**Final report**

## 1.1 Project details

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|---|---|
| **Project title** | Intelligent Energy Management for Multi-family Buildings |
| **Project identification (program abbrev. and file)** | |
| **Name of the programme which has funded the project** | EUDP |
| **Project managing company/institution (name and address)** | DTU Fotonik<br><br>Ørsteds Plads, building 343, 2800 Kgs. Lyngby |
| **Project partners** | DTU Compute,<br>Danfoss A/S |
| **CVR** (central business register) | DK 30 06 09 46 |
| **Date for submission** | 2020-09-03 |

## 1.2 Short description of project objective and results

***English version***:

This project aimed to define, develop and demonstrate an Intelligent Energy Management for multi-family buildings, which is a cost-effective solution (based on easily installable wireless sensors and actuators) suitable for both newly built as well as existing/under renovation multi-family buildings.

This project solutions were implemented and tested in three various field tests. The setups for example include temperature sensors for measuring in-house temperature in the different apartments as well as the temperature of the water in the pipes of the water-carried heating installation in different parts of the building or in different units of the installation. The system periodically collected values from temperature sensors and visualize the data using the advanced low-energy wireless communication technology and data analysis programs.

***Danish version***:

Dette projekt havde til formål at definere, udvikle og demonstrere en intelligent energiforvaltning til multifamiliebygninger, som er en omkostningseffektiv solution (baseret på let installerbare trådløse sensorer og aktuatorer)

egnet til både nybyggede såvel som eksisterende / under renovering af flerhusbebyggelse.
Dette projekt implementerede overvågningssystemet og testes i tre forskellige feltforsøg. Opsætningerne inkluderer for eksempel temperatursensorer til måling af husets temperatur i de forskellige lejligheder samt temperaturen på vandet i rørene i den vandførte opvarmningsinstallation i forskellige dele af bygningen eller i forskellige enheder i installation. Systemet indsamler med jævne mellemrum værdier fra temperatursensorer og visualiserer dataene for at sikre den mest omkostningseffektive opsætning til opvarmningsanlæg og maksimal energieffektivitet og for at hjælpe lejere med energiforbrug.

## 1.3 Executive summary

The main objectives of the Intelligent Energy Management for Multi-family Buildings project, as set out in the project application, were to develop IoT based monitoring and data collecting system in the building, to use the data intelligently for energy saving analysis and to demonstrate the system in real life field tests. The results were intended to promote an intelligent energy management solution with a high market potential for energy efficiency in multi-family houses.

Today, many devices in our everyday use (At home, office, or even public areas) are becoming "smarter" due to the evolution of small embedded devices with low power usage and costs. The evolution has led to extensions of internet connectivity into things such as refrigerators, lightbulbs, watches, parking spots, cars and commercial signs.
This project focused on a specific area of smart devices for intelligent energy management for multi-family buildings. Monitoring and controlling were deployed at remote areas due to advances in wireless communication technologies. This project developed the sensor based monitoring and controlling system based on LPWAN (Low Power Wide Area Network) technology which allow long range communication and the latest short-range Bluetooth 5 communication technology. The prototypes and evaluation results have been published in conference papers.

The collection and use of data were accomplished. The knowledge of the occupants' needs was required to optimize the indoor climate and the energy use in buildings. A mobile App called "FEEDME" was used to receive the live feedback from occupants. The data management within this project was executed through the use of own software connected to advanced time series databases.

The designed energy monitoring and controlling systems were setup and tested in different field tests with different building architecture and user groups.

- The Danfoss testbed provided by Danfoss is located in Copenhagen. This testbed is used daily as a multi-family building.(Key technology under test: NB-IoT based monitoring system)
- The DTU testbed is located at DTU campus in Lyngby Municipality. The testbed is used daily as an office and lab building. (Key technology under test: NB-IoT/LoraWAN/Bluetooth 5 based monitoring system)
- The school testbed is located in the Høje Taastrup Municipality. The building is used daily as a school. (Key technology under test: FEEDME data collection program using Bluethoot beacons to locate occupants; other technologies: LoRaWAN and GSM for sensors, smart z-wave thermostats and z-wave gateways)
- The DTU COMPUTE testbed is located at DTU campus in Lyngby Municipality. The testbed has offices, meeting rooms and rooms for lectures. Due to the CORONA lock down, there are unfortunately no actual results from this test bed.

The results of this project provided insights on "which would be most suited for the multi-family use case". Investigations and tests were performed in order to benchmark their benefits in terms of communication range, power consumption, data rate and costs. The collection of data and database infrastructure can be used for monitoring and visualization.

## 1.4 Project objectives

The original project duration was from 2018.01.01 to 2019.12.31. The project was extended to 2020.06.30 after approval from the EUDP committee. During the whole project period, three field testbed were setup and the proposed solutions were tested with emphasises on the target use cases.

There are both technical and commercial objectives defined in the Intelligent Energy Management for Multi-family Buildings project. The implementation of project with the technical design and development perspective followed the plan (original plan was modified during the request of extension) along the project. Project partners were involved with close collaboration both in technical consultancy and in project management. The technical implementation milestone were completed as agreed in the project proposal (shown in the Figure 1).

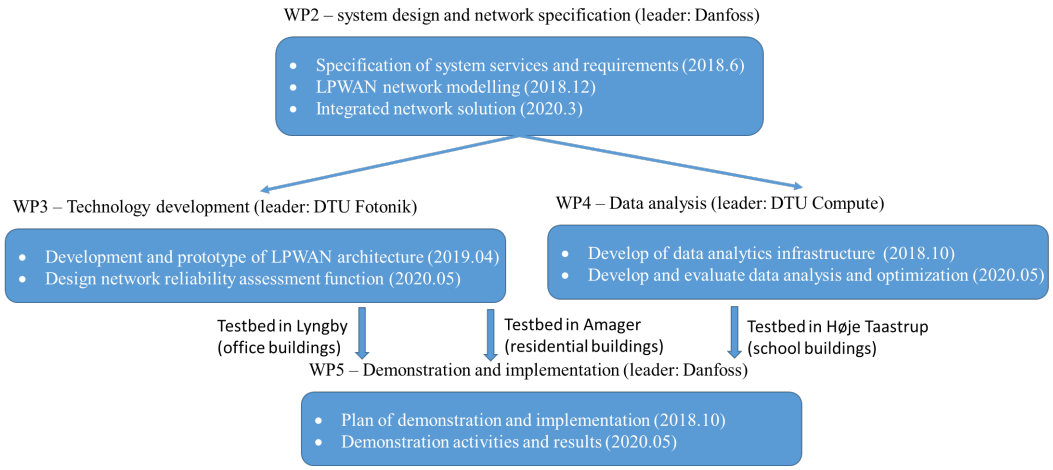

Figure 1: Implementation of technical milestones in the project

The commercial milestones and expectations were investigated and realized during the project in terms of small scale field tests (around 10 buildings) and the pre-launch of the solution in Denmark. By the end of the project, the market potential and the market competition status keeps and evolves as the project expected: "The market for building automation, consisting of remote- and centralized-control of a building's heating, indoor climate, lighting and other functions, is growing rapidly, and with it comes the prospect of huge energy savings. With the growing number of households living in multi-family houses (currently around 65milion dwellings in Western Europe and growing due to increased number of people moving to cities) there is a high market potential in a solution for energy efficiency in multi-family houses."

There were risks and challenges during the project implementation. The technical risks were overcome and the project goals were accomplished.

- Delay in project is caused by the delayed roll-out of the LPWAN technology (NB-IoT network and service) from the telecommunication operators in Denmark. NB-IoT network becomes available for accessing from 2019.

  *Solution*: the tests of NB-IoT with our developed system were carried out from 2019 Aug. The field test and analysis of NB-IoT technology were be from 2019 Oct to 2020 March.

- Field testing is proponed due to the delay in preparing the field test building.

  *Solution*: the test building in Copenhagen for the residential building use case was ready with a delay. The final implementation were carried out by 2019 autumn and tests were during 2019 to 2020.

- Data collection and analysis process is proponed due to the missing of valid winter data.

*Solution*: The winter season data for analysis were be collected during 2019 October to 2020 March. The data analysis was end in June 2020.

The major risk that not considered is the COVID-19 pandemic starting from the beginning of 2020. The main effect is the market and commercial related development. It may cause 1) Lack of financial support from the private companies for the building energy efficient renovation; 2) Shrink in the International market for the building energy efficient renovation.

## 1.5 Project results and dissemination of results

### *1.5.1 Project results*

**Technical results**: During the project period, the planned design and implementation tasks have been completed. Multiple test activities with different performance evaluation objectives have been performed at three field test places. All implementation and test results have been documented in project deliverables.

The main project contributions according to the project objectives are described in Table 1.

Table 1. Project objectives and achievements

| Objectives | Achievements |
|---|---|
| Identify services and requirements of multi-family in-building networks | System and service requirements were discussed according to the use cases from three field tests. |
| Identify and evaluate solutions for low power and long range communication | Theoretical modelling and mathematical studies were carried out for evaluation of power and coverage. |
| Develop the system architecture based on LPWAN solution | Both hardware prototyping and software design were done. |
| Design extensions in control and management algorithm to support network reliability assessment function | Network reliability assessment was finished using lab test instrument and field testing. |
| To develop tools for identification and quantification of operational performance of the buildings | Mobile app was developed |
| perform prototype and test scenarios in a realistic environment | Technologies were tested in three field test environments. Results were collected for different evaluation purposes e.g. energy, cost, range, and data rate. |

*WP2 (see deliverable D2.1, D2.2 and D2.3)*

- Specification and requirements have been discussed and reported in several meetings. Deliverable D2.1
- Modelling of LPWAN network (LoraWAN) has been done in Python simulation environment. Deliverable D2.2
- Investigation and comparison of multiple mesh network technologies. Deliverable D2.3

*WP3: (see deliverable D3.1 and D3.2)*

- LPWAN technologies (LoraWAN, Sigfox and NB-IoT) have been developed and prototyped. Deliverable D3.1
- Network reliability development and evaluation are performed for selected three technologies, e.g. Zigbee, Bluetooth 5 and NB-IoT. Deliverable D3.2

*WP4: (see deliverable D4.1)*

- Data analysis infrastructure for thermal performance of buildings has been developed. Deliverable D4.1
- Results of data analysis and optimization algorithms. D4.2

*WP5: (see deliverable D5.1)*

- Testbeds have been identified. The demonstration and implementation have been planned. Deliverable D5.1
- The actual testbed tests and results have been documented in D3.2, D4.2 and the D5.1 and D5.1_appendix.

**Commercial results**: from the end of this project, we expect the introduction of the solution (new products and implementation in the production process) to the national market and to the international market will be 1 year and 2 years, respectively.

### *1.5.2 Project evaluation*

The project has realized the objectives in the following means:
1) Various advanced and state-of-the-art technologies have been investigated and tested in real-life use cases;
2) Data analysis with data collection and monitoring has been completed.

### 1.5.2 Dissemination

During the project period, papers and presentations have been given in both academic and industrial events.

In 2018 October, we present the project overview and our preliminary design in a post "IoT based Technologies for Smart Building Energy Management" at 2nd Global Conference and Expo on Applied Science, Engineering and Technology.
In 2019 December, we presented our papers "Performance Analysis for In-building Networks Using Zigbee" as poster and another paper "Coverage Analysis for NB-IoT Network" accepted as regular paper on the IEEE Global Conference on Internet of Things (GCIoT).
In 2019 October, our paper "In-lab Testbed for Mobile Edge Caching with Multiple Users Access" was accepted and presented on the 10th International Conference on ICT convergence (ICTC).
During the project, there are two Master student thesis accomplished:

- "Performance Analysis for In-building Networks using LPWAN and Cloud Technologies", DTU Master project thesis, Svetoslav Gerganov, supervisors Ying Yan and Lars Dittmann. 2018
- "Prototyping and Performance Analysis of LPWAN Technologies", DTU Master project thesis, Radheshyam Singh, supervisors Ying Yan and Lars Dittmann. 2020.

In 2020 March, we prepared a EUDP project stand for demonstration and with two posters at DTU.
Finally, our last paper from this project "Experimental Performance Evaluation of Bluetooth5 for In-building Networks" was accepted by International Conference on Network of the Future (NoF). It will be presented online in 2020 October.
A paper and a presentation for the Conference "BEHAVE" (Copenhagen, 2021) are planned, to illustrate the FEEDME system.

### *1.5.3 Project commercial results*

The project has no immediate business results at the moment. The project is expected to open 1 engineer position in next 2 years and another one in 3-5 years. However, use of NBIOT technology, in this case for the energy meters, can open new positions in other area as telecommunications and plumbing companies. Due to market circumstances, Danfoss expects majority of additional turnover, expected to 2,4 mio€ in next two years and 12,3 mio€ in 3-5 years coming from export.

## 1.6 Utilization of project results

Business partner will use knowledge for further development and introduction of heat meters with NBIOT connectivity to the market.

In addition, the project results will help to develop further concept of continuous commissioning leading to the reduction of the heat demand in the buildings and increase of heating-related comfort for the tenants
The project showed that a perception-based control of buildings enhance occupants comfort: this result will be used to rethink and re-design the way buildings will be controlled in the future. The FEEDME technology is open source and will be further used in several other projects (and is part of several research project proposals); moreover, FEEDME will, in the near future, be part of a DTU spin-off on IoT usage in buildings and buildings' performance optimization.
The researched IoT communication technologies have been included in the development. The academia partners will utilize the testbed for teaching and demonstration.

## 1.7 Project conclusion and perspective

During the project period, project objectives and milestones have been completed. Technical design and implementation are finished with evaluation and analysis results. Three test fields have been setup with corresponding test activities in order to investigate and show the target system performances.
Well-documented research papers and reports have been published. Presentations have been given to both academic conferences and within industrial area. Project plans and objectives are completed with new findings on the potential improvement on cost-efficiency and system security.
The energy meter product will come to the market in about 1 year time and the core of the project will be commercialized in 2-year time.

## 1.8 Annex

Publications and reports:
[1] "Performance Analysis for In-building Networks Using Zigbee" accepted as poster and presented on IEEE Global Conference on Internet of Things (GCIoT), December 04-07, 2019
[2] "Experimental Performance Evaluation of Bluetooth5 for In-building Networks" accepted by International Conference on Network of the Future (NoF), October 12-14, 2020
[3] "Coverage Analysis for NB-IoT Network" accepted as regular paper and presented on IEEE Global Conference on Internet of Things (GCIoT), December 04-07, 2019
[4] "In-lab Testbed for Mobile Edge Caching with Multiple Users Access" accepted and presented on the 10th International Conference on ICT convergence (ICTC), October 16-18, 2019
[5] "Performance Analysis for In-building Networks using LPWAN and Cloud Technologies", DTU Master project thesis, Svetoslav Gerganov, supervisors Ying Yan and Lars Dittmann. 2018

[6] "Prototyping and Performance Analysis of LPWAN Technologies", DTU Master project thesis, Radheshyam Singh, supervisors Ying Yan and Lars Dittmann. 2020.
[7] "IoT based Technologies for Smart Building Energy Management", Ying Yan and Lars Dittmann, Poster presented at 2nd Global Conference and Expo on Applied Science, Engineering and Technology, October 15-17, 2018
[8] EUDP project stand with two posters for the IDA Connect IoT conference, March 2020.