ORNL/TM-2022/2435

Sensor Impact Evaluation and Verification Technical Advisory Group Meeting Minutes

Yanfei Li
Saptarshi Bhattacharya
Liang Zhang
Yeobeom Yoon
Yeonjin Bae
Piljae Im
Himanshu Sharma
Veronica Adetola
Matt Leach

April 2022

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via OSTI.GOV.

Website www.osti.gov

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Website http://classic.ntis.gov/

Reports are available to US Department of Energy (DOE) employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Website https://www.osti.gov/

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/TM-2022/2435

Electrification and Energy Infrastructures Division

SENSOR IMPACT EVALUATION AND VERIFICATION TECHNICAL ADVISORY GROUP MEETING MINUTES

Yanfei Li
Saptarshi Bhattacharya
Liang Zhang
Yeobeom Yoon
Yeonjin Bae
Piljae Im
Himanshu Sharma
Veronica Adetola
Matt Leach

April 2022

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

ABSTRACT

This report provides the technical advisory group meeting minutes and summary of detailed discussions for future development of sensor impact evaluations and verifications.

1. TECHNICAL ADVISORY GROUP MEETING MINUTES

1.1 BACKGROUND

Methods for sensor configuration/deployment have critical impacts on energy-efficient building control and thermal comfort. However, traditional sensor techniques for building operation and fault detection and diagnostics (FDD) are not optimal in terms of energy efficiency and thermal comfort, and their global effects are not thoroughly investigated. In an effort to address and overcome this limitation, a 3 year project, Sensor Impact Evaluation and Verification, was proposed. The multi-laboratory team—the US Department of Energy's Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and the National Renewable Energy Laboratory (NREL)—is conducting early-stage R&D to provide technical supports and guidelines for sensor design in building/HVAC systems to optimize building energy use, FDD, thermal comfort, and grid efficiency. The overall goal of this project is to develop a framework that enables quantitative evaluation of the impact of sensors on building HVAC control, FDD, and consequently, building energy efficiency and thermal comfort.

In FY 2020, expert interviews were conducted to technical advisory group (TAG) members to investigate the current status and limitations of sensor configuration; identify the research gaps and expectations for potential improvements in sensor configuration and deployment; and integrate expert (e.g., researcher, building operation practitioner) knowledge and experience to develop use case scenarios. A sophisticated literature review and interview responses were published in journal articles and an ORNL report.

In FY 2021, ORNL developed a physics-based emulator that represents ORNL Flexible Research Platform (FRP) equipped with control sequences suggested by ASHRAE Guideline 36-2018, and the surrogate mode is developed to perform sensitivity analysis for different sensor impacts (e.g., sensor types, sensor locations). PNNL developed the framework allows evaluation of advanced rule-based controls for a medium office prototype building and optimization-based predictive controls for a prototype large office building emulator, and focused on understanding the impact of occupancy sensors for energy efficiency and thermal comfort. NREL developed a systematic analysis workflow and tool to quantify the impact of sensor selection and accuracy on FDD performance, which further affects building energy efficiency, thermal comfort, and cost.

In FY 2022, the multi-laboratory team organized a second TAG meeting to share and discuss framework development progress with the TAG members, and to discuss future development pathways of a final evaluation tool that is beneficial for research and industry stakeholders. This report summarizes the meeting minutes and the feedback from TAG members.

1.2 PARTICIPANTS

The TAG members are as follows.

Name	Affiliation
Aravind Dasu	Intel, Programmable Solutions Group
James Fan	Carrier
Hyojin Kim	New Jersey Institute of Technology

Ian Nelson	Command Commissioning
Joe Zhou	Slipstream
Yaoyu Li	University of Texas at Dallas
Nicholas Gayeski	KGS Buildings
Zheng O'Neill	Texas A&M University
Chirag Parikh	Carrier
Paul Ehrlich	Building Intelligence Group
Amanda J. Pertzborn	National Institute of Standards and Technology
Phillip Kopp	Conectric Networks
W. Travis Horton	Purdue University

The team members are as follows.

Name	Affiliation
Piljae Im	ORNL
Veronica Adetola	PNNL
Matt Leach	NREL
Yanfei Li	ORNL
Saptarshi Bhattacharya	PNNL
Himanshu Sharma	PNNL
Liang Zhang	NREL
Yeonjin Bae	ORNL
Yeobeom Yoon	ORNL

1.3 PROJECT OVERVIEW

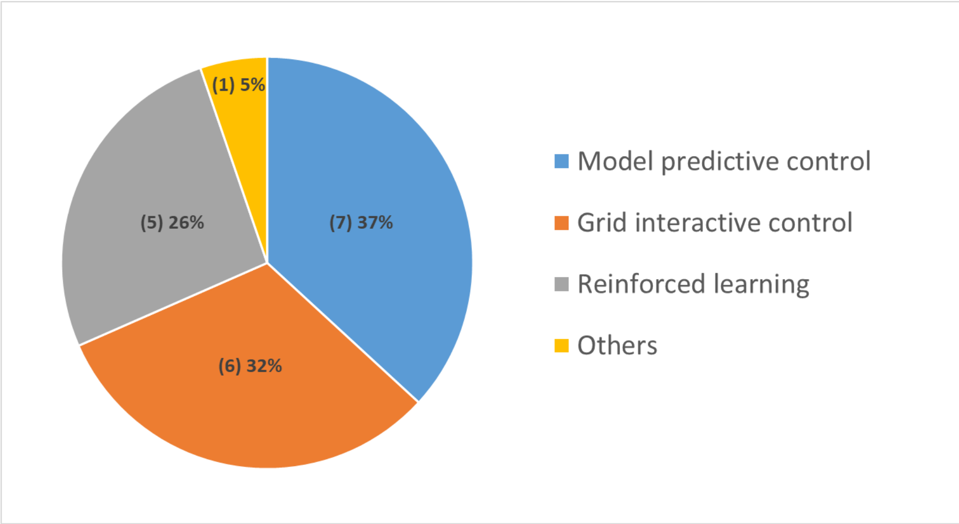
Piljae Im provided an overview of the project background, goal, technical work plan, literature review, and expert interview results.

1.4 DETAILED DISCUSSION ON PROJECT PROGRESS

Piljae Im, Veronica Adetola, and Matt Leach facilitated a detailed discussion on project progress.

Q1: We're planning to evaluate the sensor impacts based on an advanced control in addition to a rule-based control. Which advanced control should be investigated?

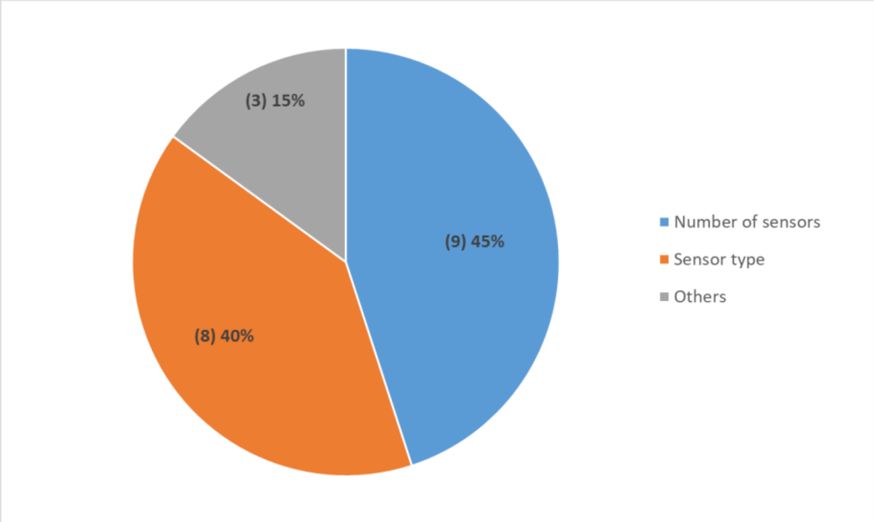
- A1:



Others: mixed use of MPC and adaptive PID

Q2: In evaluating sensor impact, what other major sensor components could be explored in addition to sensor error and location?

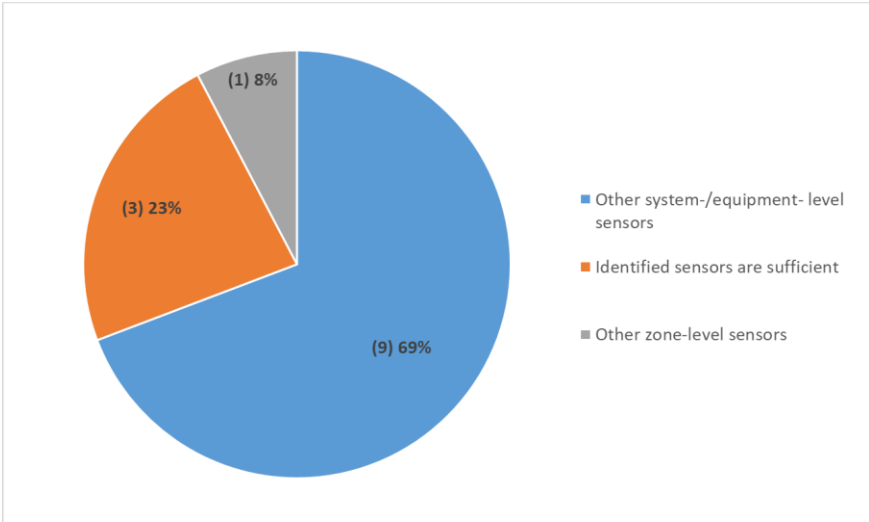
- A2:



Others: sensor drift impact, value of sensors beyond building energy efficiency, and completeness of sensing from a system perspective

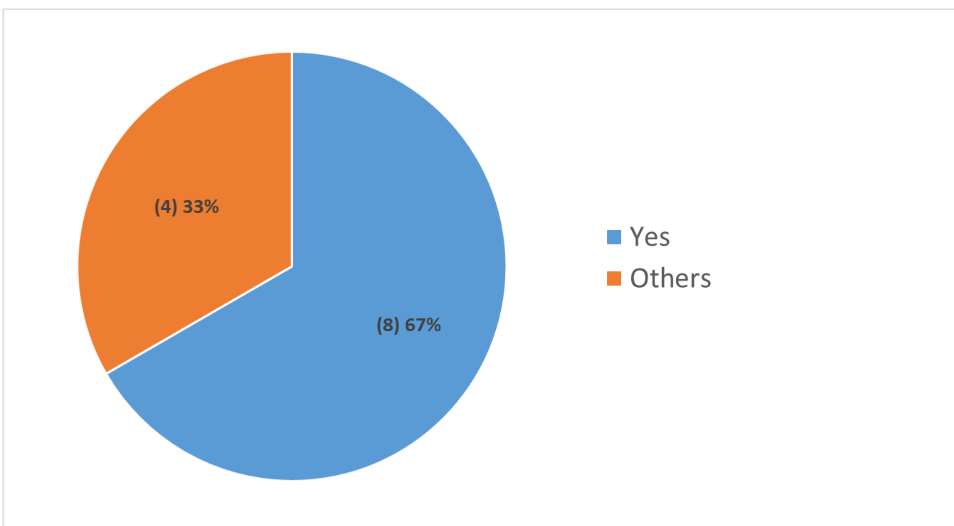
Q3: The following sensors were down-selected as the most critical for studying sensor impact on building controls for demand flexibility: power meters, zone air temperature sensors, outside air temperature sensors, and occupancy sensors. Are there other critical sensors to consider?

- A3:



Q4: Are the following demand flexibility use cases sufficient to evaluate the sensing impact on demand response control strategies?

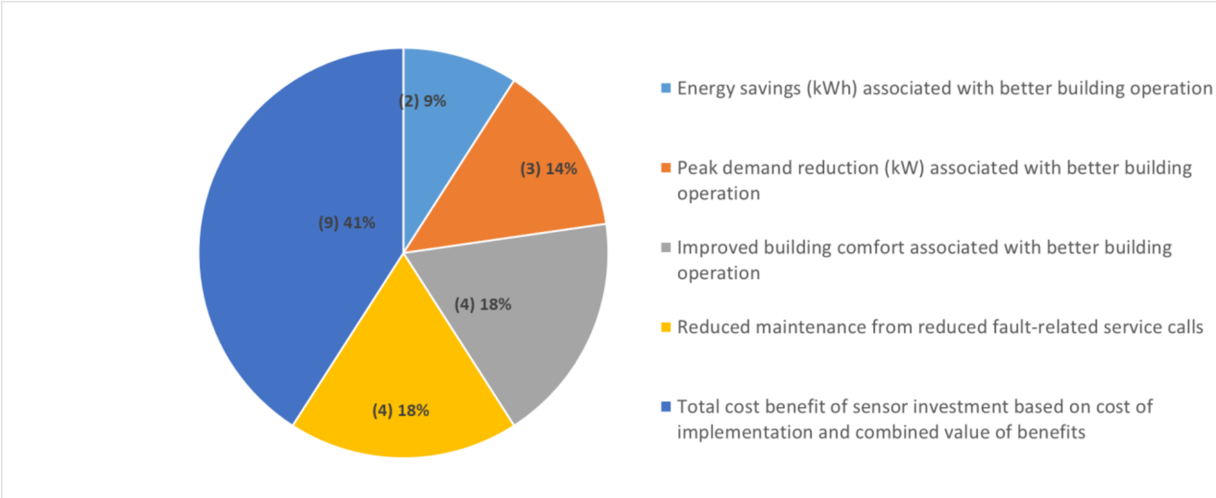
- A4:
  - The following use cases were provided
    - Peak load management based on demand charges
    - Load shifting from high price to low price times
    - Load shaping to maximize on-site renewable energy utilization



Others: occupant interaction and response, lighting/ballast control, thermal energy storage, and power quality

Q5: Which of the following would motivate you the most to invest in additional sensors to improve FDD performance?

- A5:

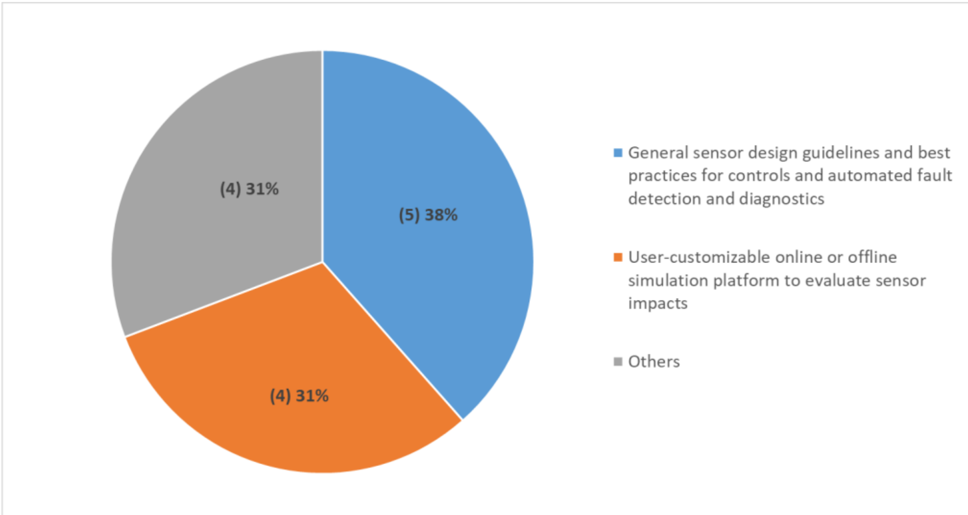


Q6: What is your key concern regarding installing new sensors for FDD?

- A6:
  - Initial and maintenance cost such as sensor calibration and cost for installation, maintenance, and/or reprogramming
  - Installation and calibration complexity, especially in older buildings
  - The balance between the cost and complexity of sensors vs. the benefit that could accrue for the owner
  - Sufficient system-level sensors—temperature sensors between coils, discharge temperatures on terminal units, submetering on plant and air handling units for key energy performance indicators
  - Sensors that can be leveraged for both control and FDD improvement (i.e., stacked value)—sensors that will provide the most benefit for the least investment (i.e., impacting the most common occupancy complaint or service call vs. those that are uncommon)

Q7: What will be the best form of a final evaluation tool for research and industry stakeholders?

- A7:



Others: tool to help with diagnostics of the root cause of the issues in automated fault detection and diagnostics, working closely with the ASHRAE Guideline 13 committee to reflect the results in the Guideline focused on design and specification of DDC systems, and a plug-in to existing DOE2/Energy+ models to recommend sensor quantity, type, and placement impact

Q8: How can this work be shaped to be more useful and attractive to the industry?

- A8:
    - More tangible results and simple examples/illustrations of how to practically use this work
    - Ability to integrate results/findings into facility assessments and rule sets
    - Demonstration projects with a simulation-based platform and experimental validation
    - Contextualized cost analysis in the framework and expanded cost analysis, including maintenance/data analysis
    - Results published in periodicals such as the *ASHRAE Journal and Engineered Systems*, and closer collaboration with ASHRAE
    - Marketing-type infographics showing the outcomes of different sensor quantities, placements, and types to the industry to stimulate the conversation
    - Feedback from building owners regarding what would be useful for them

1.5 ADDITIONAL COMMENTS FROM TAG MEMBERS

- Sensor impacts to consider based on advanced control:
    - Understanding the quality and level of advanced control possible based on the number, type, and quality of sensor data would be a very interesting outcome
    - Model predictive control and reinforcement learning, which are good for research purposes but are not currently practical in real building applications

- Major sensor components to be explored:
    - Sensor drifting in industrial practice

- Critical sensors to be considered:
    - Demand response sensors (e.g., frequency regulation for power meters)
    - More sensor types (e.g., supply temperature, compressor status, fan speed, pump speed)
    - Innovative sensor types directly related to health and safety

- Considerations for sensors to improve FDD performance and cost analysis:
  - Industry needs and long-term goals (e.g., how to diagnose faults, and especially finding the underlying cause of faults)
  - Cost, which is important when installing additional sensors in existing platforms
  - Sensor contributions to the value of the business, not only building energy savings

- Most HVAC design engineers have a limited understanding of control; industry interested in general sensor design guidelines or best practices for sensor placement and configurations through this research

- Working closely with ASHRAE 13 and ASHRAE 36 committees encouraged, as well as gaining feedback from control companies and experts in controls and sensors

2. CONCLUSIONS AND FUTURE DEVELOPMENT

This section addresses the comments from the TAG members regarding the sensor impacts evaluations and verifications. The TAG members provided comments on the current goal and future development. The comments are summarized categorized by the different participating national laboratories.

2.1 ORNL

(1) Current goal

The goal of this project is to develop a generic sensor impact evaluation and verification emulator for building and HVAC performance. Sensors are the most fundamental component of control systems, and they are used to collect environment variables that are the basis/inputs of control systems to determine the appropriate control actions. Sensors are the first step of the whole control workflow. If sensors readings are corrupted, the ultimate control benefits will be significantly compromised. Controls have been studied substantially in the past 10 years. However, sensor impacts with respect to building performance are not thoroughly studied. Sensitivity and uncertainty analyses were conducted for this project, demonstrating the significance of sensor impacts.

The developed emulator includes three major sensor components: sensor error or fault, sensor location, and sensor type (associated with control system types). These components significantly affect the control performance and building performance. In the emulator, the building model is based on EnergyPlus; the HVAC system is a user-defined component model; and the control is implemented through Python EMS based on ASHRAE 36 controls.

In addition to the simulation study, field tests have been conducted at ORNL’s Flexible Research Platform. The field tests serve to validate the sensor impact verification and evaluation emulator, and to demonstrate the sensor impact magnitudes in real buildings.

(2) Future development

TAG members identified two major future development directions, listed as follows:

- TAG members recommended considering different types of control (e.g., reinforcement learning control and model predictive control) when evaluating sensor impacts because different controls might require different sensors. In the near future, the multi-laboratory team will consider integrating reinforced learning control and/or model predictive control into the emulator.

- Regarding the final form of the sensor impact verification and evaluation emulator, TAG members suggested that design guidelines and online/offline simulation platforms would be beneficial and attractive to the industry. The team will work closely with the ASHRAE Guideline 13 committee and industry partners to determine the form of the final evaluation tool (e.g., web-based application).

The ultimate goal of the project is to further extend the features of the emulator to be a robust sensor design and configuration software package to be used by multiple stakeholders, such as engineers, HVAC system designers, and building owners.

2.2 PNNL

(1) Current goal

In this project, PNNL is focusing on sensor impact evaluation and verification, specifically for advanced controls for commercial buildings. The primary effort is in the development of a framework that allows users to select the type of sensor and building and subsequently evaluate the impact of sensor performance for the selected choices with respect to different objectives, such as energy efficiency, thermal comfort, and demand flexibility. Currently, the framework allows evaluation of advanced rule-based controls (e.g., zone temperature set point reset, zone minimum airflow reset, system-level minimum airflow reset) for a medium office prototype building, and optimization-based predictive controls for a prototype large office building emulator (developed in-house at PNNL). In FY 2021, the evaluation focused on understanding the impact of occupancy sensors for energy efficiency and thermal comfort. Ongoing work focuses on extending the developed framework to include additional sensors (e.g., temperature sensors) to an evaluation set.

(2) Future development

Future directions in this project are generally aligned with the National Roadmap for Grid-Interactive Efficient Buildings established by the US Department of Energy's Building Technologies Office. The team aims to understand the impact of sensors on demand flexibility from commercial buildings. Toward this end, zone air temperature sensors, outdoor air temperature sensors, and power meters were down-selected as the most crucial sensors connected to the demand flexibility service. The following future directions will specifically aim to incorporate TAG feedback:

- In addition to existing zone-level sensors under study, system-level sensors (e.g., supply air temperature) will be examined.

- Most of the TAG members agreed that the following use cases for demand flexibility are sufficient to evaluate sensing impact on demand response control strategies: peak load management based on demand charges, load shifting based on time-varying prices, and load shaping based on renewable energy availability. TAG members also recommended considering occupant interactions and the impact of sensing on lighting/ballast control for demand flexibility. Ongoing work is considering the impact of occupant interactions, and sensor impact on lighting controls was found to be minimal in the context of energy efficiency in earlier work.[1] The impact of such controls on demand flexibility is also expected to be minimal, owing to the relatively

[1] X. Lu, S. Bhattacharya, H. Sharma, V. Adetola, and Z. O'Neill, "Sensor Impact Evaluation in Commercial Buildings: The Case of Occupancy-Centric Controls," *Energy and Buildings*, under review.

small magnitude of power consumption by lighting devices (compared with HVAC), although the team is open to exploring this question more specifically in future work.

2.3 NREL

(1) Current goal

NREL aims to develop a systematic analysis workflow and tool to quantify the impact of sensor selection and accuracy on FDD performance, which further affects building energy efficiency, thermal comfort, and cost. The workflow contains three modules. The first module identifies important sensors for FDD. The second module evaluates the impact of sensor inaccuracy on sensor selection and FDD accuracy. The third module calculates the opportunity cost of sensors for FDD. The whole analysis workflow provides a systematic and quantitative guidance on sensor design, selection, and maintenance for FDD modeling, and the team developed a Python package to automate the workflow.

(2) Future development

TAG members' feedback on FDD-related questions (Q5 and Q6) was particularly relevant. The team will apply this feedback to shape future developments of sensor impact evaluation on FDD.

In Q5, 41% of TAG members agreed that the combined cost benefit (including energy, peak load, thermal comfort, and maintenance) is the biggest motivation to invest in new sensors. This result indicates the importance of quantifying the benefits from FDD, and the result is in accordance with the team's design of a sensor cost analysis framework, which considers the aggregated benefit from improved energy efficiency, thermal comfort, and maintenance. However, the framework does not consider peak load; this can be a future research direction. In Q6, primary concerns were the initial cost (purchase and installation) and maintenance cost (calibration). TAG members also mentioned system level sensors, which is in accordance with the team's observations on sensor cost analysis. The team found that system-level sensors will have high cost effectiveness, especially in large buildings. TAG members also mentioned about the stacked value for control and FDD. The team plans to systematically merge the impact on control and FDD in the future.

Based on the poll and comments from TAG members, the team has three major future research directions for FDD. First, building-grid integration will be considered in the workflow, such as by including building peak load or time-of-use rates. Furthermore, the quantification of the impact of FDD on building-grid-integration, such as demand response performance, can be merged into the current workflow. Second, we can further integrate the sensor impact study on FDD with the study on controls to consider the stacked effect of control and FDD. This integration can be realized by the modularization of control and FDD analyses to make them compatible with each other. Third, this research will have a larger effect on the industry and academia by developing a plug-in to the existing EnergyPlus models to determine the impact of sensor quantity, type, and placement. Although the analysis was developed in a Python package, it relies on the simulation from EnergyPlus modeling, and it mostly post-processes the simulation. With the plugin to EnergyPlus, these procedures can be further automated and can benefit the framework's application in the industry and academia.