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Life cycle approach in evaluating energy performance of residential buildings in Indian context

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ABSTRACT

The paper presents life cycle energy (LCE) analysis of different types of residential buildings (one storey, two storey, and duplex and multi storey) in Indian context. A total of 10 houses' designs were examined with energy saving features, e.g. thermal insulation on wall and roof, double pane glass for windows. One of these buildings was further examined to assess LCE performance with on-site power generation. Dynamic energy simulation tools DesignBuilder, e-Quest and EnergyPlus were used to assess energy performance of the buildings.

LCE of the buildings is varying from 240 to 380 kWh/m^2 year depending on the type (envelope) of the building and climatic conditions. LCE savings of about 5–30% are observed with thermal insulation on wall and roof along with double pane glass for windows. It is found that net zero operating energy building can be achieved by on-site power generation from PV and wind turbine. LCE of the building for net zero operating energy is evaluated to be 71.24 kWh/m^2 year.

1. Introduction

Building construction sector is experiencing a fast-paced growth in developing countries, like India, due to growth of economy and rapid urbanization. A large number of buildings are built for residential, commercial and office purposes every year. World-wide buildings consume 30–40% amount of primary energy in their construction, operation and maintenance and held responsible for emitting 40% of global warming gases [1]. In India, 24% of primary energy and 30% of electrical energy is consumed in buildings [2]. The use of electricity in this sector is growing at the rate of 11–12% annually, which is 200% more than the average growth rate of 5–6% in the economy [3]. Besides the depletion of non-renewable energy sources, this energy use contributes greenhouse gases to the atmosphere, with consequent detrimental effects. In order to reduce the detrimental environmental impacts of the buildings, new buildings need to be planned in such a way that energy consumption in construction as well as operation reduces considerably. Life cycle assessment (LCA) is the state of art tool in assessing the sustainability of buildings. In order to assess the environmental impact, it is necessary to perform an inventory analysis of building materials and the process of construction, and demolition. But, building materials production processes are less standardized because of the unique character of each building. There is limited quantitative information available about the environmental impacts of the production and manufacturing of construction materials, the actual process of construction and demolition particularly in developing countries like India.

Life cycle energy (LCE) analysis of buildings can also give a useful indication of environmental impacts attributable to buildings, if energy use of the building is expressed in primary energy terms. Life cycle energy analysis is an approach that accounts for all energy inputs to buildings in their life cycle. It includes direct energy inputs during construction, operation and demolition of building, and indirect energy inputs through the production of components, materials used in construction [4,5]. The analysis also helps in identifying the phases of largest energy consumption and to develop strategies to make buildings sustainable.

In spite of the fast-paced growth of the building sector in India, life cycle energy consumption data for this sector is not available in the public domain; whereas a lot of work has been done in cold

Abbreviations: DX, direct expansion; FC, fired clay; EPS, expanded polystyrene; RCC, reinforced cement concrete; ISHRAE, Indian Society of Heating, Refrigerating and Air conditioning Engineers; PV, photo voltaic.

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and western countries. Absence of macro-level data has been a barrier for the government to formulate effective policies to make the buildings energy-efficient. LCE data also provides clues to designing and operating energy efficient buildings, targets for implementing energy efficiency measures.

Nomenclature

m_i	quantity of building material (i)
M_i	Embodied energy of material (i) per unit quantity
E_A	operating energy per year (primary)
L_b	lifespan of the building (75 years)
OPE	operating energy (kWh/m^2 year)
LCE	life cycle energy (kWh/m^2 year)
EBE	embodied energy (kWh/m^2 year)

Subscripts

i	particular material
A	annual

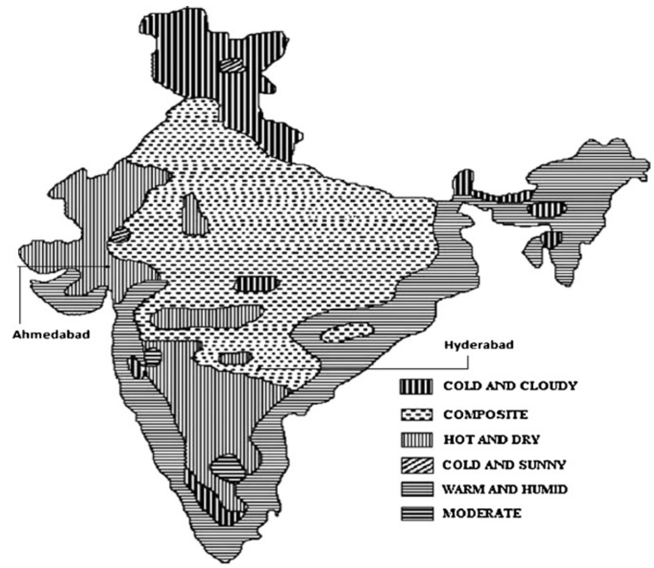

Fig. 1. Map showing two locations and climatic regions of India.

1.1. Literature review

Studies in cold countries have shown that the major part of the LCE use is in the operating phase (80–90%) and production of building materials accounts for 10–20% [4–8]. Energy used for on-site construction (including transportation of materials to the site) of the buildings and its demolition at the end of its life accounts for a minor proportion (1%) of the life cycle. Some authors have studied the effect of change of envelope materials and construction on the LCE demand of the buildings. Citherlet and Defaux [9] and Mithraratne and Vale [10] analyzed effect of insulation on buildings envelope so as to reduce LCE demand of the buildings and concluded that good insulation provides a significant reduction of energy (about 50%). Medgar and Martha [11] presented a life cycle assessment of a single-family house modeled with two types of exterior walls: wood framed and insulating concrete form (ICF). The house was modeled in five cities of different climates in U.S. The results depict that in almost all cases, for a given climate, the energy use is greater for the wood house than for the ICF house. Utama and Gheewala [12] evaluated LCE of a residential apartment in Jakarta, Indonesia, with two envelope materials: (a) double walls having external walls made from clay bricks, inner walls with gypsum plaster board and air gap in between and (b) single walls with clay bricks. Double walls had resulted in better energy performance (40% less) than single walls. Xing et al. [13] presented the life cycle assessment of an office buildings constructed in China using steel and concrete. They observed that embodied energy (EBE) and environmental emissions of steel framed building were superior to the concrete framed one. However, operating energy (OPE) use and associated emissions were larger for steel framed building due to the higher thermal conductivity of steel than concrete. As a result LCE consumption and environmental emissions of steel framed building were slightly higher. Only a few studies have been reported on LCE demand of the buildings from tropical and subtropical countries.

In Indian context, Shukla et al. [14] evaluated EBE of an adobe house. Debnath et al. [15] evaluated EBE of the load bearing single storey and multi-storey concrete structured buildings and found that EBE of load bearing wall building is lower than concrete structured buildings. Venkatarama Reddy and Jagadish [16] estimated the EBE of residential buildings using different types of masonry materials, roofing systems.

1.2. Subject of the study

From literature review it is observed that case studies in Indian context were confined to only analyzing and reducing EBE of buildings ignoring OPE and thus LCE of the buildings. Earlier, authors analyzed LCE of a single storey residential building with different envelopes and climates in Indian context [17]. The present study is divided into two parts: part A and part B. In part A, Ten buildings at two locations were studied to evaluate life cycle energy (LCE) demand of the buildings in Indian context. LCE of the buildings was evaluated for existing (conventional) and modified designs. Building designs were modified by applying energy saving measures, e.g. thermal insulation on wall and roof, double pane glass for windows to assess their impact on LCE of the buildings. In part B: one of the ten buildings, Mahendra house, was examined with on-site power generation (from PV and wind turbine) to assess LCE performance of a net zero operating energy building.

LCE of the buildings in India (a tropical country) is expected to be high compared to LCE of the buildings in cold countries due to the use of electricity for cooling derived mostly from fossil fuels (coal) in operation phase and use of energy intensive materials like steel, concrete and fired clay bricks in the construction phase. Also, as India is a tropical country with large potential for solar energy; it is expected that buildings can be made to demand zero operating energy with on site power generation using PV panels and or wind turbines. Such a study is expected to be useful for building designers for holistic evaluation of buildings from life cycle perspective.

2. Methodology

To assess LCE demand of the residential buildings, a total of 10 house designs (for details refer Table 1) were obtained from house builders, consultants and owners of the buildings from Hyderabad (Andhra Pradesh state) and Ahmedabad (Gujarat state) locations of India (Fig. 1). The two places experience three main seasons: summer, monsoon and winter in a year. Hyderabad has a mild composite climate. The summer months of April and May are hot, and the city frequently records temperatures exceeding 40 °C. The mean maximum temperature ranges between 34 °C and 40 °C in May. The monsoon is spread over a period of three months from June to August. The period from July to September is warm and humid. Winter spreads from October to February and climate is mild. The

Table 1
Details of the buildings studied.

Sl. no.	Name	Category	Floor area (m^2)	Conditioned floor area (%)	Description	External surface area per unit floor area
1	Keerthi	One storeyed	104	83	Single family, 3 BR house	2.3
2	Eashwer	One storeyed	185	60	Two family, 2 BR portion – 1, 1 BR portion – 1	1.9
3	Adil	One storeyed	62	75	Two family, single BR portions – 2	2.5
4	Anand	Duplex	183	55	Single family, 4 BR house	1.8
5	Alwal	Two storeyed	135	60	Two family, single BR portions- 2	1.7
6	RG	Duplex	175	68	Single family, 4 BR house	1.4
7	Rock town	Multi storeyed	1280	81	Multi family, 3 BR flats – 4, 2 BR flats – 8	0.9
8	Kiran Arcade	Multi storeyed	1286	45	Multi family, single BR flats – 15	1.4
9	Mahendra	Duplex	450	76	Single family, 4 BR house	1.7
10	Nirmal	Two storeyed	235	66	Two family, 3 BR portions – 2	1.5

BR: bed room.

mean minimum temperature is 9–18 °C in December and January. Ahmedabad has a hot and dry climate. Aside from the monsoon season, the climate is extremely dry. The weather is hot through the months of March to June – the average summer maximum temperature is 41 °C, and the average minimum temperature is 27 °C. From November to February, the average maximum temperature is 30 °C, the average minimum is 15 °C, and the climate is extremely dry. The southwest monsoon brings a humid climate from mid-June to mid-September.

2.1. Description of the buildings

2.1.1. Construction

All buildings, except Mahendra, are conventional houses with RCC frame work, walls filled with fired clay bricks and RCC roof. Mahendra house is an energy efficient building. It has well insulated walls and roof (RCC). The house is built with, 1.2 m wide projections all around the building to shade the walls and double glazing windows. The house is also equipped with PV system to meet part of the electricity demand and hot water requirement of the building is met by a 400-l per day solar water heating system. The buildings are categorized by number of floors they have viz. one storey, two storey, and multi storey. Each floor contains one or more family portions consisting of bed rooms, drawing room, living room, and a kitchen. Bedrooms and living hall are air conditioned. Duplex house is a two storey single family house containing drawing room, living hall and kitchen in ground floor and bed rooms in upper floor. The information of buildings such as usable floor area, conditioned area, number of families living, number of bed rooms in a portion, and operating hours are being collected. The data of the energy efficient building with regard to materials used in the construction, energy saving features are obtained from Teri publications [18].

2.1.2. Operation

Electricity from the national grid is being used for all operations of the buildings like running air conditioners, domestic appliances, hot water and lighting, etc. The indoor operating set point temperature is around 25 °C for cooling, 18 °C for heating and all lighting controls of the building are manual. Bed rooms and living hall are air conditioned using window air conditioners having COP of 3 for cooling (a typical value for commercial units in India) and 0.9 for heating (electrical resistance heating) for design conditions. Generally residential air conditioning equipment runs at off-design conditions and meets the load by cycling on and off. Therefore, performance correlations (Appendix A) for cooling capacity and efficiency are used to determine system operation at off-design conditions. For electrical resistance heating, constant COP of 0.9 is being considered. Though, electrical resistance heating is not advisable, it is common in India, as harsh winter in most parts of the country lasts only for one or two months and people do not use heat pump or boiler for heating. The air conditioner utilization is about 11 h on an average for bedrooms and 4 h for the living room starting in the evening hours for all working days. On holidays, air conditioners start working in the afternoon 13.00 h onwards. Detailed estimation of energy required for the production (embodied energy – EBE) and operation phases of the buildings from a primary energy perspective is being considered.

2.2. Embodied energy (EBE)

Embodied energy per unit quantity of the building materials is taken from the literature [14–22]. Quantity of the materials is estimated from the technical drawings of the buildings using QE-Pro software. EBE of the building is obtained by summing up the product of quantity of materials multiplied by their embodied energy per unit quantity. Table 2 shows embodied energy per unit quantity of the key building materials. The energy used for the renovation of buildings is expected to be small and is included in EBE of the building.

2.3. Operating energy (OPE)

OPE of the building includes the energy for space cooling, heating, ventilation, domestic hot water, powering appliances and lighting in its lifespan. It is estimated by energy simulation of the building using dynamic energy simulation tool DesignBuilder [23]. DesignBuilder is one of the most comprehensive user interfaces for EnergyPlus dynamic thermal simulation engine. DesignBuilder generates detailed building energy performance data for one year by simulation using real weather data. Hourly weather files of ISHRAE from DesignBuilder database are being used for simulation. The evaluated energy (electricity) performance of the buildings is then converted into primary energy using a conversion factor of 3.4 for the Indian context [24] and is termed as annual operating energy. Annual operating energy of the building is assumed to be same in future throughout its life span. Due to changes in climatic

Table 2
Embodied energy coefficients of key building materials.

Name of the material	Unit	Embodied energy per unit (GJ)	Reference source
Cement	m^3	9.648	[19]
Steel	ton	28.212	[19]
Fired clay bricks	m^3	2.235	[19]
Aggregate	m^3	0.538	[19]
Glass	ton	25.800	[16]
Copper	ton	110.000	[21]
Ceramic tiles	ton	3.333	[19]
PVC	ton	158.000	[19]
Marble/granite	ton	1.080	[20]
AC blocks	m^3	0.818	[19]
Fly ash bricks	m^3	1.341	[20]
Expanded polystyrene (EPS)	m^3	2.500	[22]

Table 3
Constructional details of case studies.

Case	Description	Exterior wall construction (outer to inner)	Roof construction (outer to inner)	Windows
A	Conventional	1.2 cm plaster, 23 cm fired clay bricks, 1.2 cm plaster	1.2 cm plaster, 12 cm cast in concrete (2% steel), 1.2 cm plaster	Fully glazed, single clear (3 mm thick) glass pane fitted in wooden frame
B	Insulated external wall	1.2 cm plaster, 23 cm fired clay bricks, 1.2 cm plaster, 5 cm EPS, 1.2 cm plaster	1.2 cm plaster, 12 cm cast in concrete (2% steel), 1.2 cm plaster	Fully glazed, single clear (3 mm thick) glass pane fitted in wooden frame
C	Insulated roof	1.2 cm plaster, 23 cm fired clay bricks, 1.2 cm plaster	1.2 cm ceramic tiles, 1.2 cm plaster, 5 cm EPS, 12 cm cast in concrete (2% steel), 1.2 cm plaster	Fully glazed, single clear (3 mm thick) glass pane fitted in wooden frame
D	Insulated external wall and roof	1.2 cm plaster, 23 cm fired clay bricks, 1.2 cm plaster, 5 cm EPS, 1.2 cm plaster	1.2 cm ceramic tiles, 1.2 cm plaster, 5 cm EPS, 12 cm cast in concrete (2% steel), 1.2 cm plaster	Fully glazed, single clear (3 mm thick) glass pane fitted in wooden frame
E	Insulated external wall, roof and double pane windows	1.2 cm plaster, 23 cm fired clay bricks, 1.2 cm plaster, 5 cm EPS, 1.2 cm plaster	1.2 cm ceramic tiles, 1.2 cm plaster, 5 cm EPS, 12 cm cast in concrete (2% steel), 1.2 cm plaster	Fully glazed, double clear (3 mm thick, 13 mm air gap) glass panes fitted in wooden frame

conditions and occupants' behavior, OPE of the building may change little in future, but this is not taken into consideration in the analysis.

2.4. Life cycle energy

The LCE of the selected building is evaluated based on an assumed lifespan of 75 years using following relation [25–27]:

$$\mathrm{LCE} = \sum m_i M_i + E_A L_b$$

where m_i is the quantity of building material (i), M_i the embodied energy of material (i) per unit quantity, E_A the annual operating energy (primary), and L_b is the lifespan of the building (75 years).

LCE demand of the building is taken as the sum of the EBE and OPE only. Energy used for on-site construction and demolition at the end of its service life was ignored in the study as they contribute little (1%) to LCE. Unit for LCE is chosen as kWh (thermal). However, normalized LCE per unit floor area and per year is useful for quick comparison of energy performance of buildings of different sizes or different design versions of a building. Hence, LCE and other energy entities (OPE and EBE) of the building are normalized to kWh/m^2 year based on their floor area and assumed lifespan of 75 years.

LCE demand is estimated for existing (conventional – case A) and modified designs of the buildings for two climatic conditions (Ahmedabad and Hyderabad locations). Building designs are modified by applying energy saving measures: adding 5 cm thick thermal insulation (a general practice in India) to wall and roof (cases B–D), and using double pane glass for windows (case E). LCE demand of the conventional building under particular climatic condition is taken as base case for calculating energy savings. The constructional details of the buildings for different designs (cases studies) are shown in Table 3. LCE demands of the modified building designs are then compared with conventional case and results are analyzed in Section 3.

Further, Mahendra house is studied with on site power generation using PV panels and wind turbine to make it a net zero operating energy building. The embodied energy of equipments (PV panels and wind turbine), for initial installation and replacement, is included in calculation of EBE of the building. Number of times the equipment replaced is calculated using the following relation:

$$N = \left(L_b / L_i\right) - 1$$

where N is the no. of times the equipment replaced in life span of building, L_b the lifespan of the building, and L_i is the lifespan of the equipment (i) (refer Table 4).

Electricity generated from PV and wind turbine is simulated using e-Quest and EnergyPlus software [28,29] for Ahmedabad climatic condition. PV panels, wind turbine and batteries are designed as explained in the references [30,31]. Specifications and other particulars of PV panels, wind turbine, and batteries are shown in Table 4.

3. Results and discussion

Table 5 shows the life cycle energy (LCE) demand of the conventional buildings under study for two geographical locations under two different climatic conditions of India. LCE of the buildings is varying from about 240 to 380 kWh/m^2 year depending on the type (geometry) of the building and climatic conditions. LCE performance of one building over the other can only be compared when there is a similarity between the buildings in one or more aspects. LCE performance of Adil (single storey), Alwal (two storey) and Kiran arcade (apartment) are compared as they consist of similar number of conditioned rooms (one bed room and one living room). For Hyderabad climatic condition, Adil house has higher LCE demand (294 kWh/m^2 year) than Alwal (266 kWh/m^2 year) and

Table 4
Particulars of the PV panels and wind turbine.

Sl. no.	Name of the item	Specifications	Unit	Embodied energy (MJ/unit)	Life span (years)	Reference source
1	Photovoltaic panels (PV)	75 W; 0.614 m^2 area made of amorphous silicon cells	m^2	4233.6	30	[30]
2	Wind turbine	22.5 kW	1 no.	162,600	25	[31]
3	Batteries	250 kWh	1 set	225,000	5	[31]
4	Inverter	8 kW, 48 V DC/220 V AC	1 no.	8000	12.5	[31]
5	Power control unit	45 kW	1 no.	45,000	12.5	[31]
6	Wiring and installation			11,800		[31]

Table 5
Life cycle energy of conventional buildings (LCE in kWh/m^2 year) for Hyderabad and Ahmedabad locations.

Sl. no.	Building name	Hyderabad	Ahmedabad
1	Keerthi	327	376
2	Eashwer	267	293
3	Adil	294	330
4	Anand	255	285
5	Alwal	266	297
6	RG	276	318
7	Rock town	317	349
8	Kiran Arcade	247	271
9	Mahendra	301	334
10	Nirmal	271	304

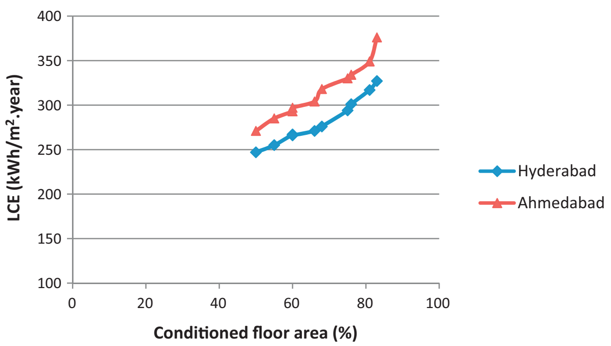

Fig. 2. Life cycle energy of the buildings vs percentage of conditioned floor area.

Kiran arcade (247 kWh/m^2 year). This can be attributed to the fact that, single storey houses (Adil) have higher external surface area per usable floor area than two and multi storey (apartment) houses (refer Table 1). This results in higher embodied energy along with higher thermal load and energy consumption by cooling and heating equipment. With increase in no of floors external surface area per usable floor area comes down and hence Kiran arcade (apartment) is showing better energy performance among the three. It is also observed that LCE demand of the buildings increases with increase in percentage of conditioned floor area (Fig. 2). Higher the percentage of conditioned floor area, greater is the OPE and LCE demand of the buildings.

3.1. LCE savings from energy saving measures

Tables 6 and 7 show LCE and LCE savings (in percentage) of the buildings from energy saving measures – thermal insulation on wall and roof, double pane glass for windows, for Ahmedabad and Hyderabad locations. For single storey houses, in Ahmedabad location, energy savings from roof insulation is about 6–20% and that from wall insulation it is 1.7–7.4%. For two storey and duplex houses roof insulation is yielding LCE savings from 3 to 7.7% whereas wall insulation is yielding 2–7%. LCE savings are less for apartment houses. It is about 2% from roof insulation and 1% from wall insulation. LCE savings, with thermal insulation, are varying even in the same type of buildings. This could be due to the change in layout of the building and conditioned floor area. Higher the conditioned floor area greater is the LCE savings. It is observed that LCE savings from roof insulation is higher than wall insulation for single storey houses. The difference in LCE savings with roof insulation and wall insulation is less for two storey, duplex and apartment houses. This can be explained as below: for single storey houses roof insulation is more effective than wall insulation because the heat load through the roof is higher than the heat load through the walls. In multi storey houses the impact of roof insulation is less compared to single storey houses because the roof insulation only reduces the heat load on the top storey leaving other storey unaffected. Hence, LCE savings from roof insulation becomes low and also difference in LCE savings from roof insulation and wall insulation becomes small as we move from single storey to two storey and multi storey houses. Similar kind of observations is made for Hyderabad location also but LCE savings, in all cases, are lower than Ahmedabad location. This indicates that energy savings also depend on local climatic conditions.

Table 6
Life cycle energy (kWh/m^2 year) and percentage energy savings (values shown in bracket) of the modified buildings for Hyderabad geographical position (mild composite climate).

Sl. no.	Name	Case B	Case C	Case D	Case E
1	Keerthi	305 (6.7)	273 (16.5)	248 (24.2)	242 (26)
2	Eashwer	262 (1.9)	253 (5.2)	248 (7.1)	245 (8.2)
3	Adil	283 (3.7)	273 (7.1)	258 (12.2)	253 (13.9)
4	Anand	244 (4.3)	250 (2)	239 (6.3)	238 (6.7)
5	Alwal	249 (6.4)	247 (7.1)	224 (15.8)	220 (17.3)
6	RG	268 (2.9)	272 (1.4)	264 (4.3)	260 (5.8)
7	Rock town	315 (0.6)	315 (0.6)	314 (0.9)	312 (1.6)
8	Kiran Arcade	245 (0.8)	245 (0.8)	245 (0.8)	244 (1.2)
9	Mahendra	296 (1.7)	297 (1.3)	291 (3.3)	289 (4)
10	Nirmal	265 (2.2)	265 (2.2)	258 (4.8)	254 (6.3)

With addition of insulation on both wall and roof, and using double pane glass for windows (case D to case E), LCE savings are further increasing. LCE savings with thermal insulation on wall and roof along with double pane glass for windows is about 5–30%. Actually, energy saving measures like adding insulation to envelope and using double pane glass for windows cause OPE of the building to decrease and embodied energy (EBE) of the buildings to increase. However, decrease in OPE is to be higher than the increase in EBE to get LCE savings. Table 8 shows (for Ahmedabad location) effectiveness of energy saving measures (B–E) for studied buildings.

3.2. On-site power generation

From the above studies, it is observed that reduction in LCE of the buildings with passive features (B–E) is limited to about 30%. To further reduce the LCE of the buildings, use of on-site power

Table 7
Life cycle energy of modified buildings (kWh/m^2 year) and percentage energy savings (values shown in bracket) for Ahmedabad location (hot and dry climate).

Sl. no.	Name	Case B	Case C	Case D	Case E
1	Keerthi	348 (7.4)	301 (19.9)	274 (27.1)	265 (29.5)
2	Eashwer	286 (2.4)	273 (6.8)	264 (9.9)	260 (11.3)
3	Adil	319 (3.3)	299 (9.4)	282 (14.5)	274 (17)
4	Anand	272 (4.6)	273 (4.2)	258 (9.5)	257 (9.8)
5	Alwal	276 (7.1)	274 (7.7)	246 (17.2)	240 (19.2)
6	RG	303 (4.7)	303 (4.7)	290 (8.8)	285 (10.4)
7	Rock town	345 (1.1)	341 (2.3)	337 (3.4)	335 (4)
8	Kiran Arcade	269 (0.7)	266 (1.8)	264 (2.6)	261 (3.7)
9	Mahendra	327 (2.1)	323 (3.3)	315 (5.7)	312 (6.6)
10	Nirmal	295 (3)	290 (4.6)	278 (8.6)	273 (10.2)

Table 8
Effectiveness of energy saving measures for Ahmedabad location (values in bracket show % increase in EBE and % decrease in OPE with reference to case A).

Sl. no.	Name	A		B		C		D		E	
		EBE	OPE	EBE	OPE	EBE	OPE	EBE	OPE	EBE	OPE
1	Keerthi	28.12	348	28.9 (2.8)	319 (8.3)	28.8 (2.4)	272 (21.8)	29.66 (5.5)	244 (29.9)	30.63 (8.9)	234 (32.8)
2	Eashwer	21.17	271	21.79 (2.9)	265 (2.2)	21.72 (2.6)	251 (7.4)	22.33 (5.5)	242 (10.7)	22.69 (7.2)	237 (12.5)
3	Adil	27.4	303	28.37 (3.5)	290 (4.3)	28.28 (3.2)	271 (10.6)	29.2 (6.6)	253 (16.5)	29.45 (7.5)	245 (19.1)
4	Duplex	21.49	264	22.4 (4.2)	249 (5.7)	21.92 (2)	251 (4.9)	24.66 (14.8)	234 (11.4)	27.08 (26)	230 (12.9)
5	Alwal	18.56	279	19.63 (5.8)	256 (8.2)	19.45 (4.8)	255 (8.6)	20.16 (8.6)	226 (19)	20.87 (12.4)	219 (21.5)
6	RG	22.12	296	22.76 (2.9)	280 (5.4)	22.48 (1.6)	280 (5.4)	23.13 (4.6)	267 (9.8)	23.9 (8.0)	261 (11.8)
7	Rock town	23.27	325	23.82 (2.4)	321 (1.2)	23.98 (3.1)	317 (2.5)	24.54 (5.5)	312 (4.0)	24.65 (5.9)	310 (4.6)
8	Kiran Arcade	21.8	250	22.5 (3.2)	247 (1.2)	22.05 (1.1)	244 (2.4)	22.76 (4.4)	241 (3.6)	22.87 (4.9)	238 (4.8)
9	Mahendra	24.54	309	25.21 (2.7)	302 (2.3)	25.06 (2.1)	298 (3.6)	25.73 (4.8)	289 (6.5)	27.07 (10.3)	285 (7.8)
10	Nirmal	23.5	280	24.1 (2.6)	270 (3.6)	23.94 (1.9)	266 (5.0)	24.55 (4.5)	254 (9.3)	25.19 (7.2)	248 (11.4)

EBE: embodied energy; OPE: operating energy.

Table 9
Energy data of Mahendra house with on site power generation (values shown in the brackets are % change in energy over case A) for Ahmedabad location.

Case study	EBE	OPE	LCE
Case A	24.5	309.5	334
Case E	27.07 (10.3)	284.7 (7.9)	312 (6.6)
Case E + 1 WT + 80 PV	63.54 (159)	77.2 (75)	140.7 (58)
Case E + 1 WT + 120 PV	66.1 (169)	48.5 (84)	114.6 (66)
Case E + 1 WT + 160 PV	68.67 (180)	19.9 (94)	86 (74)
Case E + 1 WT + 200 PV	71.24 (190)	0 (100)	71.2 (77)

generation with PV panels and wind turbine integrated with building are examined. For this study, energy efficient house – Mahendra is selected. Total or part of the electrical energy required for the operation of house is met from renewable energy sources. The selected building is studied with power generating equipment: PV panels and wind turbine. Table 9 shows embodied energy, operating and life cycle energy of the building with different number of PV units in combination with 22.5 kW wind turbine. With increase in PV units OPE and LCE of the building is decreasing and EBE of the building is increasing. For net zero energy, Fig. 3 shows energy demand (OPE) and electrical energy generated from 200 PV panels in combination with wind turbine. Part of the OPE of the building (Fig. 3) has to be met from the grid supply in the months of March, July, August and September. Excess power generated in the months April to June, October and December can be fed back to the grid. Total energy drawn from the grid is matching with total energy fed to the grid and thus building is made to demand net zero operating energy. LCE of the net zero energy building is evaluated to be 71.24 kWh/m^2 year.

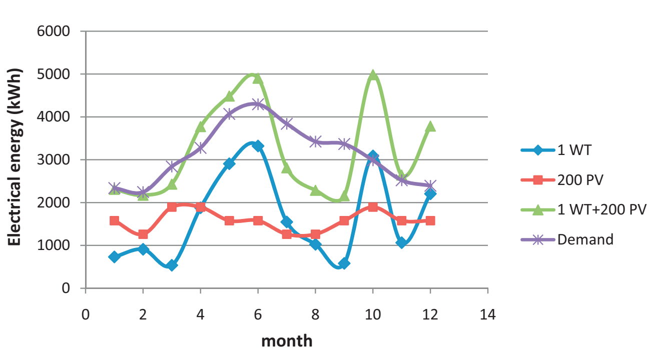

Fig. 3. On-site power generation and Electrical energy demand of the building (Mahendra) for net zero operating energy case (Ahmedabad location).

4. Conclusions

The paper presents life cycle energy demand of the one, two and multi storey (apartments) residential houses for two different climatic conditions of India (hot and dry, and mild composite). LCE of the buildings is varying from 240 to 380 kWh/m^2 year depending on the type (geometry) of the building and climatic conditions. LCE of the buildings in Indian context is falling at higher end in the range of LCE of the cold countries (150–400 kWh/m^2 per year) [24]. This is due to the use of electricity for cooling derived from fossil fuels (coal) in operation phase and use of energy intensive materials like steel, concrete and fired clay bricks in the construction phase. With insulation on wall and roof along with double pane glass for windows, reduction in LCE of the buildings is about 5–30%. It is possible to make buildings demand net zero operating energy by on site power generation from PV and wind turbine. LCE of a building with net zero operating energy is evaluated to be 71.24 kWh/m^2 year. The results of the present study are useful for building designers involved in design and construction of the energy efficient buildings from life cycle perspective. Some other cooling techniques like free cooling, evaporative cooling, solar air conditioning, etc., may be tested to bring down LCE of the buildings. Use of energy efficient cooling/heating equipment and appliances would also reduce LCE of the buildings considerably.

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Appendix A.

Generally residential air conditioning equipment meets the load at off-design conditions by cycling on and off. Three performance curves (curve objects) for cooling capacity and efficiency are used to determine system operation at off-design conditions [23,28,29]. They are:

(1) Cooling capacity function of temperature curve
(2) Energy input ratio function of temperature curve
(3) Part load fraction correlation

(1) The cooling capacity function of temperature (CCFT) curve is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil. The output of this curve is multiplied by the rated cooling capacity to give the cooling capacity at the specific entering air temperatures at which the direct expansion (DX) coil unit is operating (i.e., at temperatures different from the rating point temperatures).

$$\begin{aligned} \mathrm{CCFT} = {} & 1.1839345 - 0.0081087T_w + 0.00021104(T_w)^2 \\ & -0.0061425T_c + 0.00000162(T_c)^2 - 0.000003(T_w)(T_c) \end{aligned} \quad \text{(A.1)}$$

where T_w is the wet-bulb temperature of the air entering the cooling coil (°C) and T_c is the dry-bulb temperature of the air entering an air-cooled condenser (°C).

(2) The energy input ratio function of temperature (EIRFT) curve is a biquadratic curve with two independent variables: wet-bulb temperature of the air entering the cooling coil, and dry-bulb temperature of the air entering the air-cooled condenser coil. The output of this curve is multiplied by the rated EIR (inverse of the rated COP) to give the EIR at the specific entering air temperatures at which the DX coil unit is operating (i.e., at temperatures different from the rating point temperatures).

$$\begin{aligned} \mathrm{EIRFT} = {} & -0.6550461 + 0.03889096T_w - 0.0001925(T_w)^2 \\ & +0.00130464T_c + 0.00013517(T_c)^2 \\ & -0.00022470(T_w)(T_c) \end{aligned} \quad \text{(A.2)}$$

where T_w is the wet-bulb temperature of the air entering the cooling coil (°C) and T_c is the dry-bulb temperature of the air entering an air-cooled condenser (°C).

(3) The part load fraction correlation (function of part load ratio, PLR) is a quadratic curve with the independent variable being part load ratio (sensible cooling load/sensible cooling capacity). The output of this curve is used in combination with the rated EIR and EIR modifier curves to give the "effective" EIR for a given simulation time step. The part load fraction (PLF) correlation accounts for efficiency losses due to compressor cycling.

$$\mathrm{PLF} = 0.088065 + 1.137742(\mathrm{PLR}) - 0.225806(\mathrm{PLR})^2 \quad \text{(A.3)}$$

PLR is the part load ratio = (sensible cooling load/sensible cooling capacity).

The electrical power consumed by the DX unit (window air conditioners) for any simulation time step is calculated using the following equation:

$$\text{Electrical power for cooling} = \frac{\text{cooling capacity}_{\text{rated}} \times \mathrm{CCFT} \times \mathrm{EIRFT} \times \mathrm{PLR}}{\mathrm{COP}_{\text{rated}} \times \mathrm{PLF}} \quad \text{(A.4)}$$

For electrical resistance heating constant COP of 0.9 is being used to calculate energy consumption required to meet heating demand. The electric power for heating is calculated from the heating load divided by the COP.

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