Energy sharing potential in mixed-use cluster

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Abstract
This work presents the energy sharing potential within a mixed-use building cluster. A residential multi-storey building is considered in this work along with various commercial and institutional buildings. Commercial use include three types of buildings such as offices, supermarkets and retails, whereas, institutional buildings only include schools. Accordingly, for various mixtures of buildings (e.g. multi-storey residential and offices), seasonal total load profiles are compared using EnergyPlus simulations for Calgary, Canada. The construction of multi-storey residential and commercial buildings are adopted as per Canadian practices implementing high performance envelops ensuring energy efficiency. Further, a method of normalized load profiles and calculation of energy sharing measure is proposed to estimate the energy sharing potential among various mixtures. In most of the mixtures, the energy sharing potential is available from 9 am to 5 pm. The energy sharing potential found to be maximum between multi-storey residential and school mixture in spring, summer and fall seasons with energy sharing potential measure index of 0.366, 0.355 and 0.350, respectively. In spring and fall, multi-storey-retails mixture has second largest energy sharing potential after multi-storey-school mixture. However, in winter multi-storey-retails mixture yields maximum energy sharing potential with measure value of 0.285. In spring, summer and fall seasons, the least energy sharing potential is observed for multi-storey residential-supermarket mixture. Additionally, in winter, the minimum energy sharing is possible in multi-storey residential mixtures with offices and retails.

1. Introduction
Mixed-use building cluster combines a number of different building types, such as residential, commercial and institutional buildings. Song and Knaap (Song and Knaap, 2004) concluded that the mixed-use neighborhood development model can increase the property value due to mixture of commercial and residential areas. Apart from socio-economical benefits, the opportunities of energy sharing can be significant in mixed-use neighborhoods due to the diverse energy usage profiles. For instance, most of the commercial buildings consumes energy during the daytime, whereas, residential buildings have energy demand peaks during morning and evening hours. Hachem *et al.* studied the energy and GHG emission performance of solar mixed-use community under energy resource scenarios seeking energy positive status (Hachem et al., 2016). In other works, this research group studied the effect of design variables related to residential (Hachem and Grewal, 2019) and commercial (Singh and Hachem-Vermette, 2019) buildings in mixed-use neighborhoods on annual energy and environmental performance. However, this work did not consider the hourly demand load profiles. Walker *et al.* (Walker et al., 2018) stated the benefits of decentralized energy systems along with energy sharing in order to achieve energy neutral status of neighborhoods. decentralized energy systems and energy sharing can be highly feasible in case of mixed-use scenarios. For instance, supermarkets in mixed use building cluster can be the significant contributor to waste-to-energy generation. The diverse behavior of energy consumption and energy generation opportunities in various residential and commercial building may bring the opportunity to have a energy hub enabling energy sharing within a mixed-use cluster. This approach can result in achieving net-positive energy neighborhoods (Walker et al., 2017). Some studies were also presented to design the energy hub in residential (Rastegar and Fotuhi-Firuzabad, 2015) and commercial (Hanafizadeh et al., 2016) building clusters, with proven benefits (Walker et al., 2017). To estimate the potential of energy sharing in mixed-use cluster, the energy demand profiles of residential and commercial buildings should be analyzed in a systematic manner.

In this work, a cluster composed of number of multi-storey residential and commercial/institutional buildings s is studied. The average total hourly load profiles are estimated for each month in the year. Thereafter, the average load is estimated for various seasons. The analysis is carried out for case study location Calgary, Canada (51º N). The average seasonal total load profiles are analyzed for various mixtures of residential multi-storey building with commercial (offices, retails and supermarket) and institutional (schools). This analysis is carried out at different values of commercial to residential floor area ratios. Further, a method to evaluate the energy sharing potential is also proposed in this work. This method uses the normalized total average load profiles to evaluate the energy sharing potential measure index. Moreover, an energy sharing measure is also proposed and calculated for various building mixtures in different seasons (winter, spring, summer and fall). Ultimately, the energy sharing potential estimation in mixed-use cluster can be beneficial to evaluate which type of commercial, residential and institutional buildings can be coupled together to maximize the energy sharing. This will eventually minimize the use of energy storage and one building can compliment other. In the succeeding section, the methodology is presented.

2. Methodology

The main objective of this work is to quantify the energy sharing potential in a mixed-use building cluster. This quantification can be useful for the design of energy hub. For this purpose, the energy demands for various uses are assessed first followed by energy sharing potential analysis. In the following sub-section, the definition of mixed-use building cluster is presented.

2.1 Mixed-use building cluster

Among the residential use in mixed use cluster, this work considers a fixed multi-storey residential building of 32 apartments. The floor area of each apartment is 110 m^2 (Hachem and Grewal, 2019). Consequently, the total residential floor area is calculated as 3520 m^2. An occupancy of 2.5 person per apartment is assumed (Hachem et al., 2018). The façade width to perpendicular width ratio is kept as 1.3 in each apartment unit that refers an optimal range for passive design in northern climate (Hachem et al., 2013).

In this mixed-use cluster, the commercial or institutional area is estimated using commercial to residential floor area ratio, *C/R*. The maximum value of *C/R* ratio is taken as 1, whereas, its minimum value is 0.25 (Hachem and Grewal, 2019). For instance, *C/R* ratio of 0.25 means that corresponding to every 100 m^2 of residential floor area, 25 m^2 of commercial floor area is present within the considered mixed-use cluster. Representing high density commercial area, *C/R* ratio is considered as 1. Within the commercial usage, three types of building use such as offices, retails and supermarkets are analyzed in this work in addition to one institutional usage of school. The electrical and lighting loads for the commercial and institutional buildings are considered as per the recommendation of ASHRAE 90.1 in average load per unit area.

2.2 Modeling and simulation

The simulation of the mixed-use building is conducted using EnergyPlus (National Renewable Energy Laboratory (NREL), 2016)in conjunction with Google SketchUp (Chopra et al., 2012) with OpenStudio Legacy Plugin (National Renewable Energy Laboratory (NREL), 2014). The weather file is used for Calgary, Canada.

The hourly yearlong simulation data is extracted from the simulation for multi-storey residential and various commercial buildings in terms of heating (including space heating and domestic hot water), cooling and electrical loads. Thereafter, based upon the simulation results the seasonal average total hourly load data is calculated. This work estimates average total load profiles for various types of mixed-use cluster buildings.

2.3 Energy sharing potential

After estimating the seasonal average total load profiles, the energy sharing potential in various residential-commercial and residential-institutional mixtures is estimated. Energy sharing potential between two (or more) buildings exists when the energy consumption for one increase with the decrease in other (also called load mismatch). Energy can be diverted from one building to other (during off-peak), shaping the peaks and valleys in energy profile for the building couple. In this work, the average total load profiles are then analyzed for various building type mixtures of the mixed-use cluster, with various *C/R* ratio values.

In order to examine the load mismatch, the total load hourly profiles for various mixtures of multi-storey residential and different commercial buildings are normalized between 0and 1. Thereafter, these normalized load curves are analyzed for various seasons throughout the year; (1) spring, (2) summer, (3) fall, and (4) winter. This work also proposes an energy sharing potential measure index, Θ_s that is absolute average difference between hourly normalized load profiles. It can be defined by the following equation:

$$\theta_s = \frac{\left(\sum_{h=1}^{24} \frac{\bar{L}_{h,R} - \bar{L}_{h,R,min}}{\bar{L}_{h,R,max} - \bar{L}_{h,R,min}}\right) - \left(\sum_{h=1}^{24} \frac{\bar{L}_{h,C} - \bar{L}_{h,C,min}}{\bar{L}_{h,C,max} - \bar{L}_{h,C,min}}\right)}{h_{max}} \quad (1)$$

In Eq. 1, $\bar{L}_{h,R}$ is the average residential electrical load for a given hour (monthly average for 24 hours) in a particular month. $\bar{L}_{h,R,max}$ and $\bar{L}_{h,R,min}$ are maximum and minimum average residential electrical loads for a given month, respectively. Similarly, the load terms with subscript *C*, represent the load for commercial building(s). In the denominator, h_{max} is total number of hours in a day (i.e., 24 hours). Consequently, Θ_s is average energy sharing potential measure index between the considered cluster of residential and commercial buildings. Ultimately, its higher value is indicative of high energy sharing potential among two or more buildings.

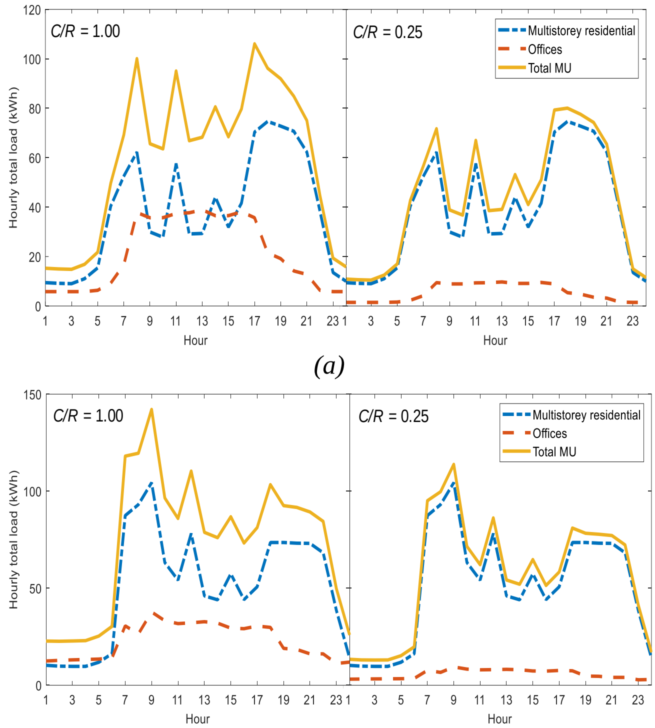
3. Results and discussion

Based upon the demonstrated methodology, this section first compares the seasonal energy profiles for various residential and commercial building combinations with both *C/R* values to understand the energy sharing opportunities. Thereafter, the comparison of energy sharing potential measure index is estimated and compared for various building mixtures in different seasons.

increases and offices load decreases due to increase and decreased occupancy, respectively.

In Fig. 2(a), the summer total load profiles for multi-storey residential and retails mixture are presented for two *C/R* ratios. The residential load profiles for summer and winter are similar to those discussed above. However, for retails the total load start increasing after 7am and gradually increases up till 17th hour and then decreases. It increases steeply between 8 to 11 hours, which is opening hours for most of the retail outlets. Accordingly, as shown in total mixed-use load curve, only one evident peak in the evening is observed in this mixture of buildings. Referring to winter total load profiles for retails indicated in Fig. 2(b), the total load first increases from 7 to 9, then marginally decreases till 17th hour. After this, it decreases due to closure of retails. Considering the combination of both these uses together, the mixed-use winter load profile observes several peaks.

The load summer and winter load curves for multi-storey residential and supermarket mixture are indicated in Figs. 3(a) and (b), respectively. Due to high energy intensity of supermarket, its energy consumption is significantly higher as compared to multi-storey residential in case of *C/R* ratio of 1.00, whereas it is comparable for *C/R* = 0.25. For summer, the supermarket total load increases from 3



(a)

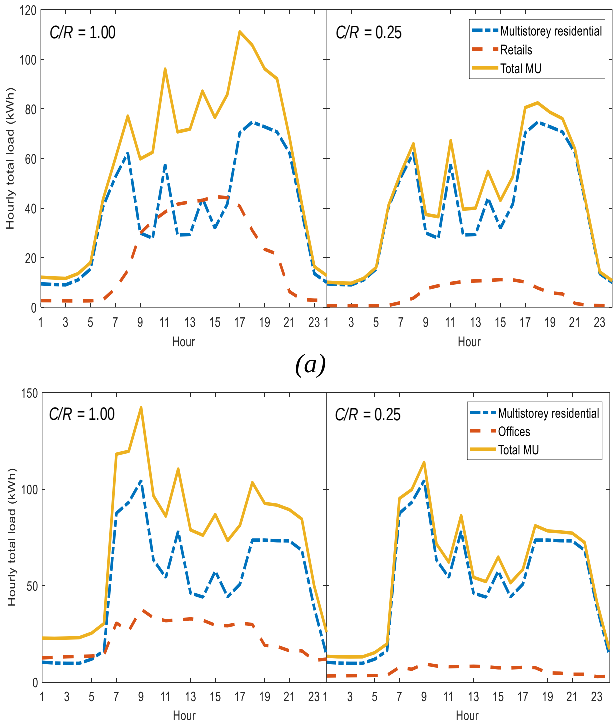
(b)

Fig. 1 Comparison of total load profiles of multi-storey residential and offices mixture for various C/R ratios in (a) summer, and (b) winter

3.1 Mixed-use hourly total load profiles

The comparison of total load profiles for a mixture of multi-storey residential and offices are presented in Fig. 1. Fig. 1(a) presents the summer total load profiles associated with both *C/R* ratios. For the multi-storey residential building, a load peak of lesser magnitude is observed in morning (around 8th hour) and a load peak of higher magnitude is resulted in the evening (around 19th hour), during the summer season. The evening peak is due to high cooling load in the summer. In the morning, after around 9am, the total average load tends to decrease. Several peaks are observed during the day, due to usage of domestic hot water for various purposes. On the other hand, based upon the occupancy in offices, the total load increases from 7am onwards and reaches a peak around 9am when the occupancy increased to maximum. Thereafter, the office total load decreases after 17th hour due to reduction in office occupancy. As far as mixed-use (multi-storey residential + offices) total load profile is considered, two major peaks are recorded, in the morning and evening, which are mainly influenced by residential use. However, for lower value of *C/R* = 0.25, the mixed-use total load profile in summer is influenced by residential use.

Fig. 1(b) presents winter total load profiles for multi-storey residential and offices mixture with both *C/R* ratios. The residential total load is more than the offices total load in all cases. In residential total load profile, one significant morning peak is observed at around 8am and then around 11am. Further, in the evening residential load

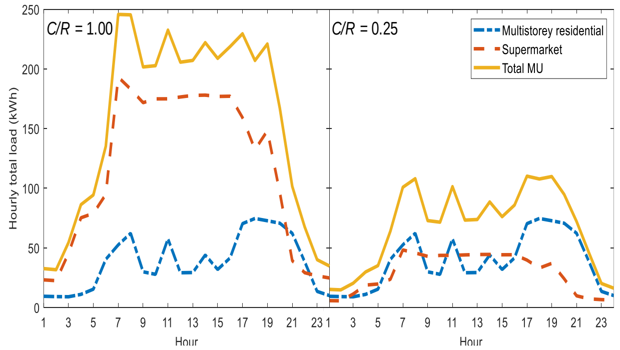


(a)

(b)

Fig. 2 Comparison of total load profiles of multi-storey residential and retails mixture for two C/R ratios in (a) summer, and (b) winter

to around 8 (due to cooling requirements), then remains almost constant till 17th hour and decreases onwards. The combined mixed-use load remains smooth during the day observing slight peak in the evening due to increased residential load. Similar supermarket load curve is observed for winter (refer Fig. 3(b)). However, a morning peak is also observed in mixed-use load profile due to changed heating load demand of the residential sector.



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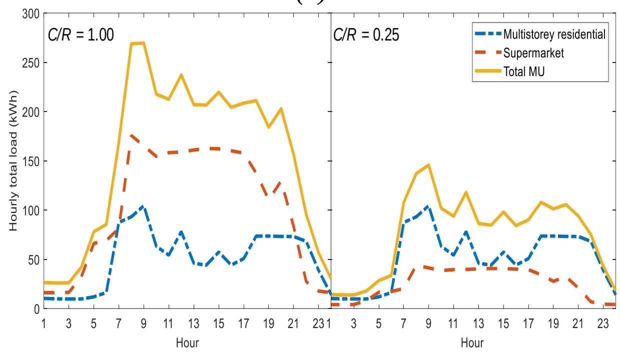
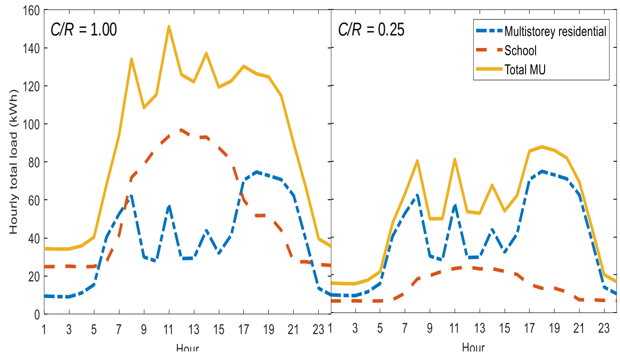


(b)

Fig. 3 Comparison of total load profiles of multi-storey residential and supermarket mixture for two C/R ratios in (a) summer, and (b) winter

Fig 4(a) presents the total load profile of multi-storey residential and school mixture in summer. Based upon occupancy pattern, the total school load start increasing at 7 and reaches a peak at around 13th hour. Thereafter, due to decrease in occupancy within the school, the total load tends to decrease. However, the total load profile for mixed-use increases rapidly from 5 to 7 due to high energy demand by both school and residential buildings. Less variation in total MU cluster load is observed during the evening as compared to day.

In a similar manner, referring to Fig. 4(b) it can be understood that a morning peak is observed around 8 close to starting time of the school. The total load further decreases and then slight increase is there between 11 and 14 hours. Considering the MU total load, two morning load peaks are observed around 7, 9, 12 and 15 hours, while no significant peak is there during the evening period. This trend holds good for all *C/R* values.



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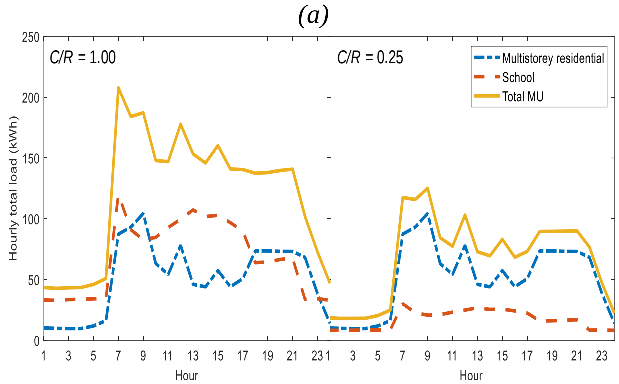


(b)

Fig. 4 Comparison of total load profiles of multi-storey residential and school mixture for two C/R ratios in (a) summer, and (b) winter

3.2 Mixed-use load mismatch analysis

In Fig. 5 the normalized hourly load profiles are presented for spring season for various mixtures of residential and commercial buildings. Referring to Fig. 5(a), for the mixture of multi-storey residential and offices, major mismatch of load is observed from 8 to 17 hours. In other words, at this period of time energy supplied from the local electric grid to the multi-storey residential building (or generated on-site using renewable energy sources) can be substituted to offices. Similarly, in the evening due to decreased office energy consumption, the load on grid is mainly imposed by multi-storey residential building. Hence during these periods, the potential for energy sharing is maximum. Here it is also worth to mention here that the normalized total load profiles remains constant irrespective to variation in *C/R* ratio. Fig. 5(b) presents the total load mismatch between multi-storey residential and retails. As indicated, the residential load is dominated over the retails from 5 to 9 hours and from 17 to 24 hours, whereas, the retails total load profile dominates the multi-storey residential load from 10 to 17 hours (accordingly energy sharing is possible). In case of the mixture of multi-storey residential and supermarket (see Fig. 5(c)), the supermarket normalized load is higher than the residential load from 7 to 17 hours, while after around 17th hour the residential load profile is higher than supermarket.

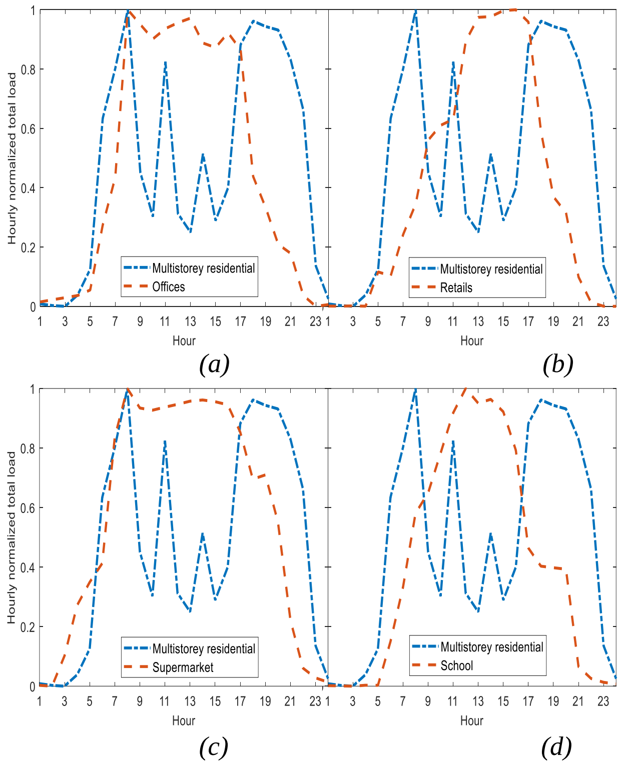


Fig. 5 Variation of normalized spring season total load curves for various mixtures of multi-storey residential with: (a) offices, (b) retails, (c) supermarket, and (d) school

Furthermore, as represented in Fig. 5(d), the school normalized total load dominates the multi-storey normalized load from 10 to 17 hours that enables sparing of energy from multi-storey residential to school. Similarly, for other morning and evening periods of load mismatch, the less energy demand of school compliments multi-storey residential building.

The summer total load profiles are presented in Fig. 6. As compared to spring total load profiles, the summer load profiles are similar. However, while comparing mixture of multi-storey residential and offices summer load profiles in Fig. 6(a) with Fig. 5(a), there is more potential for energy sharing in summers as various peak loads for residential use are comparatively less. Further, for retails and multi-storey residential mixture, the load mismatch is reduced in summer that results in decreased potential of energy sharing. However, for supermarket and school mixtures with multi-storey residential, the potential of energy sharing increases in summer as observed from Fig. 6(c) and (d).

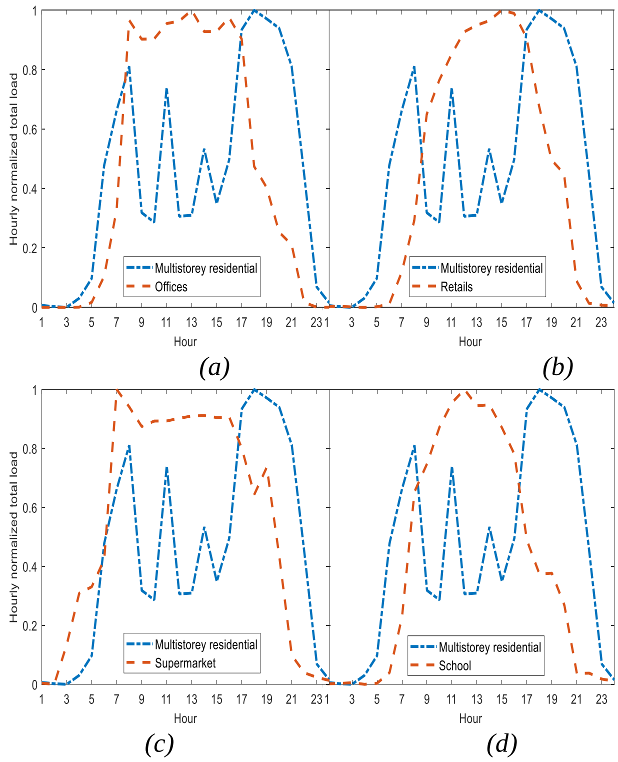


Fig. 6 Variation of normalized summer season total load curves for various mixtures of multi-storey residential with: (a) offices, (b) retails, (c) supermarket, and (d) school

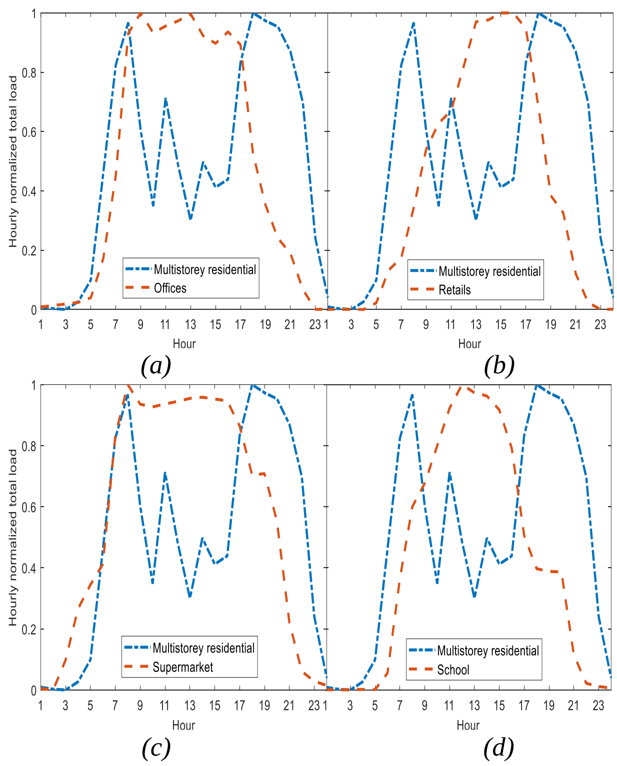
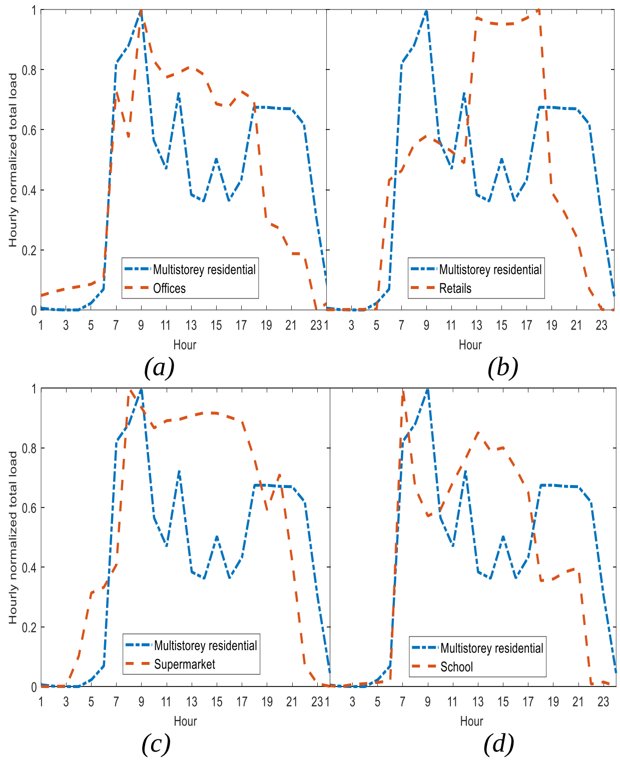


Fig. 7 Variation of normalized fall season total load curves for various mixtures of multi-storey residential with: (a) offices, (b) retails, (c) supermarket, and (d) school

The normalized total load profiles for various mixtures during the fall season are indicated in Fig. 7. Fig. 7(a) shows that the normalized office load dominates the residential load from 8 to 17 hours, whereas opposite happens from 17th hour onwards. From 5 to 7 in the morning, there is slight load mismatch between the two types of buildings. Compared to summer normalized total load profile for multi-storey residential and retails mixture, the fall load mismatch is reduced during the daytime as shown in Fig. 7(b). Nevertheless, for supermarket and school mixtures with multi-storey residential, the energy sharing potential or load mismatch decreases due to increased energy demand for residential use (refer Figs. 7(c) and (d)).



(a) (b) (c) (d)

Fig. 8 Variation of normalized winter season total load curves for various mixtures of multi-storey residential with: (a) offices, (b) retails, (c) supermarket, and (d) school

The winter normalized total load profiles are presented in Fig. 8 for various mixtures. Observing Fig. 8(a), it is evident that in the mixture of multi-storey residential and offices, both types of buildings result in similar load characteristics. Although, during 11 to 19 hours normalized office load is higher than residential and vice-versa is true from 19 to 24 hours, indicating thus some potential of energy sharing. Considering the mixture of retails and multi-storey residential buildings, the energy from retails can be spared for residential use during 7 to 13 hours and 19 to 24 hours, whereas, the residential energy can be diverted to retails from 13 to 19 hours. In Fig. 8(c), the load mismatch is indicated for multi-storey residential and supermarket mixture. The highest potential of energy sharing is possible between 10 and 19 hours between these two usage types. Additionally, there is some potential of sharing after 19th hour too, where energy from supermarket can be diverted for residential use due to decreased total load of supermarket. In similar manner, the energy sharing potential between multi-storey residential, and school can be also observed in Fig. 8(d), which appears to be way less as compared to other seasons.

Table 1: Energy sharing potential measure index, Θ_s for various building two building mixtures in different seasons

Mixture	**Residential + Offices**	**Residential + Retails**	**Residential + Supermarket**	**Residential + School**
Spring	0.342	0.361	0.304	**<u>0.366</u>**
Summer	0.338	0.332	0.309	**<u>0.355</u>**
Fall	0.336	0.337	0.290	**<u>0.350</u>**
Winter	0.211	**<u>0.285</u>**	0.250	0.212

In Table 1, energy sharing potential measure index, Θ_s (explained in Eq. 1) for various two building mixtures in different seasons are indicated. Higher value of Θ_s means greater potential of energy sharing among buildings. The bold underlined number represents the highest value in a particular season. As presented, in spring, summer and fall the highest energy sharing potential is available for multi-storey residential combinations with school, whereas Θ_s is least for multi-storey residential-supermarket mixture. The energy sharing potential measure index is also comparable in the mixture of residential and retail buildings. However, in winter, the maximum energy sharing potential measure index can be achieved by multi-storey residential mixtures with retails. It can be also noted here that the energy sharing potential measure index decreases significantly for multi-storey residential mixtures with offices and school in winter (Θ_s values are 0.211 and 0.212, respectively).

Table 2 presents the energy sharing potential measure index for more than two building mixtures (residential and commercial) for various seasons. As indicated, during the spring season, the energy sharing potential measure index, Θ_s is maximum for the mixture of multi-storey residential, office and school combination as well as for multi-storey residential, retail and school mixture (for both, Θ_s = 0.364). However, least energy sharing potential with Θ_s = 0.306 is yielded in multi-storey residential, office and supermarket mixture. In summer, the maximum energy sharing potential measure index of 0.351 is achieved in multi-storey residential, retail and school mixture. Whereas, the minimum value of Θ_s = 0.314 is resulted in the mixture of all buildings (multi-storey residential + office + retail + supermarket + school). In the fall, the minimum energy sharing potential is obtained in the combination of multi-storey residential, office and supermarket (Θ_s = 0.297). The maximum value of Θ_s = 0.348 is yielded with the mixture of multi-storey residential, office and school. Finally, in winter the energy sharing potential reduces for every mixture of buildings due to enhancement of heating loads. The maximum energy sharing potential, Θ_s = 0.268 is achieved in the combination of multi-storey residential, office and retail. Nevertheless, the minimum energy sharing potential measure index is revealed for residential office and school mixture. Here, it can be also noted that mixtures with supermarket always result in lower values of energy sharing potential measure index in all seasons, which is due to dominance of significant load imposed by the supermarket.

Comparing Table 2 to Table 1, it can be established that for all seasons the maximum energy sharing potential measure index values are higher for the mixtures consisting of set of two buildings (i.e., shown in Table 1). Interestingly, least values of energy sharing potentials in different seasons are higher, when more than two buildings are mixed. the least values of Θ_s in Table 2 for each season are higher than the minimum Θ_s in Table 1. Since, the higher values of Θ_s in various seasons are comparable in both the tables, therefore, mixing more than one commercial building type with residential is somewhere more beneficial.

Table 2: Energy sharing potential measure index, Θ_s for various building multiple building mixtures in different seasons

Mixture	**Residential + Office + Retail**	**Residential + Office + Supermarket**	**Residential + Office + School**	**Residential + Retail + Supermarket**	**Residential + Retail + School**	**Residential + Supermarket + School**	**Residential + Office + Retail + Supermarket + School**
Spring	0.353	0.306	**0.364**	0.313	**0.364**	0.326	0.330
Summer	0.332	0.324	0.348	0.316	**0.351**	0.326	0.314
Fall	0.336	0.297	**0.348**	0.301	0.346	0.311	0.313
Winter	**0.268**	0.254	0.220	0.265	0.228	0.242	0.241

Conclusion

This paper presents the energy sharing potential between multi-storey residential building and several commercial and institutional building. The seasonal total hourly average load profiles are obtained using EnergyPlus simulations. In most of the residential and other types of buildings (commercial and institutional) combinations, the energy sharing potential is available between 9 am to 5 pm. This work also proposes a normalized load curve analysis to identify the energy sharing potential evaluating load mismatch. Based upon energy potential measure quantification, the energy sharing potential measure index is estimated to be the highest for multi-storey residential and school combination in spring, summer and fall seasons with its value between 0.350 to 0.366. In these three seasons, the least energy sharing potential is observed for multi-storey residential and supermarket mixture. However, in winter the maximum energy sharing potential measure index of 0.285 is estimated for multi-storey residential and retails mixture. The energy sharing potential decreases significantly for multi-storey residential mixtures with office and schools in winter as compared to summer. For these two mixtures the energy sharing potential is least in winter. Further, mixing more than two buildings (one residential and more than one commercial) is slightly more beneficial than a couple of a multi-storey-residential and a commercial building, yielding better minimum value of energy sharing potential in various seasons.

The energy sharing among the buildings can avoid the power surge of grids leading to reduction in maintenance costs. Further, by estimating and maximizing the energy sharing potential through building mixture, the optimal utilization of on-site distributed renewable energy resources can be ensured that results in reduction in GHG emissions.

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