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Formulation of an Inclusive Demand-Side Energy Flexibility Quantification Function for Buildings with Integrated Thermal Energy Storage

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ABSTRACT

Demand-side energy flexibility (DSEF) is emerging as an effective measure to stabilize the renewable power-based grid operation and reduce building greenhouse gas emissions and energy costs. An aggregated quantification function that can effectively capture the technical and non-technical aspects related to buildings and building energy systems is still needed. This paper presents the formulation of an inclusive DSEF quantification function, termed as building energy flexibility potential function (BEFPF), by using fuzzy multi-criteria decision analysis and domain knowledge. The DSEF quantification function developed can consider the dynamic nature of buildings and building energy systems by simultaneously incorporating several factors such as system performance, charging/discharging percentage of storage systems, grid support, the cumulative energy consumption of mix, load/power shifting potential, price elasticity, acceptable delay time, temporal fluctuations, occupants behavior and comfort, rebound energy, emission control, and self-generation and self-consumption potential of the building. Each factor was assigned a weight by using the fuzzy analytical hierarchy process. The BEFPF was then used to evaluate the flexibility potential of a grid-connected building integrated with an air source heat pump and a thermal energy storage system through a simulation exercise.

Keywords: Buildings, flexibility function, thermal energy storage, quantification, demand-side flexibility.

1. INTRODUCTION

The carbon emissions from the building sector are considered as one of the major causes of global warming. The world green energy council has envisioned dual goals for the building sector as per the target of the Paris Agreement of keeping global temperature rise below 2 ^{o}C, i.e. by operating all new buildings at net zero carbon from 2030 and by operating all buildings at net zero carbon by 2050 [1]. Consequently, a rapid increase in the utilization of renewable energy sources has been observed in the world energy mix [2], which can greatly impact the stability of conventional grid systems. Studies have shown that demand-side energy flexibility (DSEF) can potentially stabilize the operation of electrical grids under dynamic generation and consumption patterns. It can also reduce building carbon emissions and overall building energy costs by optimizing the performance of buildings and building energy systems [3].

DSEF is in the development phase and several technical and non-technical advances are needed to increase the acceptability of this approach among different stakeholders including consumers, producers, regulators, grid operators, and suppliers. One of the key non-technical advancements needed is the development of a performance indicator that can effectively measure the flexibility potential of a building by capturing the interactions among the power grid, consumers, the building, and building energy systems [3,4]. Several studies have been conducted to formulate application-specific flexibility indicators according to the need of the performed study. For instance, Stinner et al. (2016) formulated temporal flexibility indicators in the form of forced and delayed flexibility [5]. Temporal forced flexibility was defined as the time required to completely charge a storage system by operating the energy system at full power, whereas temporal delayed flexibility was introduced as a term to calculate the storage discharging time by switching off the energy system. Further, temporal flexibility was updated in terms of power and energy flexibility. Junker et al. (2018) formulated a dynamic flexibility function to index the extent of building response to the grid's need for flexibility. Based on this function, a flexibility index was also introduced. The flexibility index helped measure the response of the building to the penalty signals, i.e. the flexibility index of 0 means the building does not react to penalty signals at all, and 0.25 means that 25% penalty-related cost has been saved. Building response to penalty signals was assumed linear and time-invariant [6]. Yin et al. (2017) performed a study to quantify flexibility by using setpoint variation for thermostatically controlled loads. Three main challenges for accurate quantification of a demand response (DR) model were mentioned as the model capability to capture complex thermal dynamics of the energy system, model versatility to be applied on a large scale, and fast computational time with potentially correct forecasting properties. DR potential of a specific appliance in an event hour (h) was calculated by using average baseline power during DR activity and power consumption of the appliance by using a setpoint profile [7]. Sajjad et al. (2016) statistically formulated demand-side flexibility indicators for time-variant patterns of aggregated residential loads. Categorical data analysis was used to analyze the data obtained from the smart meter. Binomial distribution was used to model demand variation by considering two response variables, i.e. increasing demand and non-increasing demand. Two metrics, including the flexibility index of aggregate demand and percentage flexibility level, were formulated to quantify the demand-side flexibility [8]. A comprehensive review to characterize and quantify demand-side energy flexibility can be found in the IEA EBC annex 67 project [3] and [4].

Although the flexibility indicators developed can represent the flexibility potential of a building or a specific energy system, these indicators have limitations to simultaneously cover a wide spectrum of building energy flexibility. For instance, Reynders et al. (2015) formulated four separate flexibility indicators including state of charge, shifting capacity, available storage capacity, and storage efficiency to quantify the flexibility potential of structural storage in buildings [9]. These indicators did not effectively cover several factors such as cost, emission, occupant comfort, and grid support that should be considered to give an overall flexibility potential of a building or a system. Similarly, other available flexibility indicators lack the capability to represent different aspects of DSEF in a single flexibility quantification function. In this study, a flexible demand-side flexibility function is developed that can integrate various flexibility indicators in a single equation. Fuzzy multi-criteria decision analysis and domain knowledge were used to formulate a flexibility function, termed as the building energy flexibility potential function (BEFPF). BEFPF can represent the interactions among the power grid, the building, occupants, and energy systems with a single value. Lastly, a simulation exercise was carried out to evaluate the flexibility potential of a grid-connected building integrated with an air source heat pump and a thermal energy storage (TES) system.

2. MATERIALS AND METHODS

2.1 Methodology

The overall methodology for the development of the building energy flexibility potential function is illustrated in Fig. 1. Initially, several flexibility indicators were selected from the available studies. The selection process of the flexibility indicators is illustrated in Fig. 2. Each selected flexibility indicator was then assigned a priority number by using domain knowledge as summarized in Table 1. The analytical hierarchy process-based pair-wise matrix was used for relative weight assignment to each flexibility indicator. Then fuzzification of the developed matrix was conducted and the relative weights were calculated. The consistency of the calculated weights was checked to validate the weight assignment process. The weight of each flexibility indicator was multiplied by the respective flexibility indicator. Lastly, all weighted flexibility indicators were added together and then divided by the sum of all individual weights. The mathematics behind the formulation of the building energy flexibility function is explained in Section 2.2.

Fig. 2 illustrates the logic behind the selection of flexibility indicators. The flexibility indicators were chosen to formulate a flexibility function that can simultaneously include several aspects of DSEF. The details about the selected flexibility indicators can be found in the chapter "Characterization of Energy

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Flexibility in Buildings" of the International Energy Agency (IEA) EBC Annex 67 report [3].

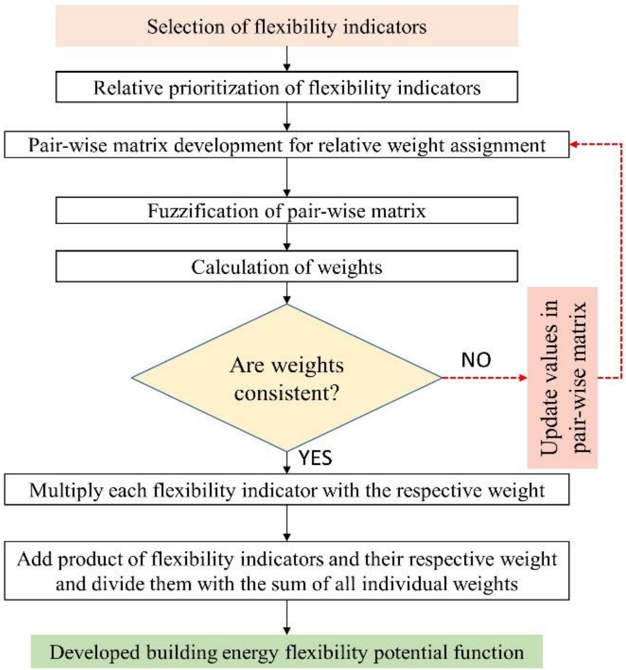

Fig. 1 Methodology for developing the building energy flexibility potential function.

2.2 Theory/calculations

Table 1 illustrates the process of attribute number assignment to each flexibility indicator. Attribute A1 was assigned with top priority, whereas A4 was assigned with the least priority. The first two attributes were given the top priority as the customer can only accept a flexibility plan if it can result in a reduction in energy costs, and a flexibility plan for a service provider is more effective if it can result in peak load shaving and thus energy cost savings. The third flexibility indicator was assigned with the second priority as this indicator is critically linked with the service providers, and consumers are not considered to be directly linked with this indicator. The next 5 indicators were assigned with the third priority level as these indicators can be controlled by taking certain measures. The storage level was assigned with the least priority as this indicator does not directly impact the overall building energy flexibility and also the storage level is partially represented in the first two flexibility indicators.

Table 1 Attribute number assignment to building energy flexibility indicators.

Sr. #	Flexibility indicator	Attribute #	Count
1	Cost saving	A1	
2	Load/power shifting potential	A1	nA1=2
3	Grid support %	A2	nA2=1
4	Emission reduction potential	A3	
5	% acceptable delay time or response time	A3	nA3=5
6	% rebound energy	A3	
7	Thermal comfort level	A3	
8	Ratio of self-generation / consumption	A3	
9	Storage level	A4	nA4=1

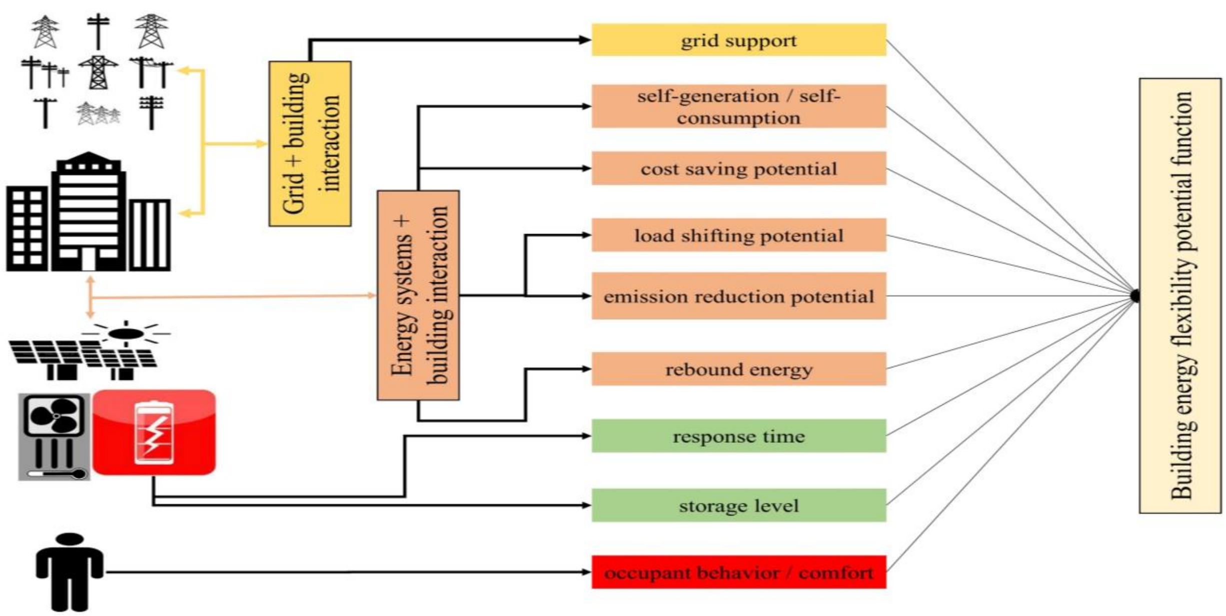

Fig. 2 Selection process of the flexibility indicators.

Table 2 summarizes the pair-wise matrix for assigning relative values to each attribute. These values were taken from the standard Saaty scale [10]. To increase the accuracy of the weight assignment process, fuzzification of the pairwise matrix was conducted by using the geometric mean (G.M) technique, as presented in Table 3. Fuzzification was achieved according to the values presented in [11]. A fuzzified pairwise matrix was used to obtain the fuzzified weights (ω) that were later converted into crisp values by performing defuzzification. The consistency index (CI) of the AHP matrix was calculated that was less than 0.1. CI of 0.089 proved that the AHP matrix is consistent.

Table 2 Pair-wise matrix for attributes of building energy flexibility indicators.

	A1	**A2**	**A3**	**A4**
A1	1	4	6	8
A2	1/4	1	3	6
A3	1/6	1/3	1	5
A4	1/8	1/6	1/5	1

After normalizing weights, multicriteria decision analysis was used to formulate the BEFPF as illustrated in Eq. (1) and Eq. (2). The sum of the weighted flexibility indicators was divided by the sum of the weights (Eq. (3)) to obtain a normalized value.

$$BEFPF = \frac{\alpha_1\omega_1 + \alpha_2\omega_2 + \alpha_3\omega_3 + \cdots + \alpha_n\omega_n}{nA_1 \times \omega_1 + nA_2 \times \omega_2 + nA_3 \times \omega_3 + \cdots + nA_n \times \omega_n} \quad (1)$$

$$BEFPF = \frac{\sum_{i=1}^{n} \alpha_i\omega_i}{\sum_{i=1}^{n} W_i} \quad (2)$$

$$\sum_{i=1}^{n} W_i = nA_1 \times \omega_1 + nA_2 \times \omega_2 + \cdots + nA_n \times \omega_n \quad (3)$$

where α represents the flexibility indicator.

It is worthwhile to note that the weight assignment process and the selection of flexibility indicators are flexible but these values must be supported by strong domain knowledge. The weights and flexibility indicators in this study were determined based on domain knowledge. The same method can be used to include or exclude any flexibility indicator but any formulated flexibility function should at least be capable of representing different aspects of DSEF with a single value.

2.3 Case Study

To test the effectiveness of the developed flexibility function, a simulation exercise was carried out by considering a grid-connected building under weather conditions of Dubai, which was integrated with an air-source heat pump and a latent thermal energy storage system using a phase change material (PCM). The building considered had a total floor area of 92 m^2 with a conditioned area of 79 m^2. The house was conditioned by using an HVAC system during off-peak hours (7:30 PM to 9:30 AM of the next day), and a latent energy storage tank (with a maximum storage capacity of 33.5 kWh) during peak hours (9:30 AM to 7:30 PM). The PCM tank was charged during off-peak hours by using the heat pump at a temperature setpoint of 7 ^oC and the unit cost during peak hours was 2.5 times higher than that of the off-peak hours that was 0.14 USD/kWh. A brief introduction to the simulation system is summarized below:

- HVAC system consisted of an air source heat pump with a maximal cooling capacity of 7.4 kW, an enthalpy recovery ventilator, a dehumidification heat pump, and a fan coil unit system.
- The heat pump temperature setpoint was 13 ^oC without integration of TES, and the supply air temperature was set at 16 ^oC.
- The house was considered to be occupied by two occupants all the time. Indoor temperature and relative humidity values for the indoor conditions were set at 24 ^oC and 47.5%, respectively.
- A thermal energy storage system was developed based on a Phase change material (PCM) with a melting temperature of 10 ^oC. Hence, the heat pump setpoint was reduced to 7 ^oC for charging the TES system.

Table 3 Fuzzification and solution of pair-wise matrix.

	A1	**A2**	**A3**	**A4**	**Fuzzy G.M**	**Fuzzy weights**	**Defuzzi fication**	**Norma lization**
A1	1,1,1	3,4,5	5,6,7	7,8,9	3.20, 3.72, 4.21	0.61, 0.60, 0.59	0.6	0.61
A2	1/5 , 1/4, 1/3	1,1,1	2,3,4	5,6,7	1.19, 1.32, 1.75	0.23, 0.21, 0.25	0.23	0.23
A3	1/7, 1/6, 1/5	1/4, 1/3, 1/2	1,1,1	4,5,6	0.62, 0.73, 0.88	0.12, 0.12, 0.12	0.12	0.12
A4	1/9, 1/8, 1/7	1/7, 1/6, 1/5	1/6, 1/5, 1/4	1,1,1	0.22, 0.25, 0.29	0.04, 0.04, 0.04	0.04	0.04

Considering the limitations of the simulation system, limited flexibility indicators from Table 1 were selected. The flexibility indicators considered and relevant formulation are presented below.

Energy cost-savings potential of the building under demand response activity was calculated using Eq. (4).

$$\alpha_1 = F_{c.s} = \frac{[P_t \times C_t]_N - [P_t \times C_t]_{DR}}{[P_t \times C_t]_N} \quad (4)$$

where P_t and C_t represent power consumed and unit cost during time interval t respectively. The subscripts N and DR represent normal or reference working conditions and working under demand response conditions, respectively.

Power shifting potential was calculated using Eq. (5).

$$\alpha_2 = F_{P.S} = \frac{P_N - P_{DR}}{P_N} \quad (5)$$

Favre and Peuportier [12] formulated an indicator for the emission reduction potential, as presented in Eq. (6).

$$\alpha_3 = F_{emi} = \int_0^T C_E(t).l(t)dt \quad (6)$$

where l represents load, C represents carbon, and the subscript E represents emissions. To simplify this expression, in the current study emission reduction was considered as a function of the overall power saved.

Thermal comfort (α_4) was calculated by calculating the number of hours when the outlet temperature of the water leaving the TES tank crossed the threshold value of 13 °C.

In the current study grid support (α_5) was considered 100% as during the demand response period 100% of the heat pump load was shifted to the thermal storage tank.

The simulation was run for the first week of June month and the data were used to calculate the flexibility potential of the building by using Eq. (2).

$$BEFPF = \frac{(\alpha_1 \times 0.61) + (\alpha_2 \times 0.61) + (\alpha_3 \times 0.12) + (\alpha_4 \times 0.12) + (\alpha_5 \times 0.23)}{2\times 0.61 + 1\times 0.23 + 2\times 0.12}$$

α_1 was calculated using Eq. (4) that indicated approximate savings of 12-22% of the energy cost as shown in Fig. 3. The case with TES proved to be highly effective in reducing the energy cost during peak hours. During off-peak hours energy costs in business as usual scenario was lower than that of considering the case with TES but overall TES-based case was more cost-effective. α_2 and α_5 were considered 100%, as during peak hours 100% of the heat pump load was shifted to the thermal energy storage system. α_3 was calculated in terms of overall power saved. In total, 0.7-15% extra energy was used when the TES system was used. The same values were considered for the emission reduction potential of the building. Major reasons behind extra energy consumption by using the TES system were the thermal losses and the change in the heat pump temperature setpoint from 13 °C to 7°C for charging the TES tanks. α_4 was calculated by dividing the number of discomfort hours by the total number of operational hours. The calculated results showed that by shifting load to the TES tank during peak hours, comfort was not compromised in the selected week. Hence, a value of 100% was selected.

The flexibility potential of the building was found by using the average values of each selected key point indicator. The flexibility potential of the thermal energy storage integrated building was found equal to 63.4%.

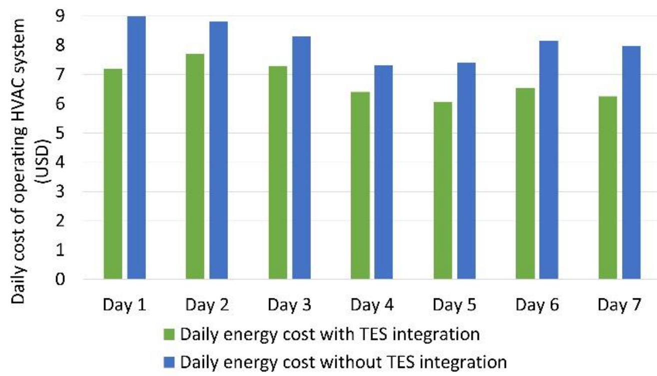

Fig. 3 Daily energy-cost of HVAC system with and without using TES.

It is worthwhile to note that because of the unavailability of a standard demand-side energy flexibility definition, it is hard to agree on the selected flexibility indicators. However, the developed methodology can be used to quantify the behavior of any type of buildings or group of buildings.

3. *CONCLUSIONS*

A building energy flexibility potential function was formulated to represent the flexibility potential of a building. The flexibility function developed can flexibly include or exclude any factor. Multi-criteria decision analysis was used to develop the flexibility function. Several flexibility indicators were selected based on the domain knowledge and each indicator was assigned a weight by using the fuzzy analytical hierarchy process.

The weight assignment process was proved consistent with a consistency index value of 0.089. The formulated flexibility function was used to calculate the flexibility potential of a grid-connected building that was integrated with an air-source heat pump and a thermal energy storage unit. The flexibility potential of the building was found equal to 63.4%, with thermal energy storage-based operation resulting in a reduction in energy cost without compromising the thermal comfort. Overall, the developed method proved to be effective in representing the flexibility potential of a building with a single crisp value and by considering several aspects such as grid support, the performance of building and building energy systems, and occupant comfort.

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