sensors, process the data into comprehensible formats and relay them to the network to enable access for monitoring and analytics.

Project partners

This project partners include two research centers and two private companies from Denmark and Malaysia:

SDU Center for Energy Informatics, Denmark

SDU Center for Energy Informatics is an interdisciplinary industry-oriented research and innovation center with a global outlook. The center was founded in 2013 with the mission to contribute to the global transition towards a reliable, sustainable, low-carbon energy system by developing ICT-based solutions that support the energy sector's digital transformation. Main activities include research and education. In the project, SDU Center for Energy Informatics contributes competencies in mathematical modeling, advanced optimisation methods and software engineering. The center is responsible for designing the automatic configuration of IoT sensors and gateways and their realisation, and developing scalable and adjustable algorithms for building energy diagnostics.

Institute of Informatics and Computing in Energy, UNITEN, Malaysia

Institute of Informatics and Computing in Energy is a research institute at Universiti Tenaga Nasional, which focuses on the research and development activities pertaining to the application of information technology and computer science knowledge to improve the operational and cost efficiency of the energy systems. UNITEN aims to create an IoT and AI building Lab for investigating cost-effective solutions for improving the operation of buildings to reduce their energy consumption. In this project, the institute is responsible for developing the methodology for retrofitting the identified buildings, and implementing the methodology, which includes installing, testing, operating, collecting results and evaluating the outcome of the IoT Living Lab project.

Develco products A/S, Denmark

DP provides white label of IoT products within smart home, smart energy, healthcare, and building management. DP acquired expertise in wireless communication for IoT and developing products based on a wide range of wireless technologies such as WiFi, Zigbee, Z-wave, and Blue-tooth. The range of wireless products includes Squid.link Gateway, Squid Smart App Wireless platform (software), SmartAMM API, White label sensors and alarms. DP IoT solution is currently tailored to single smart home and home-automation solutions, where a single gateway is responsible for accessing sensor/device data and providing to the upper-layer application. The main goal of DP at this project is to facilitate support from single-user smart homes to multi-user smart BMS applications. DP is responsible for the IoT platform that includes various sensors and devices and the Squid in this project.Link gateway.

Elbek & Vejrup A/S, Denmark

Elbek & Vejrup A/S provides business-to-business consulting and develops enterprise resource planning (ERP) solutions based on Microsoft Business framework through in-depth knowledge of specific industries. The focus is on digital transformation, maximizing the value chain processes through effective solutions to optimise the client's business processes. Elbek & Vejrup contributes with competencies in how both public and private sector business optimises critical business processes based on IT. Strong industry knowledge means that these ERP/IT solutions create competitive advantages. Elbek & Vejrup is responsible for the Cloud-based data storage and the Building Performance dashboard.

Project impacts

The proposed project aims to improve the energy efficiency and indoor comfort of residential and commercial buildings by retrofitting them with wireless sensors to monitor the indoor climate and energy consumption and take corrective actions when necessary. The building energy efficiency improvement can decrease the building energy demand, and thereby lower the electricity grid load pressure when switching from fossil fuel-based heating (oil and gas) to heat pumps as part of the transition towards a sustainable energy system. Furthermore, the building energy efficiency improvement can directly improve the global and local climate situation as less energy is needed to reach the same comfort level and well-being of occupants.

The proposed solution aims to improve the energy efficiency of buildings by collecting and analysing indoor climate and energy consumption data to diagnose the causes for discrepancies and recommend corrective actions. Data-driven analyses and diagnostics of indoor environment and energy use will effectively reduce unnecessary overconsumption of energy in buildings. The proposed solution contributes to the security of supply by eliminating the unnecessary use of energy in buildings. This will save energy that can be considered to correspond to additional production capacity. Hence, the proposed project helps to prolong the sufficiency of the existing production capacity by reducing the energy use in buildings, thereby making this energy available for other use of energy in society.

Conclusion

The CELSIUS project will develop integrated, systematic, cost-effective large-scale IoT solutions for improving the energy efficiency of medium- and large-sized buildings. The developed solutions target emerging international markets. For instance, based on the estimation by the DBS Asian Insights, the installed IoT applications for residential, commercial and industrial buildings and facilities will grow from 6.3 M units in 2016 to 75B in 2030 (Louis columbus 2018). Furthermore, in 2005, the 13 most common faults in buildings were estimated to be responsible for over 99.6 TWh and 3.3 billion $ energy waste in the USA (Kurt et al. 2005). The yearly financial impact of these faults ranges from 3.3 billion $ to 17.3 billion $, with 3.3 billion $ being the most conservative estimate, according to Familiar et al. (2012), and over 6 billion $ yearly waste due to faults, according to Evan (2011).

However, the time horizon for the full impact of the developed solutions in the CELSIUS project depends on the speed of building renovations, including retrofitting small and medium-sized buildings with building management systems (Christensen et al. 2019). The adoption speed of building energy management systems for small and medium-sized buildings is highly dependent on installation cost, economic incentives linked to energy cost, and the EU legislative framework (Ma 2022). For instance, the Energy Performance of Buildings Directive 2010/31/EU (EPBD), Energy Efficiency

Directive 2012/27/EU) includes requirements for the installation of building automation and control systems and on devices that regulate temperature at room level. Under the Energy Efficiency Directive (2012/27/EU), EU countries must make energy-efficient renovations to at least 3% of the total floor area of buildings owned and occupied by central governments. Hence, it can be expected that IoT-based building management systems, as developed in this project, will significantly impact the cost associated with the 3% required public building renovations.

Abbreviations

BMS	Building management system
DP	Develco products
ERP	Enterprise resource planning
EU	European Union
EUPD	Energy Technology Development and Demonstration
FACUS	Framework for adaptive collaborative ubiquitous systems
FDD	Fault detection and diagnosis
HVAC	Heating, ventilation, and air conditioning
IoT	Internet of thing
M2M	Machine to machine
MAPE	Monitor, analyse, plan, execute
SoA	State-of-the-Art
TC	Trust center
UNITEN	University Tenaga Nasional
WP	Work package
WSN	Wireless Sensor Network
ZPC	ZigBee PAN Coordinators

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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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