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A Framework To Assess The Interoperability Of Commercial Buildings At A District Scale

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Abstract

Expensive control technology coupled with absence of a proper framework result in buildings that operate independently for their entire operating life. This paper introduces a framework to assess the potential of buildings to function together using heat load demand patterns and buildings thermal mass. Buildings are characterized as possessing variable and stable heat demand patterns and internal conditions are modified to achieve a peak heat demand reduction. Results indicate 8% reduction in overall peak heat demand when two buildings are operated together. The analysis clearly establishes the significance of an integrated energy system that leads to a reduction in peak loads.

Introduction

According to the International Energy Agency, global building sector energy intensity (measured by final energy per square metre) fell by 1.3% per year between 2010 and 2014, due to the continued adoption and enforcement of building energy codes and efficiency standards. However, the progress has not been fast enough to offset growth in floor area (3% per year globally) and increasing demand for energy services in buildings (International Energy Agency, 2017). A growing number of countries have devised policies to improve building energy performance, but the average energy consumption per person in this sector still remains practically unchanged since 1990. To meet the required targets, average building energy use per person globally needs to fall by at least 10% (less than 4.5 MWh) by 2025. Concerted global effort is needed to rapidly expand, strengthen and enforce building energy policies across all countries to avoid inefficient building investments. Furthermore, enhancing the efficiency of existing buildings through deployment of new technologies is not the only solution to reach the desired targets.

Energy systems integration, for instance, building-to-grid integration is emerging as a new alternative to energy retrofit measures that often require high investments. There has been a growing trend towards controlling the flow of energy across different energy vectors through the integration of different systems. The implementation of integration requires the flow of data across these systems, which can be facilitated through the installation of automation systems like smart meters. For instance, dynamic energy efficiency and optimization requires a building to actively react to changes that impact consumption or generation of energy (Griego et al., 2015).

Buildings significantly differ in their characteristics and their nature of operation. A range of energy equipment assets exist within each building which increase the complexities associated with energy system integration. Furthermore, the building stock remains noticeably disconnected due to the lack of control and coordination technologies. Often advanced automation devices are only limited to large commercial buildings due to the associated costs. Alongside, advanced approaches are needed to implement the building equipment integration and electric grid coordination. These improved integration approaches will allow deployment of technology that can enable new services, namely, grid-responsive building technologies. Greater energy and business efficiency can be mined through co-optimization approaches across the meter, thus, facilitating intelligent trade-offs between comfort/quality of service and consumption. The entire integration process is termed as 'Interoperability' and is a relatively new field of research in terms of the harvested potential (Palensky and Dietrich, 2011).

Interoperability, as defined by the Pacific Northwest National Laboratory (PNNL), is the exchange of actionable information between two or more systems or across component and organizational boundaries. The information can be shared within buildings and with external parties (Hardin et al., 2015). The scope of interactions enabled by any building's interoperability span into five main categories, namely interactions between a building and internal operations, interaction among a community of buildings, interactions with building service providers, interactions with market service providers and interactions with energy distributed system operations. PNNL has drafted a building interoperability framework which provides a context and structure upon which the building connectivity use cases, standards and stakeholders can be organized and projected (Hardin et al., 2015). This draft lays out the foundation to enhance the building systems integration at different levels. Although the draft provides a promising vision of the interoperability concept, it lacks the idea of analyzing the interoperability potential of any individual building. Interoperability potential, for a single building or a groups of buildings, can be defined as the ability of an individual building to participate in the load alteration measures through changes in the internal operating conditions of that particular building provided that all the buildings operate under one authority in a community.

A small number of research studies have analyzed the ability of buildings to transact energy with other buildings and the grid. Such studies address a breadth of computational and experimental aspects of the integration. A study by Lawrence et al. (2016) explores the scope and scale of integrating smart buildings to the smart grid. The study analyzed the necessity of cost effective control methods and equipment for enhancing the integration between different energy systems. The study also highlighted the importance of development of new communication standards to avoid cyber attacks against the building control systems. A bilevel optimization framework for commercial buildings integrated with a distribution grid was proposed by Razmara et al. (2018). Although the optimization framework included detailed dynamic model for buildings and operational models for distribution grids, the study didn't take into account the interoperability potential of each individual building. Another interesting study by Xue et al. (2014) developed an interactive building power demand strategy for facilitating smart grid optimization using a building thermal storage model. The research study concluded that commercial buildings can contribute significantly and effectively in power demand management. However, the strategy considered a cluster of buildings for the simulations, thus, ignoring the effect of each building on the overall integration.

Individual building level integration generally makes use of heating, ventilation and air conditioning (HVAC) systems to control the grid dynamics. A study by Beil et al. (2016) discusses the role of buildings for serving the grid through demand response and ancillary services. Commercial HVAC systems were used to provide frequency regulation demand response using the devised control strategies. Another study by Blum and Norford (2014) used dynamic simulations to formulate ancillary service demand response strategies. Power reduction was represented as a function of cooling loads. Both studies dealt with interactions between individual building and the grid, thus, undermining the building to building interactions.

Central energy systems such as district heating (DH) grids are also emerging as potential spots to implement the energy system integration between different buildings and between buildings and the grid (Bhattacharya et al., 2016). About three quarter of the total heat supply is supplied by combined heat and power plants in the DH grid in Europe, which will clearly play a crucial role in the combined optimization of heat and electricity use (Ahcin and Sikic, 2010). A study by Sweetnam et al. (2018) implemented demand shifting techniques on a residential DH network in England. The study identified the role of building's thermal inertia in shifting the heat demand over a certain time period. Another study by Vanhoudt et al. (2017) presented different storage concepts for a DH network governed by certain control algorithms for model predictive control. Although both studies establish the significance of demand shifting in DH networks, the devised frameworks do not take into account the potential of individual buildings in enhancing the integration. Also, the optimization techniques were formulated only for residential buildings.

While the aforementioned research investigated various challenging concepts related to building to grid integration and interoperability, none of these studies devise a framework to analyze the interoperability potential of individual buildings. Moreover, the interactions are usually investigated between one or a group buildings and the corresponding impact on the power grid. Building to building interactions have not been accounted for in any of these studies. The main challenges associated with creating such a framework that addresses the aforementioned research gaps are: Firstly, buildings and their associated control systems are neither connected to each other nor integrated with the grid. Hence, it becomes difficult to achieve a unified optimal strategy. Secondly, the dynamics differ at the building and distribution grid level. The building state dynamics are much slower than the grid dynamics. Lastly, the dynamics of buildings change with the type and function, which complicates the modelling process and analysis of interoperability.

The chief contribution of this paper is an optimization framework for energy system integration and interoperability at building level that addresses the aforementioned challenges. The scope of the framework involves building to building interactions. The main objective is to measure the interoperability potential of a community of buildings using building related metrics. Besides, the framework sets out guidelines to decide whether or not a particular building will be suitable for system integration scenarios. The building to building interactions are modelled by Differential Algebraic Equations (DAEs) using grey box models for buildings. The paper establishes that interoperability enhances the use of available energy resources through data analytics and experimental simulations. The remainder of the paper is organized as follows. Section II outlines the devised methodology to measure the interoperability potential of any building. A case study to implement the methodology is discussed in Section III. Section IV mentions the analysis of results and the subsequent discussions. Conclusions and future work are presented in Section V.

Methodology

Buildings are major energy consumers today and their consumption continues to rise due to urbanization. Furthermore, a significant amount of power imbalance exists amongst different buildings. The imbalance tends to be more prevalent in commercial buildings as compared to residential buildings. Therefore, commercial buildings possess a significant potential to relieve this pressure of power imbalance on the electric grid (Lin et al., 2017). Frameworks formulated so far in literature focus on establishing a bi-directional communication between the supply and demand sides of a smart grid. Such frameworks have well established the need of proper communication standards to facilitate the interoperability between different entities in the energy system (Kolokotsa, 2016). A few other frameworks concentrate on the development of optimization routines to analyze the performance of grid and building control systems (Sun et al., 2010). The routines use model predictive control for optimizing the power consumption of HVAC systems inside the buildings (Afram and Janabi-Sharifi, 2014).

Unlike the previous frameworks, this paper aims at developing a framework to assess the interoperability between a community of buildings. The developed framework will be used to evaluate how significantly individual buildings can participate to enhance the interoperability between buildings. The framework is built upon the load demand patterns associated with any building. The patterns are impacted by local climate, heat transfer through the building envelope, daily operations and occupancy schedules. The demand patterns give a direct indication of the kind of activities undergoing inside a building. The framework also makes use of the heat capacity of a building to compute the interoperability potential. The analysis is further coupled with operation schedules to identify the potential time points for controlling the heat load demand. The schematics of the framework are depicted in Fig. 1.

Power balancing mechanisms have been usually implemented between the grid and individual building level through the adoption of control systems (Dong et al., 2013). These systems optimize the use of building components, for instance HVAC systems, to reduce the overall demand. However, the framework developed in this study examines the load variations between different buildings. The load demand patterns are analyzed for timely variations averaged over 15 min intervals. Variations in demands among a community of buildings will allow for power balancing, which can lead to a drop in the overall load demand. The statistical significance of load variations with time can be established using Analysis of Variance (ANOVA) test. ANOVA is a statistical technique used to check if the means of two or more groups are significantly different from each other (Crawley, 2007). ANOVA checks the impact of one or more factors by comparing the means of different samples. ANOVA is formulated as follows:

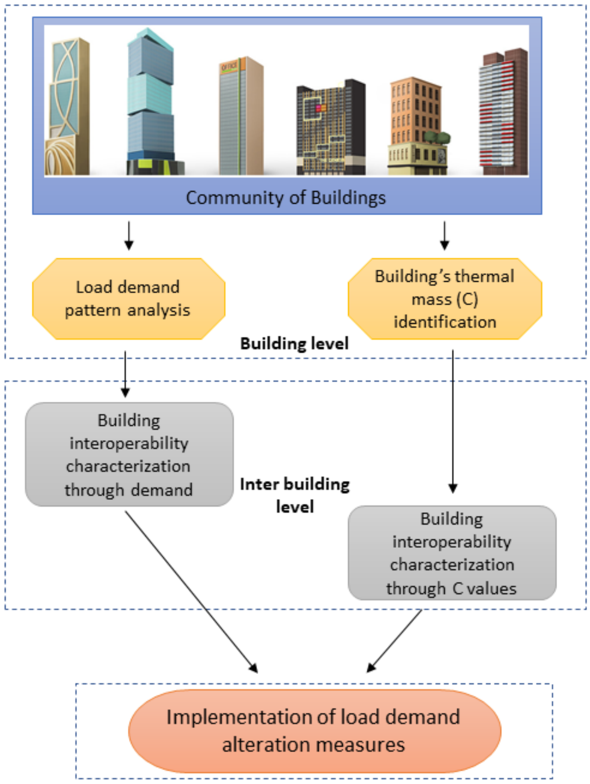

Figure 1: Schematics of the framework to assess the interoperability potential of a community of buildings.

$$NullHypotheses : H_o = \mu_1 = \mu_2 = ... = \mu_l \quad (1)$$

$$AlternateHypotheses : H_1 = \mu_l \neq \mu_m \quad (2)$$

where μ represents the mean of any group. In some instances, ANOVA procedures can be enhanced by considering additional information that is available and is known to be correlated with one or more of the factors under investigation. In this study, the different groups in ANOVA relate to the different buildings in the cluster. Each day is then considered as a sample. Performing an ANOVA test on the heat demand (W) data confirms the existence of power variations in the community of buildings. F-test statistic (ratio of two quantities that are expected to be roughly equal

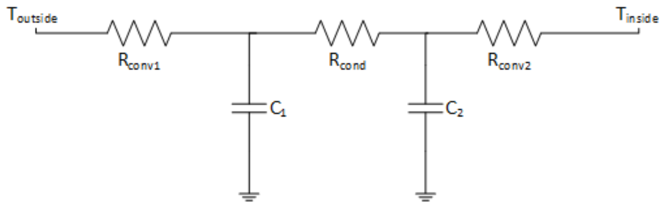

Figure 2: An RC network model for a thermal zone.

under the null hypothesis) is used to compare the results from ANOVA. A large value of F-test statistic signifies that the variability of group means is large relative to the within group variability (required for rejecting the null hypotheses).

All the buildings are modelled using grey box RC thermal networks. A typical thermal resistance and capacitance (RC) network is used to model the heat transfer and thermodynamics of the building control studies. Such networks have been widely implemented in the optimization building control systems (Bacher and Madsen, 2011; Weber and Jóhannesson, 2005). The RC network model assumes a steady state heat transfer through the building envelope. A three resistance and two capacitance model is shown in Fig. 2. The RC network considers the building as a single zone where the resistance parameters represent the thermal resistance of the building envelope, exterior and internal walls' convection. Building dynamics of the above network can be represented as

$$\frac{C_1 dT_1}{dt} = \frac{T_{outside} - T_1}{R_{conv1}} + \frac{T_2 - T_1}{R_{cond}}. \tag{3}$$

$$\frac{C_2 dT_2}{dt} = \frac{T_{inside} - T_2}{R_{conv2}} + \frac{T_1 - T_2}{R_{cond}}. \tag{4}$$

where T_1 and T_2 temperatures are assumed at nodes containing C_1 and C_2. R_{conv1}, R_{conv2} and R_{cond} are physical parameters of the building envelope. C_1 represents the lumped capacity of the exterior walls and C_2 represents the lumped capacity of the interior walls and zones. The units of parameters T, R and C are K, K/W and J/K respectively. Each building has a different set of RC parameters. The crucial parameter that is analyzed in the development of the framework is building thermal mass, represented by C (MJ/K), as the capacitance signifies the heat retaining property or thermal mass of the wall. Building heating/cooling load alteration potential can be characterized using the building thermal mass (MJ/K) and the equivalent temperature, which is used to represent the thermal status of the building and acts as a measure of thermal comfort (K). Also, the employed indoor air set-point temperature and the duration of adopted power demand control directly influence the thermal mass parameter. Furthermore, buildings usually act as thermal storage devices and as such, the parameters of RC networks aid in the prediction of charging/discharging rate of a building in the form of thermal energy. Building with high C values respond slower to change in temperatures than building with low C values.

The overall interoperability characterization process is described in Fig. 3.

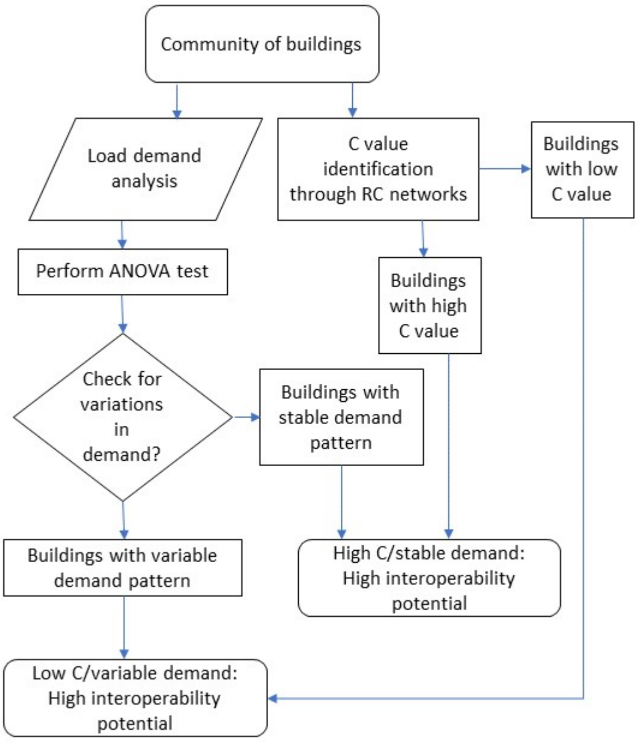

Figure 3: Interoperability characterization process.

Case study

To demonstrate the application of the devised framework, buildings connected to the district heating network at the University College Dublin's (UCD) campus are analyzed for heat load demand variations. For simplicity, the operation of only four buildings is assessed from a community of 10 buildings in the network. The buildings are selected based on the level of heat load demand fluctuations and the range of C values. All the buildings are modelled using RC networks and a standard set point temperature of 21^{o}C is assumed for all the occupied regions. The heat load profiles are analyzed for a specific day for all the buildings and are depicted in Fig. 4. The profiles of the selected buildings are described below.

Restaurant: A building with a C value of 122 MJ/K occupying an area of 1818 m^2. The building consists of a main cafeteria and a few retail shops. The heat load demand increases between 11:15 and 15:15, i.e, during lunch hours. The demand profile reflects the occurrence of several peaks during this period.

Student Centre: A building with a C value of 158 MJ/K occupying an area of 5510 m^2. The building has a few offices, an auditorium, a pharmacy and a cafe. The heat load profile reflects a stable and constant profile with a few load fluctuations occurring at

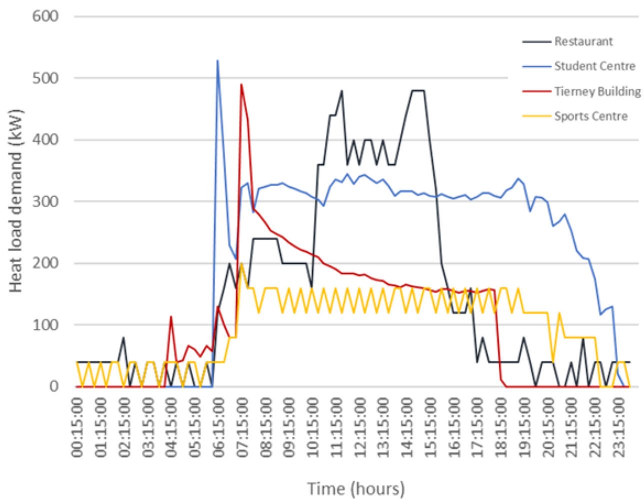

Figure 4: Heat demand profiles for the buildings selected for analysis.

specific times along the day.

Tierney Office Building: A building with a C value of 258 MJ/K occupying an area of 3390 m^2. The building mainly consists of offices and is used for administration work. The load demand variations are smooth and decay towards the end of the day. Load fluctuations are absent throughout the time period.

Sports Centre: A building with a C value of 198 MJ/K occupying an area of 3123 m^2. The building has courts dedicated for different games, for instance, basketball and badminton, and a gym. The load demand profile reflects cyclic variations in heat demand throughout the day. Although the peaks are not high as compared to the other buildings, the variation in demand is quite evident.

The ANOVA test is carried out to establish the significance of variations amongst the heat demand profiles of selected buildings. ANOVA test considers the selected buildings as separate groups. The null hypothesis in ANOVA states that there is no difference in means of different groups. The research hypothesis captures any difference in means and includes, for example, the situation where all four means are unequal, where one is different from the other three, where two are different, and so on.

When comparing the variations in demand over 24 hours between different buildings, restaurant and student centre are found to possess large variations in heat demand compared to Tierney building and sports centre. Furthermore, the demand variations between restaurant and student centre are found to be insignificant. This suggests that means of both the test groups are the same and similar variations exist in the profiles. Any kind of load demand alternations couldn't be achieved between the restaurant and student centre and as such, the interoperability potential of the two buildings is not significant. However, a high potential for load balancing exists between the restaurant or student centre and Tierney building. Similarly, load balancing could also be achieved with the sports centre.

Alongside, another ANOVA test is performed using the demand profile of each individual building to investigate the recurring patterns of fluctuations for multiple days. A low value of F statistic is obtained for the restaurant, student centre and Tierney building, which establishes the existence of cyclic patterns in heat demand over multiple days. However, demand patterns for the sports centre are found to be non-periodic as evident from the high value of F statistic. The acyclic demand pattern won't allow for load balancing alterations and therefore, will reduce the interoperability potential of sports centre.

The analysis is further extended to account for the C values of the selected buildings. As stated above, C value affects the response time of the building's thermal mass when subjected to a temperature change. A high value of C increases the response time of the building's mass. Hence, Tierney building has the highest response time followed by sports centre, student centre and restaurant. Power demand alterations are easier to implement in a building with a high value of C coupled with low variations in load demand. For instance, a high C building will respond slower to a temperature change and thus will maintain the desired comfort conditions even when the set-point temperature is lower than required. Alongside, the low demand fluctuation will allow the building to jump back to the set-point temperature without increasing the overall heat demand. Hence, based on the above explanation, the Tierney building possesses the highest potential for the implementation of power demand alterations.

Load demand alterations are usually applied during the time instance of peaks occurring in load demand. Buildings with high variations in heat load demand provide such instances and as such, any control measures in other buildings should be implemented at these peak time stamps. The restaurant and student centre are ideal for providing the peak times for implementation of load alteration control measures. Based on the above observations, a simulation experiment is conducted using Modelica to simulate the heat load demand and determine the response of buildings when subjected to a step change in temperature.

Building with a high C value and variable demand profile would possess a lower interoperability potential. This is due to the fact that the building would respond slower to the demand alterations and any changes in the internal operating conditions might lead to an increase in the overall peak demand. Besides, the variability in the demand profile would lead to complications in the identification of the peak time stamps.

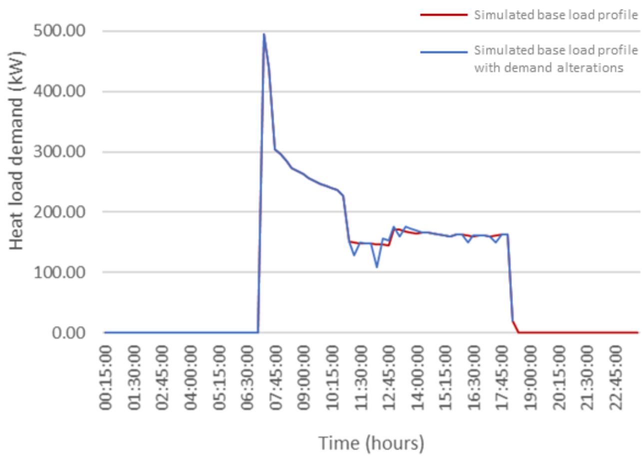

Figure 5: Simulated and modified heat demand profiles of Tierney building.

Discussion and result analysis

Out of the four buildings analyzed, only buildings with the highest interoperability potential are simulated. Therefore, the student centre and Tierney building are chosen to perform the simulations. All the alterations are implemented on Tierney building while the peak time stamps are identified using the load profile of the student centre. The Modelica BuildingSystems library is used to develop the building model. The open-source library is developed for dynamic simulation of the energy behavior of single rooms, buildings and whole districts. The simulation models of the library describe the dynamic energy balance of the building envelope inclusive its boundary conditions (ambient climate, user behavior) (Udk Berlin, 2017). The buildings are assumed to be occupied from 8:00 until 18:00. The set-point temperature is assumed to be 21^{o}C in all zones. All the factors except temperature affecting the heat demand are assumed to be constant throughout the experiment. Step changes in set-point temperature are introduced at 11:15, 12:15, 13:15, 16:15 and 17:30 for the Tierney building. The change is introduced when peaks occur in the load profile of student centre. Also, the temperature is reverted back to the original value after 15 min of application. The simulations are run on a 15 min basis and the load demand profile is obtained for the same day for which the measured demand is observed. The result is shown in Fig. 5.

The dip in demand for the modified heat demand profile relates to the time when the set-point temperature is reduced by 1^{o}C. At 11:15, the modification of the set-point temperature to 20^{o}C reduces the corresponding heat demand from 150 kW to 140 kW. The high C value of Tierney building delays the heat transfer from the walls, thus, maintaining the desired internal building conditions. When the set-point temperature is restored back to 21^{o}C at 11:30, an increase of 1.5 kW in the demand is observed. Although set-point temperature modifications result in an increased demand in the next time stamp, the overall peak demand of the system is reduced by 4.5% during that time. A similar phenomenon is observed at all time stamps of modification in set-point temperature. A larger dip in demand is observed at 12:15, particularly, due to the increased outside temperatures. The heat flow rate is reduced and thus, less heat is required to maintain the desired comfort conditions.

The set-point modification results in 8% reduction of the overall peak heat demand of the buildings in consideration. It is worthwhile to note that the set-point temperature fluctuations in the Tierney building introduces fluctuations in heat load demand. However, at the same time, the peak heat demand is also reduced when the two buildings are considered to function together.

Conclusions

With a drive towards achieving an integrated energy system, there is a need for a holistic approach to integrate the existing and new entities in the energy systems framework. Building to grid and building to building integration possesses enormous potential to enable consumer and energy-related benefits. Presently, controls for energy-related components and systems within residential and commercial buildings often deliver sub-optimal energy operations. These systems are generally unaware of perturbations and potential opportunities for more efficient operations, both within and outside the building envelope. Even though sophisticated, optimized control methods and concepts are known, deployed control and dispatch of loads and on-site generation are often still rudimentary, requiring heavy human interaction and extensive customization, which are neither cost-effective nor scalable. Besides, the communication standards for achieving integration at such a scale are still being developed.

Although a few integration frameworks already exist in literature, a few solely focus on building to grid integration while the others focus on developing the communication standards to enable integration. This paper introduces a framework that enables building to building integration and interoperability. The framework can be used to assess the potential of each building to participate in the integration process. Building's thermal mass and heat load consumption data are the crucial parameters to calculate the potential using the framework. Buildings have the potential to play a critical role in the realization of any grid modernization solution. The devised framework will enable an integrated energy system network. As buildings and industrial energy use/consumption drive system peak demand, peak demand reduction can be made possible through the use of this framework. Ultimately, inter-operable buildings will enhance the deployment of distributed generation.

The addition of an optimization process to the framework that automatically detects the peak time points and identifies the optimal reduction in set-point temperature would enhance the value of this research.

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