Joint Optimization of HVAC and Active Insulation Control Strategies in Residential Buildings

Amin Sepehri
Student Member

Gregory Pavlak, Ph.D.
Member ASHRAE

ABSTRACT

Increasing building construction thermal resistance has been shown to be an effective traditional way of improving building energy efficiency. In this approach, the opaque building envelope is often deemed to be a static system that keeps the indoor environment isolated from the outdoor environment. More recently, active insulation systems (AIS) have been conceptualized to enable active control over building envelope thermal properties, allowing the thermal resistance to be optimally modulated in response to changing environmental conditions. Dynamically tuning the building thermal performance can lead to increased energy savings, reduced operating costs, and reductions in operational carbon emissions. When paired with thermal mass, AIS can also increase building load flexibility for providing demand response and grid services. Building flexibility can further be improved if the building is also equipped with optimized HVAC system controls. In this configuration, the AIS and HVAC systems can be beneficially coordinated to optimally condition the space based on the desired operational objectives.

In this work, we quantify the potential benefits of jointly optimizing AIS and HVAC system controls by applying model predictive control to a detailed whole-building energy model. The example building is an all-electric single-family residential building, satisfying IECC 2012, in Baltimore, MD. To highlight the increase in benefits from jointly optimizing HVAC and dynamic envelope systems, we compare the results to the performance achieved when optimizing HVAC and AIS systems individually. Results showed that the combined optimization of HVAC and AIS control was able to achieve 13% peak demand reduction, while savings 3% energy. This is in contrast to only a 10% peak reduction and 16% increase in energy use for the case with optimized HVAC only. These results ultimately motivate further exploration, integration, and joint optimization of dynamic envelope and HVAC system components.

1. INTRODUCTION

Buildings account for over one-third of global energy consumption and 40% of total direct and indirect carbon emissions [1]. Improving its energy efficiency (EE) would significantly reduce costs and facilitate the transition to a decarbonized energy system. While increasing resistance in building construction has been shown to be an effective traditional way of improving building EE, it has resulted in static thermal behavior that neglects the dynamics of electric power system due to the increasing integration of wind and solar resources, which are variable in nature. The static nature also precludes opportunities to increase efficiency by leveraging passive heating and cooling by favorably adapting the building thermal characteristics to changing environmental conditions, and by utilizing building envelope integrated

Amin Sepehri is a PhD student in the Department of Architectural Engineering at Penn State, State College, PA. **Dr. Pavlak** is an Assistant Professor of Architectural Engineering at Penn State.

thermal storage. Thus, active insulation systems (AIS) were introduced to to address these shortcomings by achieving dynamically tunable thermal envelope performance in buildings.

Technologies like AIS can ultimately be used to create Grid-interactive efficient buildings (GEBs). According to a roadmap report by the U.S. Department of Energy Building Technologies Office [2] GEBs are energy-efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to the optimize energy use of grid services, occupant needs, and cost reductions in a continuous and integrated way. GEBs are believed to be efficient, connected, smart, and flexible [2]. That is, GEBs can provide efficient building services such as thermal and visual comfort, indoor air quality, hot water, and so on. They are also connected through two-way communication between technologies and the grid. Being smart, they support advanced buildings and energy system control including co-optimization of multiple end-uses and DERs (e.g., generation and storage) [3], incorporation of input predictions (e.g., weather, occupancy, and grid needs) into the optimization [4], [5], and optimization for multiple objectives (e.g., overall energy use, carbon emissions, peak shaving, and load shifting) [6]. Recently, Li and Pavlak [7] revealed a diverse range of tradeoffs between building energy cost and carbon emission reduction objective and thus insisted on understating the incentive signal dynamics before the development of new control technologies for GEBs. Finally, GEBs can provide a flexible load control that responds to the electric grid accordingly. For instance, Swaminathan and Pavlak have shown that such building flexibility can reduce the required size of battery storage in building-level microgrids [8].

Given this context, in this work we jointly optimize the controls of AIS and HVAC systems using detailed-whole building energy models to explore the potential synergy between operations of both systems. We also provide an intricate comparison of the savings with respect to the AIS- and HVAC-only approaches. Section 2 provides additional context through the review of relevant literature. Section 3 describes the building models used in this study, optimization environment, and performance comparison scheme. Results for three simulation case studies are presented in section 4, followed by closing remarks in section 5.

2. RELATED WORK

Researchers could show that excessive construction insulation caused thermal discomfort during summer overheating in [9]–[11]. However, Park et al. [12] used a simplified two-step control strategy for AIS in residential buildings and reported average reductions of 15% and 10% in annual cooling and heating energy use respectively. Moreover, dynamic insulation has proved to be an appropriate mate for PCM utilization since it harnesses PCM latent heat during a complete phase change process [13].

So far, miscellaneous approaches have been taken to reach the same AIS behavior. For instance, Kimber et al. [14] presented a multilayered wall that could switch from conductive to the insulated state by positioning thin polymer membranes within a wall to create stagnant air. Breathing wall is another common approach based on convection (air) mechanism to ensure a proper Indoor Air Quality (IAQ) by providing enough air infiltration into the building. According to Imbabi [15], it is an ideal solution for both new build and retrofit applications. Another insulation type based on convection (air) mechanism is translucent façade elements. Pflug et al. proposed a translucent insulation panel that is moved vertically or rolled up/down between two fixed layers to switch between the insulating and conducting states by switching the wall U-value [16]–[18]. Unlike breathing walls, they showed large improvements in the summer thermal comfort in addition to a cooling demand reduction of 29.6%.

Thermal diodes are another way of achieving AIS. Varga et al. [19] worked on a numerical solution of the heat transfer problem to characterize thermophysical properties (i.e., conductivity, diffusivity, and specific heat) of a thermal diode in a heat pipe panel. They showed that the thermal diode conductivity could be altered by three to five times between the forward and backward heat transfer. The last mechanism covered in this literature review is differing gas pressure inside a vacuum insulation panel. Benson et al. [20] designed variable-conductance vacuum insulation (VCI) which used an electronic heater to change the temperature of the hydride. Once the temperature was changed, hydrogen adsorption and desorption provided the lower and upper limits of the insulation layer.

Most of the aforementioned technologies are either conceptual or only tested as prototypes. However, researchers have utilized simulation tools to evaluate the effects of AIS by controlling the solid-state conductivity. Developing a simulation strategy, Favoino et al. [21] showed the potential of AIS to reduce building energy use, followed by Jin et al.'s work [22] which showed an annual energy saving potential of 50%. Menyhart and Krarti [23] used a modified RC model to simulate the AIS control mechanism with two steps (low-R and high-R). They reported a potential range of total energy savings of 7% to 42% compared to a baseline with static insulation. Shekar and Krarti [24] expanded on this work by optimizing the R-value by a genetic algorithm in an office building and reported a maximum potential saving of 17% in annual heating and cooling energy costs. While all of those studies have estimated the potential reductions in total energy use, Antretter et al. [25] used the Energy Management System (EMS) feature of EnergyPlus to develop a rule-based control algorithm to model AIS and illustrated a flexible control of charging and discharging of AIS from both exterior and interior sides of a wall. They showed that such control could then result in a dynamic building energy management that has the potential to provide grid services like load shedding and shifting. Expanding on the last work, Mumme et al. [26] showed a smarter building envelope by coupling thermal storage to AIS. They also claimed a more flexible building envelope when AIS is accompanied by pre-conditioning. However, neither the AIS control nor the pre-conditioning schedule was operationally optimized.

To the best of our knowledge, no work thus far has jointly optimized HVAC setpoint and AIS controls, and few studies used detailed-whole building energy models. This study partially fills this gap by performing a joint optimization of HVAC and AIS controls. An intricate comparison of the savings to the AIS- and HVAC-only approaches is provided to better understand the potential interactions and synergies between the two technologies.

3. METHODS

To quantitatively evaluate the benefit of jointly optimizing building HVAC operations and dynamic envelope properties a framework was developed that couples detailed whole-building energy models with optimization algorithms to generate optimal control decisions for the proposed systems. The following subsections provide more detail on the building energy models used in this study, and the components of the optimization framework.

I. Building Models

The baseline model is a single-family DOE residential prototype building. It is located in Baltimore, MD (Climate Zone 4A) with a net conditioned area of 220.82 m^2 (2377 ft^2), and heating and cooling are provided by an all-electric heat pump system with heating and cooling setpoints of 20˚C (68˚F) and 24˚C (75.2˚F), respectively. The baseline exterior wall construction is adopted from Antretter et al. [25] to include thermal mass (concrete 140 mm (5.51 in)) between two insulation layers. Two insulation layers satisfy the total R-value required by IECC 2012. The outside wall layer is covered by cladding stucco (10 mm (0.4 in)), and the inside layer is Gypsum board (10 mm (0.4 in)).

There are five AIS configurations that are considered in this work (**Figure 1**). While the baseline model is always at configuration 4 with both the interior and exterior insulation layers in the On state (i.e., On-On), the optimizer can choose any configuration from 1 to 4. Configuration 3 means the exterior layer is Off while the interior layer is On (i.e, Off-On), configuration 2 (i.e, On-Off) is the opposite case 3, and configuration 1 (i.e, Off-Off) is with both layers at Off state with total insulation resistance of only 0.007 m^2K/W (0.04 ft^2˚Fh/Btu). Configuration 5 resembles configuration 2 with On-Off structure. While configuration 5 satisfies the total required R-value at the exterior layer, configuration 2 had the total resistance split between the interior and exterior layers. As a result, configuration 5 allows all thermal mass to be available for preconditioning of the space via HVAC control in addition to having full insulation, which makes it ideal for an HVAC-only case study to assess the maximum power of HVAC system to precool the space.

II. Optimiztion Environment

A model predictive control (MPC) framework is applied in this study through a variant of the metaheuristic PSO

Configuration	Assembly (Exterior to Interior)	Schematic
1	Cladding Stucco + Mass + Gypsum	S Mass G
2	Cladding Stucco + Ext. Batt R7.5 + Mass + Gypsum	S B Mass G
3	Cladding Stucco + Mass + Int. Batt R7.5 + Gypsum	S Mass B G
4	Cladding Stucco + Ext. Batt R7.5 + Mass + Int. Batt R7.5 + Gypsum	S B Mass B G
5	Cladding Stucco + Ext. Batt R15 + Mass + Gypsum	S B Mass G

Figure 1. Wall constructions used to simulate the range of AIS states.

algorithm [27] for optimizing AIS and HVAC operations. The algorithm generates a candidate control vector ascandidate solutions (particles) and expects the cost of that control strategy to then move the particles around in the search space over the particle's position and velocity. The local best variant of PSO is used from the `PySwarms` optimization package for Python. The optimization problem to be solved is the minimization of a blended cost function of energy and peak demand as described in Equation (1) below,

$$\min_{T_{setpoint},\, AIS} \left(\sum_{t=1}^{24} E_{cooling}(t) * w_1 + max\left(E_{cooling,\ 4pm-7pm}\right) * w_2 \right) \quad (1)$$

$$s.t. \quad 20°C\ (68°F) \leq T_{setpoint}(t) \leq 24°C\ (75.2°F) \quad \forall t \in \{1...24\}$$

$$AIS(t) \in \{1, 2, 3, 4\} \quad \forall t \in \{1...24\}$$

where $E_{cooling}$ is energy use associated with the cooling system in kW, w_1 is the weighting factor corresponding to the daily energy use component, w_2 is the weighting factor corresponding to the peak of energy use from 4 to 7 pm, $T_{setpoint}$ is the cooling HVAC setpoint temperature in ˚C, and AIS is the AIS configuration state. The optimization cost function is set to minimize the peak demand in addition to the total building cooling energy by varying the cooling setpoint temperature and AIS configuration.

III. Performance Comparison

Three case studies are included in this study: HVAC-only, AIS-only, and HVAC+AIS (i.e., Merged case). Their performances are compared to a baseline case with no preconditioning and no AIS control on August 10 when there was a suitable outdoor drybulb (DB) temperature swing. Given all thermal mass available for preconditioning the space (AIS at state 5), one simulation allows the optimizer to find the optimum precooling strategy (HVAC-only) before the peak happening at 4 pm with a setback to 24˚C (75.2˚F) at 7 pm (**Figure 2**). Note in this case that all required R-value is satisfied at the exterior insulation layer to assess the maximum HVAC contribution to the total savings.

Like HVAC-only, there is an AIS-only case study where the setpoint is kept steady at 24˚C (75.2˚F), and the optimizer decides only on the optimum AIS control strategy (**Figure 3**). The maximum power of AIS control in total savings is quantified in this simulation. Lastly, the Merged case study allows the optimizer to adjust both AIS and HVAC controls in parallel, looking for synergy or an interaction between the two types of controls.

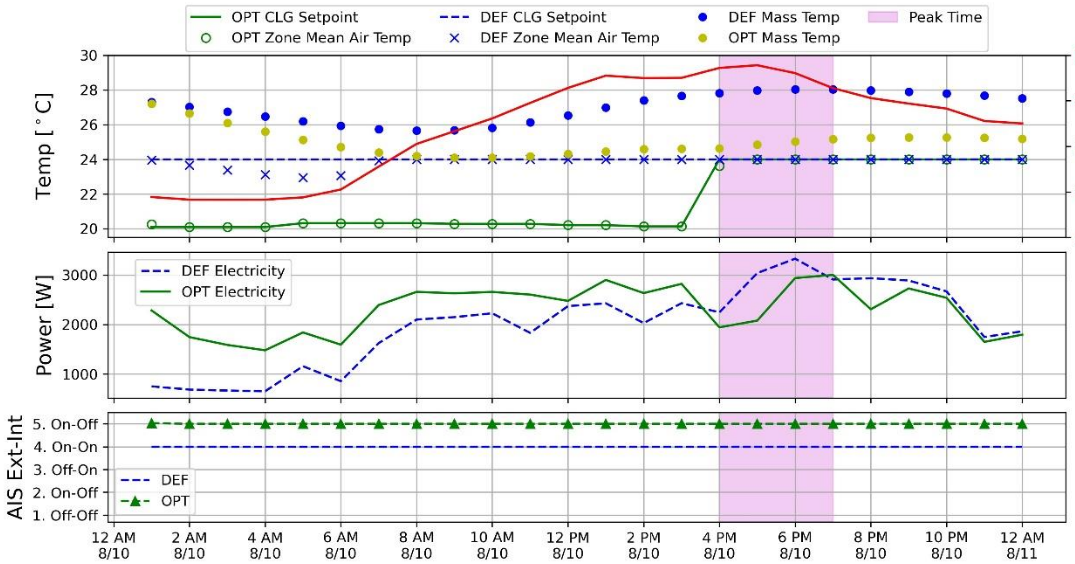

Figure 2. Results of HVAC-only optimization for August 10.

4. RESULTS

This section provides three sets of plots for each of the three case studies to compare their results with the baseline scenario. Each plot consists of three panels displaying relevant temperature trajectories (i.e., cooling setpoint, zone air temperature, and mass temperature for both default (DEF) and optimum (OPT) cases on the left axis, and outdoor DB on the right axis) in the top panel, total building power draw in the middle panel, and AIS control in the bottom panel.

Results for the HVAC-only case study are compared to the baseline in **Figure 2**. Mass temperatures start from the same thermal history at the beginning of the day; however, adjusting the setpoint at 20˚C (68˚F) for the OPT case, the space is preconditioned, and OPT mass temperature diverges from the DEF mass temperature gradually until the maximum difference of 3˚C (5.4˚F) happens during the peak time. That is, construction mass is charged during off-peak, and then discharged during the on-peak period. The middle panel compares hourly power draws of the building with the highest DEF peak of 3.33 kW happening at 6 pm. From this panel, a clear peak demand reduction of 10% is obvious from 3.33 kW to 3.00 kW while increasing the overall energy consumption by 16%, which can be understood from the area under the curves. The bottom panel displays no AIS optimization in this test and both the baseline and HVAC-only case studies remain at constant controls of 4 and 5, respectively. As mentioned in the Methods section, configuration 5 is only used in this test since it allows for assessing the full capability of the HVAC system to lower the cost function by charging the thermal mass from the interior, while satisfying the total R-value requirement.

Results for the AIS-only case study are compared to the baseline in **Figure 3**. From the top panel, mass temperatures start from the same thermal history at the very beginning of the day; however, it diverges from the DEF since AIS is at configuration 3 in the OPT case. In other words, no exterior insulation lets the thermal mass be charged by the cool ambient air in the nighttime to be then discharged later in the day. The bottom panel illustrates how the AIS control starts from configuration 3 to decrease the thermal mass temperature; followed by 4 to keep the thermal mass temperature low enough for a discharge at configuration 2 in the peak period. The middle panel compares hourly power draws of the building with the highest DEF peak of 3.33 kW happening at 6 pm. From this panel, a clear peak demand reduction of 10% is obvious from 3.33 kW to 3.00 kW while decreasing the overall energy consumption by 6%, which can be understood from the area under the curves.

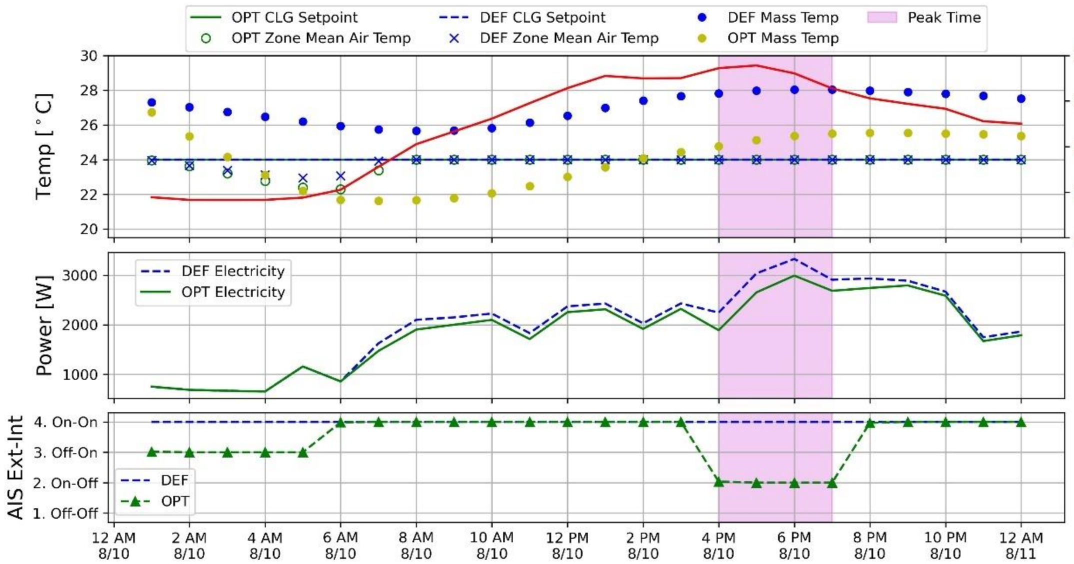

Figure 3. Results of AIS-only optimization for August 10.

Results for the Merged case study are compared to the baseline in **Figure 4**. From the top panel, mass temperatures start from the same thermal history at the very beginning of the day; however, it diverges from DEF since not only AIS starts at configuration 3, but also CLG setpoint is allowed to be lower than 24˚C (75.2˚F) in the OPT case. AIS control in this test is similar to the AIS-only test, except it shifts to configuration 2 sooner than the peak period to allow additional charging due to the low CLG setpoint from 2 pm to 4 pm. Hence, a 13% peak reduction from 3.33 kW to 2.90 kW appears in the middle panel in addition to a 3% reduction in the overall energy consumption.

Table 1 summarizes total savings in addition to savings achieved by overall daily energy consumption and peak demand reduction. Case study 1 known as HVAC-only could decrease the cost function by 4% mainly due to the 10% savings achieved by peak demand reduction. This demand savings was able to offset the 16% increase in energy consumption. On the other hand, case study 2 known as AIS-only could achieve higher total savings of 9% with reductions in both the peak demand and energy consumption of 10% and 6%, respectively. Finally, case study 3 known as Merged had the highest total savings of 10% with the highest reduction of 13% in peak demand and moderate energy savings of 3%.

5. CONCLUSION

In this study MPC was applied to show how AIS and HVAC control optimization can significantly contribute to both energy savings and peak load reduction. Unlike case 1 that uses more overall energy to reduce the peak demand, case 2 leads to a lower peak while achieving less energy consumption (**Table 1**).

According to the hourly mass temperature profiles (**Figures 2-5**), that achievement is due to the construction thermal storage that can be charged during cool nighttime outdoor and discharged during the hot daytime environment. Having merged both AIS and HVAC controls in case 3, even more peak demand reduction is achieved while also achieving notable energy savings.

Table 1. Savings associated with each of the case studies

Case Study	Details	Energy Savings	Peak Demand Reduction	Total Savings by Cost Function
1	HVAC-only	-16%	10%	4%
2	AIS-only	6%	10%	9%
3	Merged	3%	13%	10%

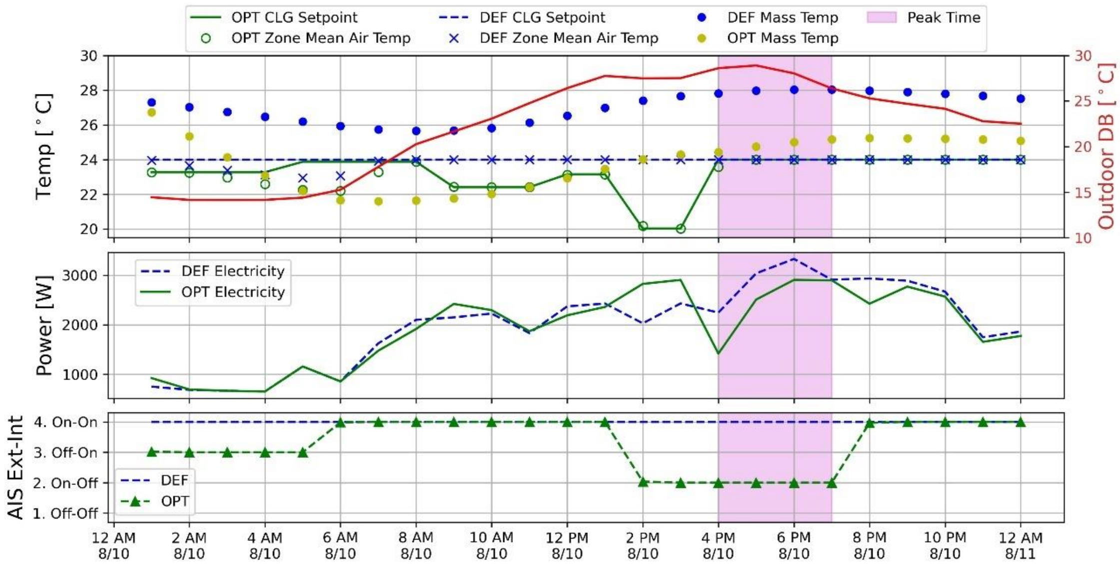

Figure 4. Results of the Merged optimization for August 10.

Overall, the results highlight how active envelope, HVAC control, and building thermal storage can work together to achieve both flexibility (e.g., load shifting) and efficiency. Consequently, GEBs employing active insulation, intelligent HVAC controls, and thermal storage can contribute to greater affordability and reliability of the power system, reductions in greenhouse gas emissions through lower energy consumption, and more renewable energy integration through their flexibility.

Although the largest savings was observed for the Merged case, the total savings was less than the sum of AIS-only and HVAC-only cases. In other words, the technologies were observed to be complimentary but not synergistic. The AIS and HVAC control essentially provide two mechanisms for charging the same envelope thermal mass, thus, there are limitations on how much energy can be stored and how quickly the mass can be charged and discharged. Future work could condiser integration of phase change materials and/or active thermal storage with active envelopes to explore optimal system designs that improve upon these initial results.

Lastly, the largest limitation of this study is perhaps that the savings have only been quantified for a single day, building type, and climate zone. Executing the joint optimization with detailed whole building models is a computatially intensive task, thus, the work here was intended to explore the joint potential under favorable conditions to determine if further exploration is warranted. In the future, this work will be expanded to examine the joint optimization of HVAC and AIS controls in different climate zones, and for a full year of weather conditions.

ACKNOWLEDGMENTS

Computations for this research were performed on the Pennsylvania State University's Institute for Computational and Data Sciences' Roar supercomputer. This content is solely the responsibility of the authors and does not necessarily represent the views of the Institute for Computational and Data Sciences.

REFERENCES

[1] "Energy efficiency – Topics - IEA." [Online]. Available: https://www.iea.org/topics/energy-efficiency. [Accessed: 15-Jul-2021].
[2] DOE, "A National Roadmap for Grid-Interactive Efficient Buildings," p. 166, 2021.
[3] M. Sadat-Mohammadi, S. Asadi, M. Habibnezhad, and H. Jebelli, "Robust scheduling of multi-chiller system with chilled-water storage under hourly electricity pricing," *Energy Build.*, vol. 218, 2020.

[4] M. G. Yu and G. S. Pavlak, "Assessing the performance of uncertainty-aware transactive controls for building thermal energy storage systems," *Appl. Energy*, vol. 282, no. PB, p. 116103, 2021.
[5] M. Sadat-Mohammadi, J. Khazaei, and S. Asadi, "Uuncertainty-based scheduling of multi-chiller system with thermal energy storage under real-time prices," pp. 1–5, Nov. 2021.
[6] M. G. Yu and G. S. Pavlak, "Extracting interpretable building control rules from multi-objective model predictive control data sets," *Energy*, vol. 240, p. 122691, 2022.
[7] L. X. Li, G. S. Pavlak, L. X. Li, and G. S. Pavlak, "Pattern Analysis of Dynamic Grid Incentives and the Implications on Optimal Control of Building Thermal Energy Storage Pattern Analysis of Dynamic Grid Incentives and the Implications on Optimal," 2021.
[8] S. Swaminathan, G. S. Pavlak, and J. Freihaut, "Sizing and dispatch of an islanded microgrid with energy flexible buildings," *Appl. Energy*, vol. 276, no. June, p. 115355, 2020.
[9] T. S. Larsen and R. L. Jensen, "Comparison of measured and calculated values for the indoor environment in one of the first Danish passive houses," *Proc. Build. Simul. 2011 12th Conf. Int. Build. Perform. Simul. Assoc.*, pp. 1414–1421, 2011.
[10] R. S. McLeod, C. J. Hopfe, and A. Kwan, "An investigation into future performance and overheating risks in Passivhaus dwellings," *Build. Environ.*, vol. 70, pp. 189–209, 2013.
[11] K. M. S. Chvatal and H. Corvacho, "The impact of increasing the building envelope insulation upon the risk of overheating in summer and an increased energy consumption," *J. Build. Perform. Simul.*, vol. 2, no. 4, pp. 267–282, 2009.
[12] B. Park, W. V. Srubar, and M. Krarti, "Energy performance analysis of variable thermal resistance envelopes in residential buildings," *Energy Build.*, vol. 103, pp. 317–325, 2015.
[13] R. A. Kishore, M. V. A. Bianchi, C. Booten, J. Vidal, and R. Jackson, "Enhancing building energy performance by effectively using phase change material and dynamic insulation in walls," *Appl. Energy*, vol. 283, no. November 2020, p. 116306, 2021.
[14] M. Kimber, W. W. Clark, and L. Schaefer, "Conceptual analysis and design of a partitioned multifunctional smart insulation," *Appl. Energy*, vol. 114, pp. 310–319, 2014.
[15] M. S. E. Imbabi, "A passive–active dynamic insulation system for all climates," *Int. J. Sustain. Built Environ.*, vol. 1, no. 2, pp. 247–258, 2012.
[16] T. Pflug, T. E. Kuhn, R. Nörenberg, A. Glück, N. Nestle, and C. Maurer, "Closed translucent façade elements with switchable U-value - A novel option for energy management via the facade," *Energy Build.*, vol. 86, pp. 66–73, 2015.
[17] T. Pflug, B. Bueno, M. Siroux, and T. E. Kuhn, "Potential analysis of a new removable insulation system," *Energy Build.*, vol. 154, pp. 391–403, 2017.
[18] T. Pflug, N. Nestle, T. E. Kuhn, M. Siroux, and C. Maurer, "Modeling of facade elements with switchable U-value," *Energy Build.*, vol. 164, pp. 1–13, 2018.
[19] S. Varga, A. C. Oliveira, and C. F. Afonso, "Characterisation of thermal diode panels for use in the cooling season in buildings," *Energy Build.*, vol. 34, no. 3, pp. 227–235, 2002.
[20] D. K. Benson, T. F. Potter, and C. E. Tracy, "Design of a variable-conductance vacuum insulation," *SAE Tech. Pap.*, vol. 103, no. 1994, pp. 176–181, 1994.
[21] F. Favoino, Q. Jin, and M. Overend, "Design and control optimisation of adaptive insulation systems for office buildings. Part 1: Adaptive technologies and simulation framework," *Energy*, vol. 127, pp. 301–309, 2017.
[22] Q. Jin, F. Favoino, and M. Overend, "Design and control optimisation of adaptive insulation systems for office buildings. Part 2: A parametric study for a temperate climate," *Energy*, vol. 127, pp. 634–649, 2017.
[23] K. Menyhart and M. Krarti, "Potential energy savings from deployment of Dynamic Insulation Materials for US residential buildings," *Build. Environ.*, vol. 114, pp. 203–218, 2017.
[24] V. Shekar and M. Krarti, "Control strategies for dynamic insulation materials applied to commercial buildings," *Energy Build.*, vol. 154, pp. 305–320, 2017.
[25] F. Antretter, B. Cui, D. Hun, and P. Boudreaux, "Assessing the potential of active insulation systems to reduce energy consumption and enhance electrical grid services," *Therm. Perform. Exter. Envel. Whole Build.*, 2019.
[26] S. Mumme, N. James, M. Salonvaara, S. Shrestha, and D. Hun, "Smart and efficient building envelopes: Thermal switches and thermal storage for energy savings and load flexibility," *ASHRAE Trans.*, vol. 126, pp. 140–148, 2020.
[27] C. D. Corbin, G. P. Henze, and P. May-Ostendorp, "A model predictive control optimization environment for real-time commercial building application," *J. Build. Perform. Simul.*, vol. 6, no. 3, pp. 159–174, 2013.