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A framework to formulate and aggregate performance indicators to quantify building energy flexibility

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HIGHLIGHTS

- A framework to develop and aggregate energy flexibility indicators was introduced.
- A new Aggregated Energy Flexibility Potential function was developed.
- Multicriteria decision analysis was used to aggregate performance indicators.
- Thermal energy storage and photovoltaic systems provide enhanced energy flexibility.

ARTICLE INFO

Keywords: Building energy flexibility, Quantification, Indicators, Flexible sources, Aggregation

ABSTRACT

Building energy flexibility is being considered an emerging strategy allowing the demand side actively support the operation and control of variable resources-based energy supply. This study presents the development of a framework to formulate and aggregate energy flexibility indicators (EFIs) to evaluate building energy flexibility. EFIs were developed/selected using the important characteristics of building energy flexible sources, performance factors linked with flexibility services and penalty factors posed by the grid. A multicriteria decision analysis method was then used to develop an Aggregated Energy Flexibility Potential (AEFP) function that can consider the interactions between the power grid, buildings and building energy systems to represent the building’s overall energy flexibility potential with a single dimensionless value. AEFP can help determine cost-effective energy flexible sources and solutions for increased energy flexibility. The performance of the EFIs and AEFP developed was evaluated via a case study with two distinct scenarios through simulations. The photovoltaic system provided a peak power demand reduction of 94%, emissions reduction of 46% and energy cost reduction of 54% to the building with an AEFP value of 0.74 (i.e. 74%), whereas a thermal energy storage system coupled with an air conditioning system helped reduce peak power demand by 56.4%, CO\textsubscript{2} emissions by 14.5% and energy cost by 32% with an AEFP value of 0.54 (i.e. 54%). Both scenarios verified the effectiveness of the developed EFIs and AEFP for evaluating building energy flexibility.

1. Introduction

Building energy flexibility is gaining increased attention due to its ability to support a rapid transition from fossil fuels to clean energy resources without significant infrastructural alterations and large investments. Building energy flexibility is the ability of a building to modulate its demand and generation in a specific period according to grid and user needs, and local climate conditions [1]. An energy-flexible building should be able to facilitate the integration of renewable energy sources by enhancing the resilience of the power grid and reducing building energy costs, peak load demand and seasonality without disrupting occupant thermal comfort [2]. To effectively explore building energy flexibility, it is important to identify cost-effective energy flexible sources that can be included in a flexibility plan. These sources are primarily categorized into generation sources, building loads or consumption sources, and storage sources [3]. Generation sources such as solar photovoltaic (PV) panels can be used to cover building demand, reduce peak demand from the power grid, and charge storage systems. Additionally, excess power generation can be exported to the grid. Consumption sources can be divided into shiftable, non-shiftable,
curtailable, and non-curtailable sources. Shiftable or curtailable sources such as the change of setpoints for thermostatically controlled loads can increase energy flexibility. Storage sources such as thermal energy storage (TES) and electrical batteries can increase building energy flexibility through load shifting [4-7]. Evaluation of energy flexibility offered by these different sources is essential to determining and selecting cost-effective energy flexible sources for increased energy flexibility. To achieve this, energy flexibility indicators (EFIs) are often used, which can also assist in developing a contractual framework among different stakeholders such as end-users and service providers [8].

Many EFIs have been developed and used in previous studies to quantify and evaluate the flexibility potential of either a specific system or a specific building. As shown in Table 1, several key factors can be used to characterize EFIs. EFIs linked with the key factor “time” can be used to identify the temporal performance of energy flexibility measures including the period of excessive or reduced onsite generation with respect to building demand, response time, delayed and forced flexibility, and activation time. EFIs linked with the key factor “power/energy” can be used to calculate the variables such as the amount of power shifted or reduced, energy flexibility offered by the available energy sources, the amount of inflexible energy, and rebound energy. Similarly, other indicators listed in Table 1 can be used to calculate the flexibility offered by onsite generation and storage systems and their associated cost benefits. A few generalized indicators have also been summarized in Table 1 to calculate the overall flexibility potential of a building, occupant comfort, and building smart index. It is worthwhile to note that a single EFI may simultaneously cover several factors.

Although different energy flexibility indicators have been reported in previous studies, a framework that can lead to the selection/development of system-specific EFIs and overall building-level quantification function through the interlinking of different flexibility services and performance factors based on the stakeholders’ preferences, has not been reported yet. Performance factors are important to estimate the footprint of flexible operation and provide information about systems’ temporal performance, such as how quickly they can react to flexibility needs, and how long they can operate without disrupting occupant comfort. In most of the available studies, the direct effect of performance factors such as response time, occupant comfort, and effective flexible duration, is usually overlooked in the calculation of flexibility potential. The inclusion of such critical performance factors can help accurately capture the true value of the achieved flexibility and hence increase the effectiveness of the flexibility quantification process. Furthermore, the lack of a comprehensive framework and the unavailability of an aggregated energy flexibility quantification function hinder a detailed understanding of the overall flexibility potential of buildings or building energy systems. For instance, in [15], a number of flexibility indicators were developed to evaluate the flexibility potential of different sources including building thermal mass, appliances, HVAC systems, storage tanks, and occupants’ behaviors but the aggregation of these indicators and the effect of performance factors linked with flexibility services along with the stakeholders’ interaction were not reported. Farulla et al. [37] provided an in-depth review of the EFIs reported in several studies for the quantification of building energy flexibility. A range of studies reviewed in [37] was mainly focused on developing the indicators to quantify the flexibility potential of individual systems and specific flexibility measures but none of the reviewed studies reported a method or framework for aggregation of EFIs by considering the stakeholders’ preferences and interaction.

In this study, a systematic approach was used to develop EFIs by considering the penalties introduced by service providers, performance factors linked with flexibility services, and output and controlled variables of the participating systems. Furthermore, a multicriteria decision analysis methodology was used to aggregate different EFIs and performance factors in order to develop an overall building-level energy flexibility indicator, which was termed as Aggregated Energy Flexibility Potential (AEFP) function. The originalities of the work include: a) the introduction of a framework for the development and aggregation of EFIs, which provides a general guideline for the formulation of EFIs by screening important factors of the energy flexible sources, b) the introduction of new updated EFIs for the evaluation of flexibility potential of building energy flexible sources, which also considered the performance factors to represent the near-true value of the achieved flexibility and, c) the formulation of a new Aggregated Energy Flexibility Potential function for overall building-level flexibility quantification, which can capture the interactions between the building, power grid, occupants, and building energy systems, and hence, can provide valuable insights into building energy flexibility potential and support decision-making. Overall, this study can lead towards standardization of EFIs and can be used to develop new EFIs by considering the priorities and interaction of stakeholders. The performance of the proposed method was evaluated via a case study with two distinct scenarios through simulation exercises.

2. Framework development

2.1. Outline of the framework

Fig. 1 presents the outline of the framework used to develop/select and aggregate energy flexibility indicators to quantify the flexibility potential of buildings and building energy systems. It consists of three main steps. Firstly, a systematic approach to developing energy flexibility indicators was introduced, which consists of three main sub-steps.

Table 1

<table>
<thead>
<tr>
<th>Key factor</th>
<th>Example EFIs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/energy</td>
<td>Flexible power [9]; flexible energy [9]; inflexible energy [9]; load flexibility [12]; electrical appliances flexibility [13]; rebound energy [8]; flexible energy efficiency [8]; power shifting potential [14]; power shifting efficiency [14]; flexible demand [15]; available electrical energy flexibility [16]; wind power system flexibility [17] and; HVAC flexibility [13].</td>
</tr>
<tr>
<td>Storage</td>
<td>Thermal storage flexibility [13]; building thermal mass flexibility [13]; storage capacity [18] and; state of charge [19].</td>
</tr>
<tr>
<td>Cost</td>
<td>Flexibility cost [19,20]; expected flexibility savings index [21] and; flexibility as procurement cost avoided [22].</td>
</tr>
<tr>
<td>Onsite generation</td>
<td>Onsite flexible surplus renewable fraction ratio [9]; onsite flexible electric load fraction [9]; onsite electrical energy fraction [9]; annual mismatch ratio [23]; load cover factor [24]; supply cover factor [24]; energy autonomy [24]; mismatch compensation factor [25]; onsite energy ratio [23]; load matching index [26]; renewable energy fraction [27]; renewable energy matching [27]; maximum hourly surplus [23] and; maximum hourly deficit [23].</td>
</tr>
<tr>
<td>Grid interaction</td>
<td>Grid control level [28]; grid interaction index [26]; no grid interaction probability [29]; absolute grid support coefficient [30]; relative grid support coefficient [30]; connection capacity credit [34]; peaks above limit [31]; dimensioning rate [31]; kVA credit [31] and; spark spread [32].</td>
</tr>
<tr>
<td>Generalized indicators</td>
<td>Flexibility factor [9,23]; comfort index [34]; volume shifted flexibility factor [23]; occupant behavior flexibility [1-]; building energy flexibility potential function [4].</td>
</tr>
</tbody>
</table>

homogeneity index [35] and; flexibility index [19,36].
The first sub-step is the identification of energy flexible sources as part of building response to the grid needs. In the second sub-step, important characteristics of the energy flexible sources including output and controlled variables, performance factors linked with flexibility services such as occupant comfort and temporal performance, and penalty factors posed by the grid were identified and used to develop energy flexibility indicators in the last sub-step. In the second step, EFIs/performance factors were selected and used to represent the interactions between the building, building energy systems, and grid by considering the collaboration of different stakeholders, including government, consumers, and aggregators. A fuzzy analytic hierarchy process (FAHP) was used to assign relative weights to the EFIs and performance factors, and the multicriteria decision analysis approach was then used to develop an inclusive building energy flexibility quantification function. Further details about how to aggregate EFIs and performance factors are provided in Section 2.3. Lastly, a case study with two different scenarios was designed to respectively evaluate the effect of a thermal energy storage system on the flexibility enhancement of an HVAC system, and an onsite generation system on building energy flexibility enhancement.

2.2. Selection/development of energy flexibility indicators

A set of EFIs were introduced and used in this study to interlink the hierarchy of different flexibility services offered by building energy sources. The flexibility indicators are formulated based on the process illustrated in Fig. 1, in which the energy flexible systems were first identified, and relevant system characteristics were then selected to develop EFIs. Identification of energy flexible systems and their characteristics along with performance factors linked with flexibility services is important to gauge whether a building has enough sources to offer energy flexibility and which source should be called in case of a mismatch between generation and demand. As flexibility services are based on the interactions between the grid, buildings and building energy systems, factors related to these systems were hence identified and
used for developing EFIs. For instance, grid penalty factors were selected to indicate the functions on which grid penalties are based. As most grid penalties are imposed in terms of cost that varies as a function of time (demand hours), time and cost were hence selected as the penalty factors. Controlled variables were selected to identify the factors that can be controlled to generate the desirable flexible service. For example, for curtailable loads, the power input to the system can be controlled, and similarly, for shiftable loads, the power input and time of use can be controlled during flexible operation. Performance factors were selected to measure the robustness of flexibility services, i.e., does a flexible source provide flexible services for the desired time period without jeopardizing the occupants’ comfort? Lastly, the main output variables with respect to the desired outcome of a flexible measure were selected, and one of the leading output variables for most of the building energy sources is power consumption.

2.2.1. Indicators for onsite generation sources

Using the identified variables, an indicator termed “building energy autonomy (γ)” was first introduced, as expressed in Eq. (1). This indicator can be used to represent the level of independence of a building from the grid with respect to the cumulative electricity demand of the building at each time step i.

\[
\gamma_i = \frac{P_{ex} + P_{es}}{P_{con}} \text{ where } i = 1 \ldots n \tag{1}
\]

where P symbolizes the power, and the subscripts gen, st, and con, respectively represent self-generation, storage, and consumption. For onsite storage, the (+) sign represents that the power generated onsite is used to charge the storage system, whereas the (−) sign means the power discharge of the storage system.

A value >1 (i.e., \( \gamma > 1 \)) indicates the availability of extra power that can be exported to the grid or supplied to the other buildings in the vicinity at each time step i, which can be calculated using Eq. (2) [39].

\[
P_{es} = (P_{gen} - P_{es} - P_{con}) \tag{2}
\]

where \( P_{es} \) represents the amount of excess power available for export, in which the subscript ex represents export.

The duration of excessive self-power generation (\( t_{ex} \)), when the power produced by the onsite generation systems is more than the building demand and charging needs of the storage system, can be calculated using Eq. (3).

\[
t_{ex} = \frac{1}{1} \sum_{i=1}^{\gamma} \left( f(\gamma) - f(0) \right) \tag{3}
\]

where \( f(\gamma) = \begin{cases} 1 & \text{if } \gamma > 1 \\ 0 & \text{if } \gamma \leq 1 \end{cases} \) and \( t_{i} \) represent discrete time intervals.

The total amount of CO2 reduced (CO2\(_{1e}\)) can be calculated using Eq. (4), which is based on the same concept reported in [38].

\[
CO2_{1e} = \sum_{i=1}^{n} (P_{con} - P_{es} + P_{ex}) \times CO2_{grid} \tag{4}
\]

where \( CO2_{grid} \) represents the CO2 emissions of the local energy network in kg/kWh, and \( P_{es} \) represents the amount of total power imported from the grid.

CO2 reduction potential (CO2\(_{1e}\)) can be considered as a function of total power demand reduction potential (\( P_{e} \)), which can be calculated using Eq. (5).

\[
CO2_{1e} = P_{e}(\%) = \left( \frac{\sum_{i=1}^{n} (P_{con} - P_{es} + P_{ex})}{\sum_{i=1}^{n} P_{con}} \right) \times 100\% \tag{5}
\]

From the perspective of service providers, the most important characteristic of an energy flexible building is its ability to modulate the required demand for the desired time period. An indicator, as shown in Eq. (6), was developed to calculate the flexibility potential during peak demand hours, and temporal performance was also included in Eq. (6), which can be calculated using Eq. (7).

\[
P_f(\%) = \left( \frac{\sum_{i=1}^{n} (P_{con} - P_{es} + P_{ex})}{\sum_{i=1}^{n} P_{con}} \right) \times 100\% \times t_e \tag{6}
\]

\[
t_e = \text{Activation time required} \tag{7}
\]

where \( t_e \) is a performance factor that considers the temporal performance of a flexible source.

The introduction of \( t_e \) was the originality of Eq. (6), as it is important to consider the effective flexible service time to measure how long a flexible source is active during the desired demand response period.

Energy cost savings is an important factor for the successful implementation of an energy flexibility plan. Consumers can only be interested in flexibility services if they can reduce overall energy expenses without risking their comfort and other functional needs. Eq. (8) can be used to calculate the flexibility potential in terms of energy cost savings.

\[
F_C(\%) = \text{Max} \left[ 1 - \frac{\sum_{i=1}^{n} (P_{con} + C_{inc}) - (P_{ex} + C_{inc})}{\sum_{i=1}^{n} P_{con} + C_{inc}} \right] \times 100\%, 0 \tag{8}
\]

where \( C \) is the cost of electricity that is a function of demand hours.

2.2.2. Indicators for building energy systems

EFIs were also formed to estimate the flexibility offered by building energy systems. Eq. (9) can be used to calculate the flexibility potential of building energy systems in terms of peak power demand reduction.

\[
P_f(\%) = \left( \frac{\sum_{i=1}^{n} (P_{con} - P_{ex})}{\sum_{i=1}^{n} P_{con}} \right) \times 100\% \times t_e \tag{9}
\]

where the subscripts F and N respectively represent the parameters considering the system working under flexible and normal or business-as-usual (baseline) conditions. In discrete time intervals, the flexibility potential in terms of peak power demand reduction can also be calculated using Eq. (9) for each time interval.

The flexibility potential in terms of energy cost savings can be calculated using Eq. (10) [21].

\[
F_C(\%) = \frac{\sum_{i=1}^{n} (P_{con} - P_{ex}) \times C_{inc}}{\sum_{i=1}^{n} P_{con} \times C_{inc}} \times 100\% \tag{10}
\]

A negative value in Eq. (10) indicates an ineffective flexible measure in terms of energy cost savings.

The total power demand reduction potential (\( P_e \)) of a flexibility measure can be calculated using Eq. (11) [39]. The same expression can be used to calculate the CO2 reduction potential for energy flexible sources.

\[
P_e(\%) = \text{Max} \left[ \left( \frac{\sum_{i=1}^{n} (P_{con} - P_{ex})}{\sum_{i=1}^{n} P_{con}} \right) \times 100\%, 0 \right] \tag{11}
\]

A possible drawback of a flexible measure can result in a rebound effect that can impact the grid stability. Rebound effect or rebound power is the excessive power demand during the off-peak demand hours.
when power demand considering the flexible measures exceeds that in business as usual case. Eq. (12) can be used to calculate the rebound power \( P_{rb} \) [8], whereas Eq. (13) can be used to estimate the rebound period \( T_{rb} \). Eq. (14) can be used to gauge the intensity of rebound power during the off-peak demand hours, and the same equation can be used to calculate the intensity of rebound at discrete time intervals. The calculation of the rebound period and intensity of the rebound can offer opportunities to smooth the rebound power curve.

As the pre-bound effect is also considered an increase in power consumption because of the pre-emptive measures for a flexibility event, hence Eqs. (12)–(14) can also be used to calculate the pre-bound effect associated with the up-flexibility actions such as pre-cooling/heating by using HVAC systems.

\[
P_{rb} = (\text{Max}[P_{\text{on}} - P_{\text{off}}, 0])_{\text{off-peak}}
\]

\[
T_{rb} = \left( \sum_{i=1}^{n} f(P_{ah}) \right)_{\text{off-peak}}, \quad \text{where } f(P_{ah}) = \begin{cases} 1 & \text{if } P_{ah} > 0 \\ 0 & \text{if } P_{ah} \leq 0 \end{cases}
\]

\[
I_{rb}(\%) = \left( \text{Max}\left(\sum_{i=1}^{n} (P_{\text{on},i} - P_{\text{off},i})/\sum_{i=1}^{n} P_{\text{off},i}\right), 0\right)_{\text{off-peak}} \times 100\%
\]

### 2.3. Development of an aggregated energy flexibility potential function

The success of a building energy flexibility plan depends on the fulfillment of multiple objectives linked with different stakeholders. Different stakeholders can have different preferences. For instance, energy cost savings can be the leading objective for consumers but not for the government, whose major interest is in emissions reduction and increased utilization of sustainable energy resources. Aggregators or service providers are primarily concerned about the safety of the supply side. Energy flexibility indicators can gauge the potential of any flexibility service individually but lack effectiveness in simultaneously representing the interactions between different stakeholders and flexibility services. Hence, an inclusive building energy flexibility function that can simultaneously represent the interaction between different stakeholders in terms of distinct flexibility services can better represent the performance of a flexibility plan.

As shown in Fig. 1, based on the interactions between stakeholders, the main flexibility services and performance factors can be shortlisted. Peak demand management was selected to indicate the interaction of the building with the power grid, where a building can modulate its demand, i.e., increase or decrease as per grid needs. A decrease in demand can be attained by reducing the power for shiftable or curtailable loads. Similarly, an increase in power demand can be achieved by increasing the power consumption of curtailable loads, activating shiftable loads, or charging the onsite storage. The total power demand reduction potential was also selected which can also provide information about the reduction in carbon emissions. Other flexibility services/effects considered included energy cost savings (consumer priority), occupant comfort (consumer priority), emissions reduction (government priority), temporal performance (aggregator priority), and rebound effect (aggregator priority). Each flexibility indicator can be calculated using the respective EFIs, as formulated in Section 2.2. It is worthwhile to note that in this study several updated EFIs were used. However, the existing EFIs or new EFIs can also be used in this method for demand flexibility analysis.

To aggregate the selected flexibility services/effects, a multicriteria decision analysis model was used. Firstly, each selected energy flexibility service/effect was assigned a priority number, as an example presented in Table 2. In this example, the priority numbers were assigned based on grid and building interaction to prioritize the preferences of the aggregators and consumers, as both are the key stakeholders in successfully implementing a building energy flexibility plan. Peak demand management and energy cost savings were given the top priority. Total power demand reduction, occupant comfort, and temporal performance were given the second priority, whereas emissions reduction and rebound effect were given the lowest priority, as both are the byproducts of other flexibility services. Each priority number was assigned a numeric value on a relative scale of importance by using the Saaty scale [40]. It is noted that the priority could be different and is highly dependent on the objective of an energy flexibility plan.

The relative weights were assigned to each EFI/performance factor by using the fuzzy analytic hierarchy process based pair-wise matrix (Table 3). Fuzzification was achieved by using the geometric mean technique, whereas defuzzification was achieved by using the center of area method. The consistency ratio of the matrix was 0.06 which is below 0.1, proving the consistency of the weight assignment process.

The weights obtained from the FAHP matrix (Table 3) were multiplied with each corresponding EFI/performance factor and were then added together. Lastly, they were divided by the sum of all individual weights to formulate an overall building-level energy flexibility indicator, termed as Aggregated Energy Flexibility Potential (AEFP) function, as expressed in Eq. (15).

\[
\text{AEFP} = \left( \frac{\sum_{i=1}^{n} \omega_i \times \text{AEFP}_i}{W} \right)_{i=1, \ldots, n}
\]

where \( \alpha \) is the sum of the EFIs/performance factors in each priority (P), \( \omega \) represents the weight obtained by using Table 3, and W represents the cumulative weight that can be calculated using Eq. (16). It is worthwhile to note that in Eq. (15), only fraction values should be used. If a lower

| Table 2 | Priority number assigned to each attribute as an example. |
|---|---|---|
| Sr. # | Flexibility service/effect | Priority # |
| 1 | Peak demand management | P1 |
| 2 | Energy cost savings | P1 |
| 3 | Total demand reduction | P2 |
| 4 | Temporal performance | P2 |
| 5 | Occupant comfort | P2 |
| 6 | Emissions reduction | P3 |
| 7 | Rebound effect | P3 |

| Table 3 | Weight assignment using fuzzified AHP pairwise matrix [G.M: Geometric mean]. |
|---|---|---|---|---|---|
| | P1 | P2 | P3 | Fuzzy G.M | Fuzzy weights | Defuzzification |
| Membership functions | Normalization |
| 1, 2, 3 | 1.82 | 0.40 | | |
| 1, 3, 4 | 2.30 | 0.62 | | |
| P1 | 1/4 | 5 | 2.71 | 0.92 | 0.64 | 0.60 |
| 1/4 | 1/ | | | |
| 3, 1, 2 | 0.17 | | | |
| P2 | 2/1 | 4 | 1.126 | 0.44 | 0.30 | 0.28 |
| 1/1 | 5/ | 4/ | | |
| 3, 1, 1 | 0.37 | 0.08 | | |
| P3 | 3/2 | 1 | 0.55 | 0.19 | 0.13 | 0.12 |
value of an EFI is desired, the obtained value must then be subtracted from 1.

\[ W = \sum_{i=1}^{n} \beta_i \times \omega_i \]  

(16)

where \( \beta \) represents the number of EFIs/performance factors in each priority, as illustrated in Table 2.

3. Performance test and assessment

The performance of the developed EFIs and quantification function was evaluated via a case study of a Solar Decathlon house under two distinct scenarios, that is, to evaluate the impact of a thermal energy storage system on the flexibility enhancement of an HVAC system, and the impact of onsite generation on building energy flexibility.

The floor area of the Solar Decathlon house is 92 m², as shown in Fig. 2. This house was designed and participated in the 2018 Solar Decathlon competition, and it mainly consists of two bedrooms, one kitchen-dining area, two bathrooms, and one living area. The building was assumed to be occupied by two occupants all the time.

3.1. Scenario I: Thermal energy storage system to enhance flexibility of an HVAC system

In this scenario, an HVAC system, which consists of a phase change material (PCM) based TES system, an air-source heat pump (ASHP), a fan coil unit system, an enthalpy recovery ventilator (ERV), and a dehumidification heat pump (DHP) was considered to condition the building. The TES system was used to provide cooling from 9:30 am to 7:30 pm and this time period was considered the peak demand hours. The ASHP was used to charge the TES system and provide cooling from 7:30 pm to 9:30 am of the next day, and this period was considered the off-peak demand hours. The nominal cooling capacity of the ASHP was 6.35 kW. The ERV system was used to recover sensible and latent heat from the exhaust air and pretreat the outside air. The DHP was used to handle the latent thermal loads of the building, and a fan coil unit system was used to supply the conditioned air to the building. The impact of the TES system on the flexibility enhancement of the HVAC system was evaluated by using the developed EFIs. The TES system used is shown in Fig. 3. The TES system consisted of two tanks, each with a height and a diameter of 1.2 m and 0.829 m, respectively. The nominal cooling capacity of both tanks was 33.5 kWh, and the PCM and water were used for heat storage and heat transfer fluid inside the tanks, respectively. Each tank contained 169 PCM-filled tubes. The melting temperature of the PCM used was 10 °C with the density, thermal conductivity, specific heat and latent heat of 1400 kg/m³, 0.7 W/m.K, 2.85 kJ/kg.K, and 116 kJ/kg, respectively. The following assumptions were considered in the simulation.

- The unit cost of electricity was 2.5 times higher during the peak demand hours compared with that during the off-peak demand hours which was 0.14 USD/kWh.
- Both the ERV and the DHP were functional during the complete simulation time. Because of the operation of the DHP, both the ASHP and TES systems were used to just handle the sensible thermal load of the building.
- The ASHP was operated at a setpoint of 5 °C in order to charge the TES system and provide cooling during off-peak demand hours. For inflexible operation (i.e. without using the TES system), the ASHP setpoint temperature was 10 °C, whereas the supply air temperature was set at 16 °C throughout the simulation period.
- Indoor temperature and relative humidity were set at 24 °C and 50%, respectively.

Firstly two simulation exercises were performed in TRNSYS for the baseline operation and flexible operation, respectively, and the obtained datasets were used to calculate the performance of different flexibility services by using the information presented in Sections 2.2 and 2.3. The TES model used was well valided in [41]. The ASHP model used was provided in the standard TRNSYS library and was supported with the supplier-provided technical datasheets. The simulation period was 24 h, starting from 7:30 pm and ending at 7:30 pm of the next day, under the weather conditions of Dubai, United Arab Emirates, as this Solar Decathlon house participated in the Middle East Solar Decathlon Competition in 2018. The weather data of the selected test period are shown in Fig. 4.

Fig. 5 shows the performance of different flexibility indicators in evaluating the flexible performance of the TES system coupled with the HVAC system. It can be found that by shifting the load to the TES system during peak demand hours, around 56.4% of the HVAC peak power consumption/demand was reduced. A 32% reduction in the HVAC operational cost was also achieved. It is noted that the operation of the DHP, ERV, fan, and water pump was the main cause of energy consumption of the HVAC system during the peak demand hours. The TES system proved to be effective in providing energy flexibility in terms of peak demand reduction and cost savings. As the HVAC system was assumed completely grid-powered, the overall reduction in power consumption/demand (around 14.5%) resulted in the same percentage reduction in carbon emissions. The intensity of rebound was around 24.2% while 100% temporal performance was achieved as the TES system was functional throughout the peak demand hours.

The most important factor concerned in this study was peak demand reduction i) to provide stability of the grid by reducing stress on the grid during peak demand hours, and ii) to provide energy costs reduction of the building. Fig. 6a) shows the temporal changes in the HVAC energy flexibility in terms of power demand reduction during peak-demand hours. The system showed high flexibility potential from 11:00–14:00, which was also the period of high sensible thermal load demand of the building. Fig. 6b) summarizes the power consumption of the HVAC system, ASHP, and DHP. The HVAC power consumption included the power consumption of the fan, pump, ASHP, DHP, and ERV. It can be observed that during the peak-demand hours, the ASHP was completely switched-off, which resulted in a high peak demand reduction. However, during the off-peak demand hours, the charging operation of the TES system increased the overall energy consumption of the ASHP, which resulted in increased HVAC energy consumption. The power consumption of the DHP remained relatively stable irrespective of the flexible or baseline operations. A high rebound can also be observed during off-peak demand hours, which can be evaluated using Eqs. (12)–(14). A high rebound from 19:30–23:00 was due to a sharp increase in the power consumption of the HVAC system, which was mainly because of the high charging rate of the TES system. Moreover, the ASHP setpoint was also reduced from 10 °C to 5 °C in order to charge the TES system, which also caused higher power consumption during off-peak demand hours. Fig. 6c) further analyzes the impact of sensible and
latent loads on the energy flexibility of the HVAC system. Because the TES system was used to handle the sensible loads of the building only, hence at higher sensible loads, an increase in the flexibility potential of the HVAC system can be observed. However, DHP was used to handle the building’s latent loads, and was also being used during the peak and off-peak demand hours of the flexible operation. Hence, DHP power consumption was increased because of the increase in the building latent loads, which negatively impacted the overall flexibility potential of the HVAC system during the peak demand hours.

A major reason behind the emergence of rebound was the charging

Fig. 3. Thermal energy storage system [41].

Fig. 4. Outdoor conditions [T_{DB}: Outdoor dry-bulb temperature, RH: Relative humidity].

Fig. 5. System performance based on different energy flexibility indicators.
operation of the TES system during off-peak demand hours. In the absence of onsite generation, the rebound effect is inevitable but adjustable within the constraints of the system. A high rebound in the first two hours of the off-peak demand hours was recorded (Fig. 7) due to the high charging rate of the TES system. The overall intensity of the rebound was around 24%. As the intensity of rebound is a function of power consumed by the system, a value obtained for the intensity of rebound at any time period showed the same percentage of increase in the cost to operate the system during the off-peak demand hours.

The AEFP value of the HVAC system by using the TES system during the peak-demand hours and by considering the interactions between stakeholders and different energy flexibility services was also calculated by using the AEFP function as presented in Section 2.3. Based on the constraints of the analyzed system, different energy flexibility indicators were selected and their values were calculated, as shown in Fig. 8. It is noted that this figure was generated based on the same dataset and the same test conditions used for analysis in Fig. 5 – Fig. 7. Aggregation of the energy flexibility indicators was achieved by using Eq. (15), and the Aggregated Energy Flexibility Potential of the flexibility measure was found to be 0.54 (54%), as presented in Fig. 8. The value of 0.54 of the

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**Fig. 6.** Flexibility potential and energy profiles of the HVAC system.
AEFP represented high temporal and comfort performance with a significant reduction in peak power demand and cost of the HVAC system, but relatively low performance in reducing emissions and overall power demand by shifting the ASHP load to the TES system during the peak demand hours. It is noted that in this case study, occupant comfort was given preference in order to achieve the desired flexibility service without jeopardizing the comfort conditions, and it was maintained constant at the desirable settings.

3.2. Scenario II: Impact of onsite generation on building energy flexibility potential

In Scenario II, a 5 kW PV system was integrated with the same building as used in Scenario I. The efficiency of the PV panels was assumed to be constant at 15.3% and a constant efficiency inverter was used to convert direct current to alternating current with an efficiency of 92%. The effect of onsite generation on enhancing building energy flexibility was analyzed under the same thermal load and working conditions as that of Scenario I. The operation of the HVAC system was also the same as the inflexible operation in Scenario I without considering the TES system. Moreover, the flexibility potential of the whole building was evaluated by considering a single flexibility source only, i.e. onsite generation system.

In this scenario, two simulation exercises were performed, i.e. one for normal conditions without considering the onsite generation system, and the other for the flexible conditions with the consideration of the PV system. Fig. 9a) shows self-generated power and grid power import as well as the power exported to the grid. The PV system reduced the peak power demand significantly and extra power generation was exported to the grid. The cost of the exported electricity was assumed to be 0.05 USD/kWh. The negative values in the right-side y-axis of Fig. 9a) indicated the power exported to the grid. Eq. (1) was used to calculate building energy autonomy (ϒ) that varied throughout the daytime and peaked from 8:00 to around 15:00. As shown in Fig. 9b), a value of ϒ above 1 indicated that onsite generation exceeded the power demand of the building and can potentially export the excessive power to the grid.

Fig. 7. Illustration of rebound power and intensity of rebound.

Fig. 8. Performance evaluation of different flexibility services and relevant effects on the AEFP.
that can be calculated using Eq. (2). The power consumption of the HVAC system and other appliances is presented in Fig. 9c. The HVAC system was the major consumer of electricity in the building. Among appliances, kitchen appliances were the major cause of the increase in power consumption. The power consumption of the major components of the HVAC system was the same as that of the normal operation in Scenario I (Fig. 6b) due to the use of the same working conditions and the same time period.

The overall performance of this flexible measure was calculated by using different energy flexibility indicators and the results are shown in Fig. 10. The PV system provided a 46% reduction in the overall building carbon emissions and the same reduction in the overall power demand of the building was also recorded. Building flexibility potential in terms of the peak power demand reduction and the energy costs were 75% and 54%, respectively, proving the effectiveness of onsite generation in enhancing the overall energy flexibility of the building. The PV system also proved to be robust in eliminating rebound effects but showed slightly lower efficiency in terms of temporal performance and provided flexible services for 80% of the peak demand hours.

The AEFP was calculated and is shown in Fig. 11 by considering different flexibility services and using the same process as illustrated in Scenario I. Fig. 11 was generated using the same test conditions and the same dataset as those used in Figs. 9-10. The AEFP value was 0.74 (74%). The best performance was observed in terms of peak power demand reduction (94%) and rebound effect reduction (100%).

Overall, the impact of the onsite energy generation system was more significant on the flexibility potential improvement of the building in terms of the selected flexible measures. It is worthwhile to note that performance optimization was not achieved in either of these scenarios and hence further improvement can be possible through appropriate
optimization. It is noted that the main purpose of this case study was to illustrate the performance of the developed EFIs and AEFP, and how these indicators can lead to improved building energy flexibility.

Both scenarios verified the effectiveness of the developed indicators in evaluating the flexibility potential of buildings and building energy systems. The AEFP function developed proved to be effective in evaluating different aspects of energy flexibility by considering the distinct priorities of the stakeholders. The framework introduced to develop the AEFP is generic and flexible, which can be used to include or exclude additional flexibility services and sources. In addition, it can also be used to compare the performance of different flexibility sources and trace further performance improvement opportunities.

4. Conclusions

A framework to develop and aggregate building energy flexibility indicators was presented in this study, which can be used to quantify the aggregated energy flexibility potential of buildings and building energy systems. A multicriteria decision analysis (MCDA) model was adopted to develop an inclusive building energy flexibility indicator, which was termed Aggregated Energy Flexibility Potential (AEFP) function, to aggregate different energy flexible services and performance factors based on the interactions between different stakeholders. The developed indicators and AEFP were evaluated by performing a case study with two distinct scenarios, i.e. evaluating the impact of thermal energy storage (TES) on the flexibility enhancement of an HVAC system, and an onsite generation system on building energy flexibility. The TES system reduced the HVAC peak power demand by 56.4%, overall power demand and emissions by 14.5%, and energy cost by 32%. The AEFP was found to be 54%. The AEFP value for the onsite generation system was 74% and the onsite generation system helped achieve a 94% reduction in peak power demand, a 54% reduction in building energy costs, and a 46% reduction in both carbon emissions and overall power demand of the building. The indicators developed demonstrated a high value in evaluating the flexibility of buildings and building energy systems and offered insights into different performance factors, which can aid in
making informed decisions for optimizing energy usage and improving overall system performance. The framework introduced can be used to further develop energy flexibility indicators, and the method used to develop AEFP has the potential to include more flexible services and factors based on the specific requirements of a particular application. One of the limitations associated with the development of the AEFP function is the subjectivity of the weight assignment process, as preferences of different stakeholders can vary, and hence weights need to be adjusted accordingly. Overall, the AEFP function can be used to compare the flexibility potential of different systems and the combinations of different systems to determine cost-effective energy flexible solutions. Furthermore, it can also be used to calculate the overall flexibility potential of a single building or a cluster of buildings. However, for any comparison purposes, the same set of EFIs and criteria for weight assignment should be used.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability**

Data will be made available on request.

**References**


