Residential buildings in India: Energy use projections and savings potentials

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Abstract
As the electric energy consumption from residential buildings is predicted to rise by more than eight times by 2050, it is of vital importance for India to develop energy-efficiency strategies focused on the residential sector to limit the current trend of escalating energy demand. This study investigates impeded growth in energy consumption in the Indian residential buildings and documents energy saving potentials that can be achieved with the focused policy and market efforts. The study specifically focuses on assessing the role of building envelopes in relation to comfort air conditioning systems and appliances in order to ensure energy efficient dwellings for urban and rural residential sectors.

The study conducted a survey of 800 households, in four-climate zones of India, to map current equipment penetration rate and electricity consumption patterns. Key information including residential unit area, monthly energy consumption, connected load, number of appliances & their power rating, as well as operational patterns, has been gathered in a survey. Building energy modelling (using EnergyPlus) was then deployed to quantify comfort benefits and energy savings potentials of better performing building envelopes.

The trends observed during survey and building energy modelling analysis, along with the information from past studies, have been used to derive residential electric energy projections till 2050. The projections in the study have been segregated by three end use segments (air conditioning, envelope, and equipment) for urban and rural residential sectors. Projection scenarios show that the electricity consumption will rise by more than eight times under the business-as-usual scenario. With the focused policy and market efforts, the electricity rise in residential sectors can be restricted to five times, four times, and three times that of current energy use under modest, aggressive, and very aggressive scenarios.

Context
India's domestic electricity consumption has increased from 80 TWh in 2000 to 186 TWh in 2012, and constitutes 22 % of total current electrical consumption (Central Electricity Authority, 2013).

An increase of 400 % in the aggregate floor area of buildings and 20 billion m^2 of new building floor area is expected by 2030 (Satish Kumar, USAID ECO – III Project, 2011). Furthermore, due to the constant increase of Indian GDP, consumer purchasing power is predicted to grow leading to greater use of domestic appliances. Consequently, household electrical demand is expected to rise sharply in the coming decade. This growth of residential floor space, combined with expectations of improved domestic comfort, will require an increase in electricity production.

Hence, it is of vital importance for India to develop energy-efficiency strategies focused on the residential sector to limit the current trend of unsustainable escalating energy demand. This study investigates methods of restraining growth in energy consumption in the Indian residential sector and documents energy saving potentials that can be achieved with focused policy and market efforts.

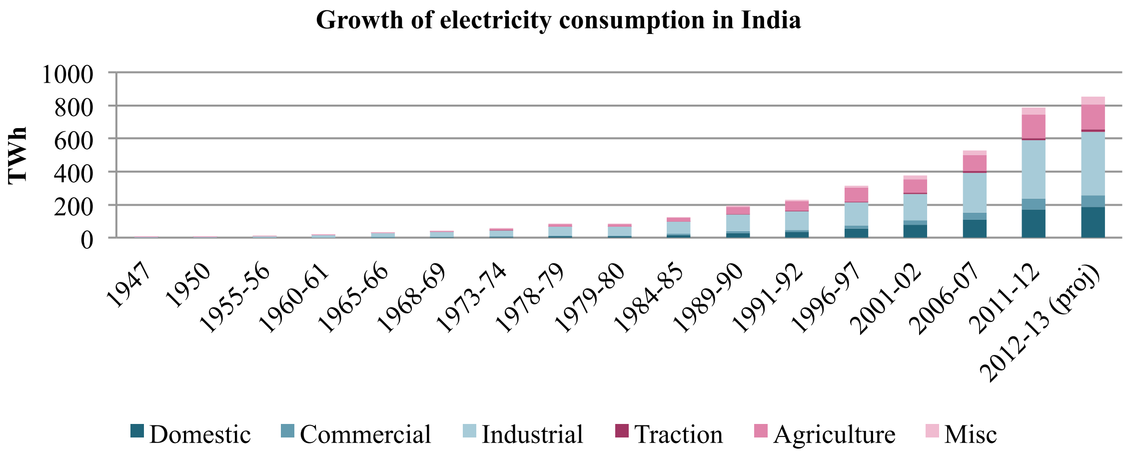


Figure 1. Growth of electricity consumption in India (Planning commission, 2011).

Objectives

An overall scenario assessment of the residential sector has been undertaken to gain a better appreciation of the long-term mitigation potential of this sector. The study specifically focuses on assessing the role of the building envelope in relation to comfort air conditioning systems and appliances in achieving energy efficiency in dwellings. This study answers the following six sub-objectives:

1. To bridge the current gap between building performance and modelling data.
2. To provide quantitative information on residential building energy use.
3. To determine the severity of growth rates in energy consumption in this sector and identify the savings potentials.
4. To assess the needs and benefits of policy interventions in the residential sector.
5. To recommend future actions to target and harvest saving potentials.
6. To provide a reference point with measured data to increase robustness of future impact studies.

Methodology

As shown in Figure 2, the starting point of the survey was field data collection from four cities representing distinct climate zones in India. Analysis of the survey data helped in comprehending the various factors involved in energy consumption in the Indian residential sector. Findings from the survey and a review of standard floor plans in India helped to develop and calibrate the building energy models for Indian residences.

SURVEY METHODOLOGY

The Literature Review has indicated the need to collect good quality data in order to better understand residential energy consumption patterns and appliance penetrations. The objective of the survey design was to gather residential energy consumption data to complement nationally available statistics.

Scope of the survey

The total sample size was 800, divided equally between the four cities – each representing a different climate zone. The fifth climate zone of India, cold, has not been included in the sample due to its smaller area and lower urbanisation rates, together with a lower level of construction activity in comparison with the other climate zones (J. Chadchan, 2012). Approximately 30 surveys in each city were conducted with more detailed questionnaires and plans, which attempted to map the characteristics of home appliance use. These detailed questionnaires provided opportunity to better understand the usage of home appliances and air conditioning systems in residences.

Based on the literature review and past studies, the following elements have been identified as key variables:

- Residential floor area – It is important to correlate floor area with annual and seasonal energy consumption. Definitions of floor area can vary and this can lead to data interpretation errors. In this study, the survey team has been instructed to gather gross floor area inclusive of enclosed balcony areas. Surveyors gathered this information based on inputs from residence owners.
- Dwelling type and number of floors – The focus of the study was energy consumption in single-family attached/detached homes and multi-family apartment complexes. Surveyors gathered this information based on site observation.
- Number and location of air conditioning systems – The location of air conditioning systems is an important variable in understanding the service level of the home. Typically, residences in India operate in mixed mode, operating air conditioning only when the home is uncomfortable. Primary bedrooms are the preferred location for installing air conditioning systems. Occupants expecting higher comfort and living standards also install air conditioning systems in living and dining rooms. Surveyors gathered this information through site observation.
- Number of bedrooms – The number of bedrooms is an important variable in correlating energy consumption and is related to the number of occupants. Surveyors gathered this information through site observation.

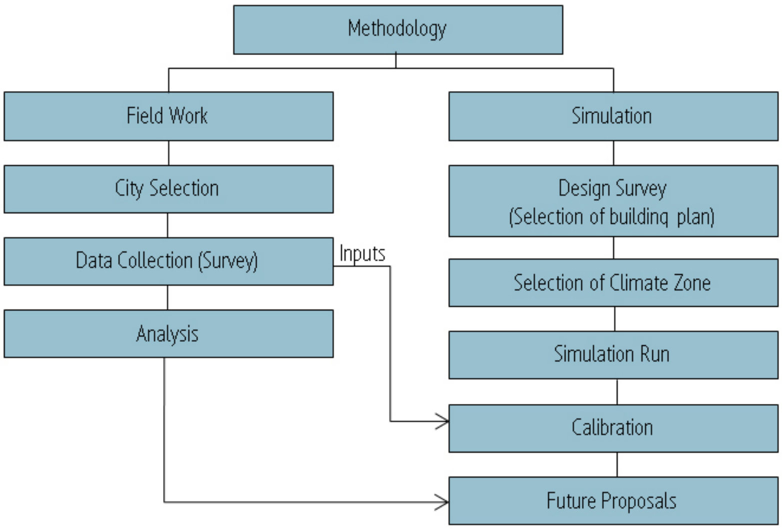


Figure 2. Process showing the methodology of the study.

- Number of occupants and age groups – The number of occupants and their age groups is another important variable and this information has been gathered using occupant interview.
- Number of appliances, their power usage and operational patterns – One of the key objectives of the survey was to collect information on appliance penetration. This has been gathered during site visits. Due to the inaccessibility of some appliances and the intrusion on privacy of checking the power ratings of each appliance, sometimes requiring displacement or removal of the appliance, appliance power ratings have been collected in only a fraction of the homes.
- Year of construction –The age of the construction can influence the energy consumption of the building and has been gathered from occupant interview or through background research on the construction.
- Energy consumption (monthly or bi-monthly) – Monthly and bi-monthly energy consumption for the past year has been gathered from utility bills to assess seasonal variations in energy consumption.
- Connected load – Connected load is another important variable gathered during the survey to assess whether energy consumption correlates well with the planned maximum load.
- Floor plan layout, including air-conditioned and unconditioned areas –This information, to analyse the impact of layout as well as to determine the proportions of air-conditioned and unconditioned areas, either required measurement on-site or floor plans, demanding a greater level of involvement by occupants during data collection. Hence, plans of the residential buildings have been collected for only a fraction of the homes.

While the income level of the residence has been identified as an important variable, discussions with several residents indicated a reluctance to share this personal information with the surveyors. Therefore, the location of air conditioners, numbers of bedrooms and air conditioners and the area of the home have been used as an indication of income levels.

City selection
The variation in climate, in terms of temperature and relative humidity, leads to varying degrees of comfort and, therefore, energy consumption. Four representative cities based in different climate zones were selected for the survey:

- Ahmedabad, city, representing a hot and dry climate zone (Bureau of Energy Efficiency, 2011).
- Pune, city, representing a temperate climate zone (Udyayar R, 2013).
- Mumbai, city, representing a warm and humid climate zone (Bureau of Energy Efficiency, 2011).
- Delhi, city, representing a composite climate zone (Bureau of Energy Efficiency, 2011).

Sample size
Around 200 houses (dwelling units) were surveyed per city, giving a total of 785 collected during the field survey.

Survey results & analysis
The floor area and occupancy distribution is presented in Figures 3 and 4. As can be seen in Figure 4, 80 % of sampled households have 3–6 occupants living in the residence. Similarly, about 78 % of sample households have a floor area between 50–150 m^2. This distribution of household area and occupancy is in line with the studies reviewed in the literature review section.

Appliance details
Table 2 provides the average number of different appliances used in the four cities. An average household will have approximately 8.0 tube lights, 8.8 CFL/Bulb, and 1.6 air conditioning units. At the city level, Delhi has the highest average with 15 tube lights and Ahmedabad and Mumbai the lowest

Table 1 provides average values for the four cities.

	Average		Average
No. of Occupants	4.0	Floor Area	106 sq.m
Connected Load	4.8 kW	Energy Consumption (annual)	3,755 kWh

Average data collected for four cities.

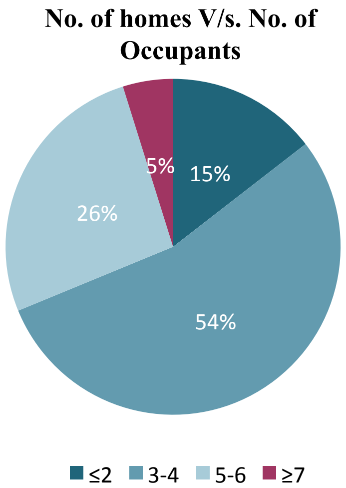


Figure 3. No. of homes vs. no. of occupants.

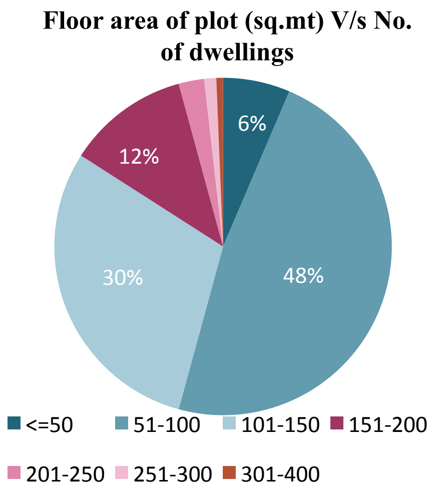


Figure 4. Floor area of plot vs. no. of dwellings.

Table 2. Appliances average for four cities.

Appliance type	Average	Appliance type	Average	Appliance type	Average
Tube lights	8.0	Refrigerator	1.0	Electric Kettle	0.1
CFL/Bulbs	8.8	Water Pump	0.3	Fans	3.3
Television	1.6	Microwave Oven	0.8	Grinder	0.5
Washing Machine	0.9	Toaster	0.5	Laptop	1.2
Geyser	1.5	Air Conditions (Compressor)	1.6	Air Cooler (Evaporative)	0.1

average with 5.8. For CFL/bulb, again Delhi has the highest average with 12.6 and Mumbai the lowest with 5.8. Delhi also has the highest AC average at 2.4, and Ahmedabad has the lowest at 1.6. The average fan count is 3.3, whereas the air cooler national average is 1.96.

Energy consumption

Figure 5 demonstrates the distribution of annual energy consumption among the varying range of floor areas, with different AC units, and belonging to different climate zones. The charts below show that the energy consumption in the majority of units lies below 5,000 kWh, and also that Delhi has the highest energy consumption. This is to be expected due to the composite climate; where both heating and cooling are required to keep space comfortable, as well as higher income levels in the capital city. Average household consumption is higher than in the past studies (Swiss Agency for Development and Cooperation, 2011), (Bhatt, Rajkumar, Jothibasu, Sudirkumar, Pandian, & Nair, 2005). It is noted that the surveyed households represent the increased energy consumption scenario and can provide basis or projecting future energy use.

Energy Performance Index (EPI)

The EPI values for different numbers of bedrooms with different numbers of AC units are shown in the table below. This demonstrates that a 1 bedroom hall kitchen apartment (BHK) unit will have a higher EPI, due to intensification in the use of appliances. Also, residential units with a higher number of AC units have a higher EPI. The increased use of air conditioners has steadily increased the energy consumption of households.

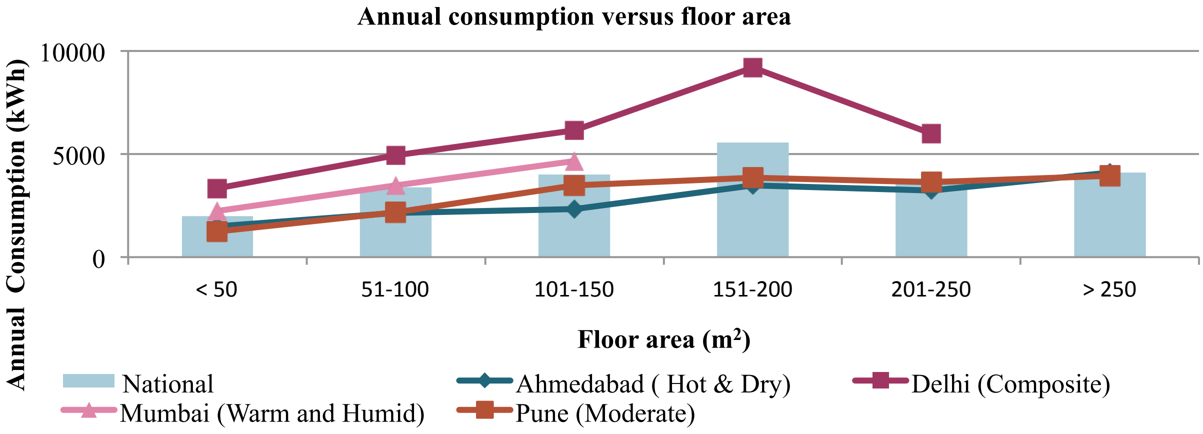


Figure 5. Annual energy consumption vs. floor area (City wise).

Table 3. EPI for different unit size and no. of AC.

EPI (kWh/m^2)	Number of AC							
Bedroom	0	1	2	3	4	5	6	Average
1	38	50	74					46
2	21	33	52	68	46			40
3	14	22	36	45	40	44	*	35
4	13	14	31	55	52	51	42	42

However, once the number of air conditioners reaches more than three, energy consumption stabilises or reduces, indicating that usage patterns vary significantly for homes with more than three air conditioning systems.

Only one sample was encountered which had three bedrooms with six air conditioning units installed, leading to a very high EPI. This data point has been flagged as an outlier and has been indicated with an asterisk (*) in Table 3.

BUILDING ENERGY MODELLING METHODOLOGY

Building energy modelling was performed in EnergyPlus, taking into account building geometry, outdoor weather conditions, the thermal characteristics of the building envelope, construction methods and the materials used, building operational modes and appliance usage. The survey data provided input for the building energy modelling calibration. The following methodology was adopted for the building energy modelling run:

Building plans

A residential building design survey was conducted in order to develop building plans. A range of plans from different cities was collected and their designs considered. Approximately 57 building designs across the country were analysed during the design survey. Based on survey, two standard building plans were selected for each of four types of residential buildings: 1BHK, 2BHK, 3BHK and tenement, for four different climate zones, with differing construction styles, organisation, ventilation and equipment use.

A 1BHK flat would have either a living area or bedroom to one side or diagonally opposite each other, with other facilities occupying the spaces left vacant. Similarly, a 2BHK flat would have either bedrooms to one side or at diagonals, with living area, kitchen and toilet occupying the remaining spaces and a 3BHK would have three bedrooms around the living area with kitchen and toilets. This is (Planning Commission, 2011) shown in the following plans.

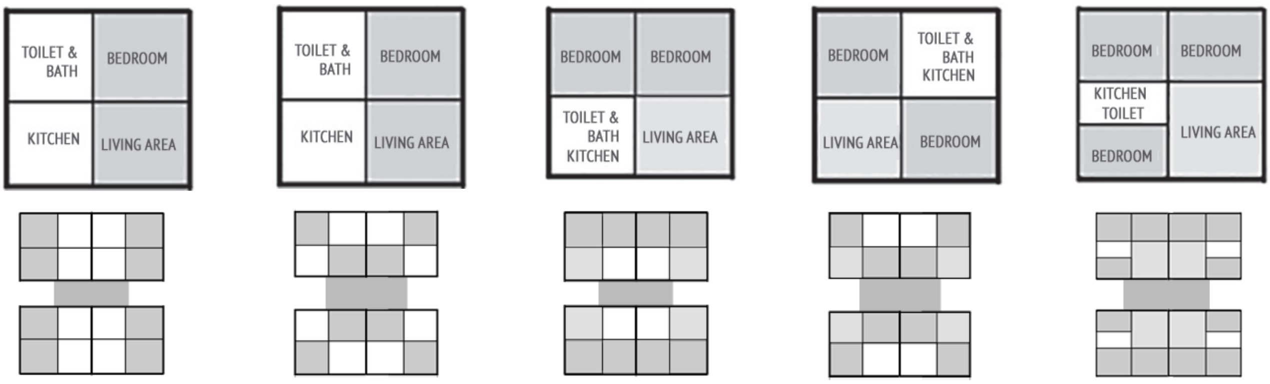
Construction materials, construction methods and their thermal characteristics

To assess the energy efficiency benefits of different envelopes, three types of building envelope have been considered: the Business As Usual (BAU) envelope, the Energy Conservation Building Code (ECBC) equivalent envelope and the ECBC+ envelope, characterised by more exacting requirements than ECBC. In using the ECBC+, construction was selected with regard to economic considerations (Rawal, Vaidya, Ghatt, & Ward, 2012). The selected envelope properties for each are shown in Table 4.

A more efficient envelope also reduces air infiltration to the building and requires increased mechanical ventilation to maintain air quality. Hence, the sum of infiltration and mechanical ventilation has been maintained at 1 Air Change per Hour (ACH) for all three envelopes.

Operation mode

Based on the survey and discussions with residents, the building has been modelled as a temporal mixed mode building. Temporal mixed mode buildings operate with natural venti-



Case 1: 1BHK (type1) Case 2: 1BHK (type2) Case 3: 2BHK (type1) Case 4: 2BHK (type2) Case 5: 3BHK

Figure 6. Indian residential building plan general layout.

Table 4. Building envelope properties. Source: CEPT-TWG Study on tiered approach for ECBC enforcement.

	BAU Envelope Properties	ECBC Envelope Properties	ECBC+ Envelope Properties
Wall	230 mm brick wall U-Value – 1.722 W/m^2-K	Insulated 230 mm brick wall U-Value – 0.44 W/m^2-K	Insulated 230 mm brick wall U-Value – 0.35 W/m^2-K
Roof	150 mm concrete roof U-Value – 2.942 W/m^2-K	Insulated 150 mm concrete roof U-Value – 0.409 W/m^2-K	Insulated 150 mm concrete roof U-Value – 0.409 W/m^2-K
Window	U-Value – 5.8 W/m^2-K SHGC – 0.82 VLT – 0.8	U-Value – 3.3 W/m^2-K SHGC – 0.25 VLT – 0.2	U-Value – 3.3 W/m^2-K SHGC – 0.20 VLT – 0.16
Floor	U-Value – 2.942 W/m^2-K	U-Value – 0.248 W/m^2-K	U-Value – 0.248 W/m^2-K

lation when comfortable and use air conditioning only when the building becomes uncomfortable. Similarly, the survey data indicates that air conditioners are primarily located in bedrooms. Thus, only the bedrooms have been modelled with air conditioning, while the other spaces are modelled as naturally ventilated.

Occupant behaviour, in terms of running fans and opening windows, has been modelled from an extensive study of occupant thermal comfort (Manu, Shukla, Rawal, De Dear, & Thomas). This study also indicated that Indian occupants are more adaptive compared to Fanger's PMV models. Therefore, the adaptive thermal comfort model (ASHRAE, 2010) has been used to determine the occupant's thermal comfort in the building.

Each building design was simulated in three operational modes: naturally ventilated mode, mixed mode with hybrid AC operation and mixed mode with scheduled AC operation. In the fully naturally ventilated operational mode, it was assumed that the internal doors between the rooms were always open and that opening of the external windows and operation of ceiling fans would be determined by indoor and outdoor temperatures (Manu, Shukla, Rawal, De Dear, & Thomas). Each room inside a residence was considered as a separate thermal zone.

To model users who adopt based on outdoor conditions, windows are opened if the zone temperature is higher than the outdoor air temperature and if the zone temperature is higher than the air conditioner's set point, thus all of the thermal zone's operable windows will open only if both conditions are satisfied, Table 5 – Tzone > Tout and Tzone > Tset.

HVAC controls

Based on discussions with residents on operational patterns and detailed surveys questionnaires, the air conditioning unit usage months have been limited to 3–7 months, depending upon the climate. The heating period has also been adjusted to a timeframe of 2 months (only in the composite climate). The seasonal load and base load analysis provided the necessary information to determine the air conditioning operation of temporal mixed mode buildings. Further based on the inputs, two types of HVAC control strategies have been designed in simulation.

Mixed mode (Hybrid) – AC is available to run from 22:00 hours to 06:00 hours (overnight) in the bedroom. The air conditioners are turned on when opening the window is not sufficient to maintain the indoor set point. For the remainder of the time, bedrooms are operated in the naturally ventilated mode. Other spaces in the residence are operated in naturally

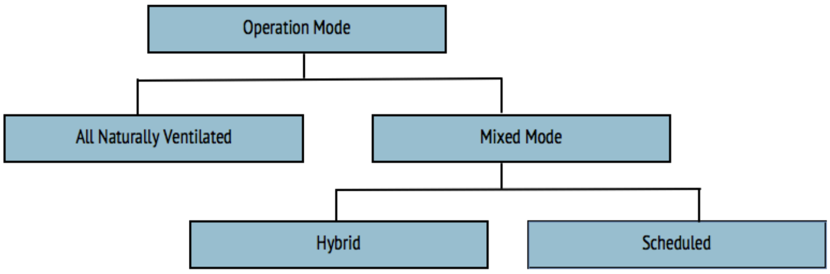


Figure 7. Building operation mode type.

Table 5. Explanation of Tzone.

Tzone	Air Temperature inside the zone
Tout	Outdoor Air Temperature
Tset	Temperature set-point (Taken 2 °C less than the comfort temperature based on the adaptive model).

Table 6. Occupants and appliances, building thermal heat gain.

People	2 persons in 1BHK, 4 persons in 2BHK and 5 persons in 3BHK
Appliances	1,120 W in 1&2BHK, 1,220 W in 3BHK

ventilated mode throughout the day. The space set points are calculated based on the ASHRAE 55-2010 adaptive thermal comfort model.

Mixed Mode (Scheduled) – AC runs continuously in the bedrooms from 22:00 hours to 06:00 hours (overnight) to maintain space set points, and the windows are kept closed throughout the period. This is considered realistic as the survey revealed that few residents keep windows open at night due to outdoor noise, safety and air pollution.

The AC set-point temperature is set according to the adaptive model (ASHRAE, 2010) and the ventilation control temperature is 2 °C below the AC set-point temperature.

Internal heat gain

The occupants and appliances add to the building's internal heat gain. Appliance heat gains were calculated based on survey data. The input details for the internal heat gain are as follows in Table 6.

Building energy modelling run chart

Building energy models have been carried out for four cities (Ahmedabad (hot and dry), Bangalore (moderate), Mumbai (warm and humid), and Delhi (composite)), which represent four major climate zones of India.

Each of the envelope and equipment efficiency cases was then simulated twice, once with no appliances and once with the use of appliances. This was done to understand the variation in energy consumption (appliances and AC) due to the appliances' loads. Figure 8 shows the building energy modelling run chart for the study.

Building energy modelling analysis

The Figure 9 demonstrates that, in hot and dry, warm and humid, and composite climates, ECBC and ECBC+ envelopes can reduce air conditioning energy consumption by 40 % and 66 % respectively without taking into consideration potential efficiency improvements of appliances. As expected, in moderate climates, the impact of ECBC and ECBC+ envelopes can eliminate the need for air conditioning and provide 30 % overall savings.

As seen in the figure, the energy consumption of both HVAC control strategies generated near identical results indicating little benefit (only 1 EPI difference) from mixed mode HVAC operation. This approach should be further explored with different set points and comfort levels to evaluate the benefits of mixed mode air conditioning operation.

Percentage of uncomfortable hours

Figure 10 shows the percentage of uncomfortable hours during occupied periods with BAU, ECBC and ECBC+ envelope characteristics (without air conditioning system in each climate zone annually and for winter and summer. These uncomfortable hours are calculated to demonstrate the efficient envelopes can significantly reduce uncomfortable hours and thus the need to operate air conditioning systems. The increase in uncomfortable hours for BAU has been stacked above the ECBC uncomfortable hours for easy visual comparison. The data has been averaged over 1BHK, 2BHK, and 3BHK apartments. The graph indicates that, using ECBC compliant construction, uncomfortable hours can be decreased by almost 40 % to 100 %.

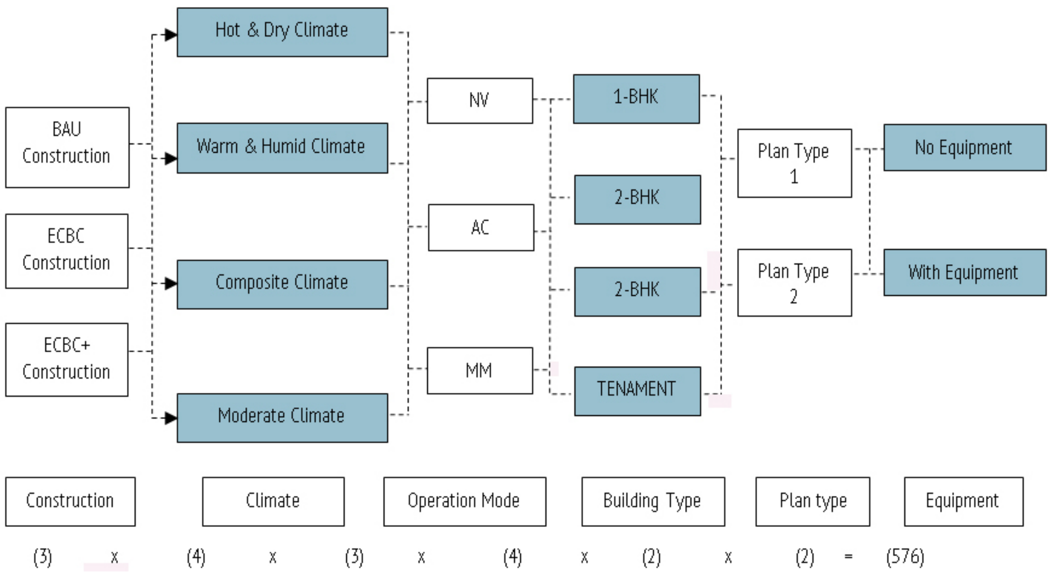


Figure 8. Building energy modelling run chart.

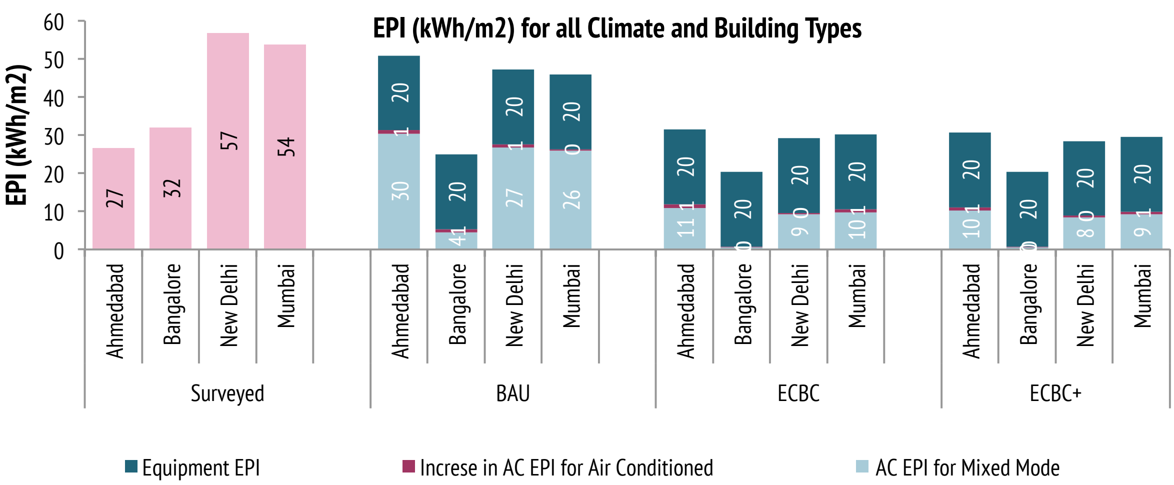


Figure 9. EPI (kWh/m²) for all climate and building types.

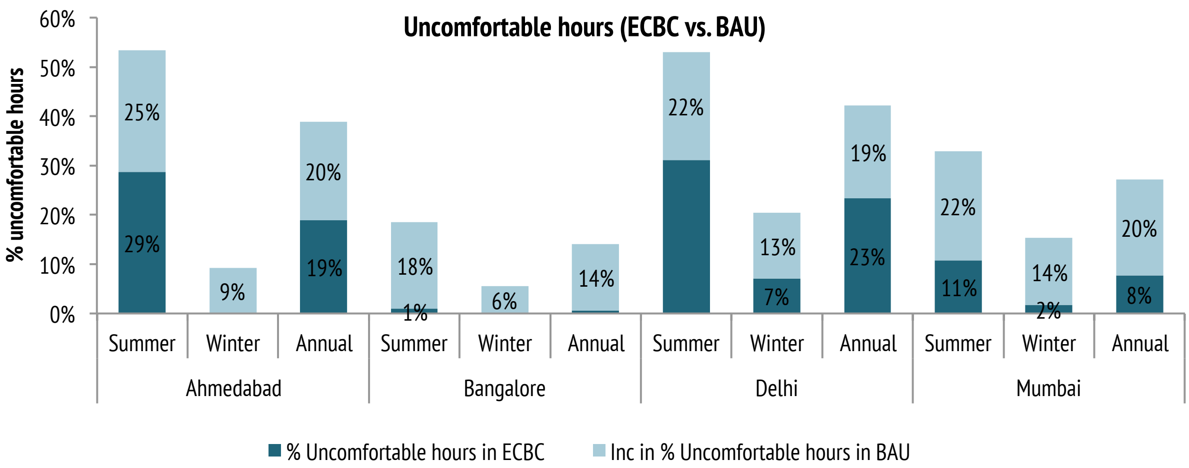


Figure 10. Uncomfortable hours (ECBC vs. BAU).

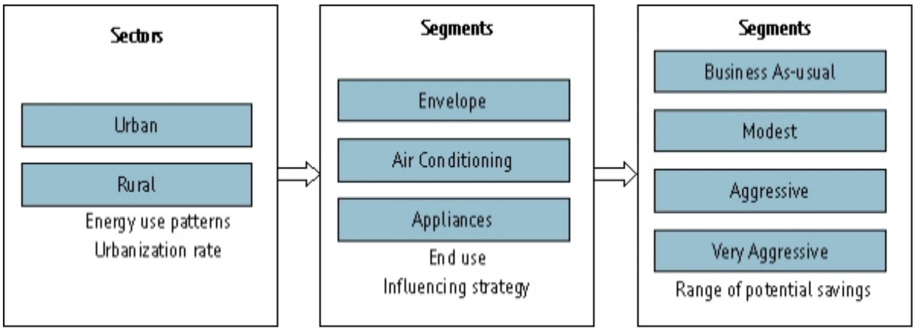


Figure 11. Developed scenario for future residential projections.

Table 7. Projection scenarios for various envelope efficiencies and AC and appliance efficiencies.

Projection scenario	Envelope efficiency	Air conditioning and appliance efficiency
Business-As-Usual	Business As-usual	Natural Rise
Moderate	ECBC, Low Penetration	Moderate Rise
Aggressive	ECBC, High Penetration ECBC+, Low Penetration	High Rise
Very Aggressive	ECBC +, High Penetration	Very High Rise

Scenarios for energy use projections

This section consists of the analysis of building energy modelling results and provides four projections for future residential energy use up to 2050.

PROJECTIONS' ASSUMPTIONS

The trends observed in the field and building energy modelling analysis, together with information from past studies, have been used to derive residential energy projections until 2050. These projections have been developed to estimate the increase in electricity consumption in the residential sector, and do not include other fuel sources. Figure 11 outlines scenarios developed for future residential projections.

As established in earlier studies, urban and rural households in India have different energy consumption patterns and, therefore, independent projections have been developed for each sector. This distinction is also important due to rapid rates of urbanisation and differing income levels in rural and urban areas. In addition, the residential retrofit market in building envelopes in India is difficult to determine and, therefore, zero uptake has been assumed in the projection analysis.

The projections have been further differentiated by three end use components: air conditioning, envelopes, and appliances. As shown in the above sections, efficient envelopes can significantly reduce air conditioning energy use in households and thus have been entered as a separate section in the projections. The appliances component comprises of lighting, ceiling fans, refrigerators, televisions and other miscellaneous electrical devices (including cooking equipment). The appliance projections and efficiency factors have been incorporated from literature review and national statistics (Satish Kumar, USAID ECO – III Project, 2011; Dhar, 2012; NSSO, 2010; Planning commission, 2011).

To further identify savings potentials in the residential sector, four projection scenarios have been developed for India – business-as-usual, moderate, aggressive, and very aggressive scenarios. The business-as-usual scenario represents the natural progression scenario of residential energy use with minimal or no external influence. This scenario is different from a frozen scenario since natural increases in appliance and construction efficiency have been incorporated into the projection.

BUSINESS-AS-USUAL SCENARIO

As seen in Figure 12, electricity consumption is projected to rise by more than eight times under the business-as-usual scenario. This rise is driven primarily by three factors – increase in population, greater availability of electricity for residents and higher electricity use for comfort and appliances. Currently, urban and rural equipment plays a major role in domestic energy consumption and this is expected to continue to increase.

MODERATE SCENARIO

The moderate scenario reflects the achievable electricity savings as a result of current policy and market-driven strategies. As seen in Figure 13, the rise in electricity consumption can be curbed to a potential fivefold increase. This is a significant improvement on the business-as-usual scenario, showing that a 27 % reduction in energy use is achievable with modest efforts.

The moderate scenario demonstrates that the implementation of minimum international codes and standards, such as the Internal Energy Conservation Code (IECC) 2009, can reduce lighting and air conditioning energy use by 35 % and 19 % respectively. This scenario assumes a 5 % use of ECBC envelopes in the new building market by 2050 as a result of modest policy efforts which can lead to 7 % reduction in total electric consumption.

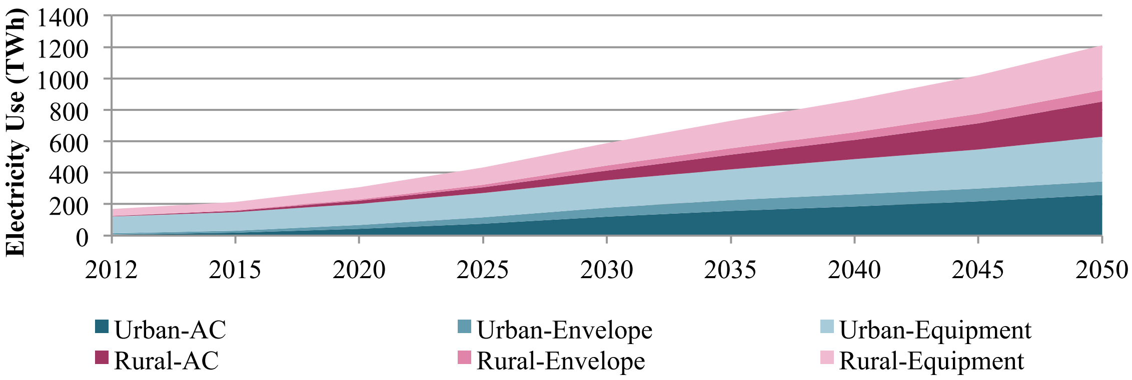


Figure 12. Electricity consumption projection in residential sector – BAU scenario.

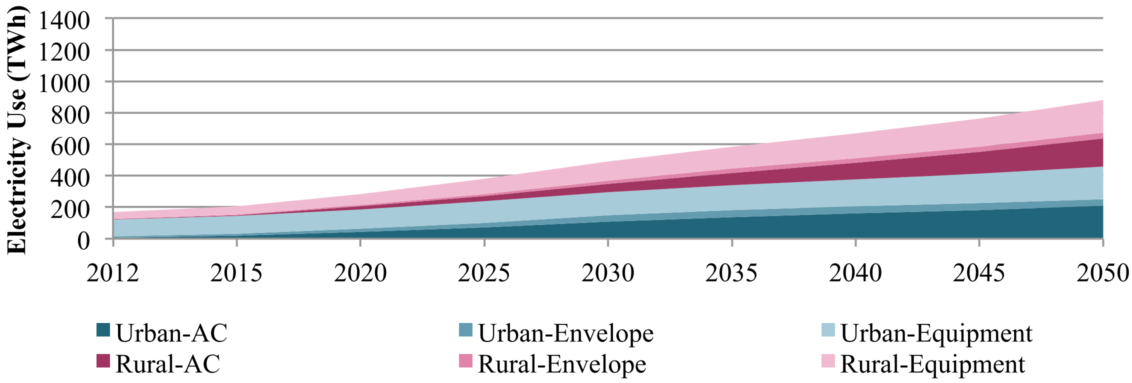


Figure 13. Electricity consumption projection in the residential sector – moderate scenario.

AGGRESSIVE SCENARIO

The aggressive scenario reflects electricity savings with an aggressive policy and market-driven approach. As seen in Figure 14, the rise in electricity consumption can be limited to four times that of current use. This scenario yields an additional 23 % of savings over the modest projection scenario and a 44 % energy use reduction compared to business-as-usual.

The aggressive scenario demonstrates that using high efficiency conventional air conditioners in new residential buildings can reduce energy use by 35 % compared to business-as-usual. Similarly, efficient lighting, ceiling fans, refrigerators, and televisions in new buildings can produce reductions of 50 %, 42 %, 45 % and 33 % respectively over the business-usual scenario. This scenario assumes penetrations of 50 % by ECBC and 10 % by ECBC+ envelopes in new buildings by 2050 which can provide 9 % reduction in total electrical energy consumption.

VERY AGGRESSIVE SCENARIO

The very aggressive scenario is intended to reflect electricity savings with very focused and aggressive policy and market-driven strategies. Under this scenario, as shown in Figure 15, the increase in electricity consumption can be restricted to three times the current residential use. This scenario yields 24 % of additional savings over the aggressive projection scenario and a 57 % energy use reduction compared to business-as-usual.

The very aggressive scenario demonstrates that using state-of-the-art, conventional air conditioners in residential buildings can reduce energy use by 52 % compared to business-as-usual. In this scenario, the use of advanced and highly efficient technology is assumed. Similarly, very efficient lighting, ceiling fans, refrigerators, and televisions in new buildings can produce reductions of 57 %, 56 %, 56 % and 45 % respectively, over business-as-usual. This scenario assumes a 30 % penetration of ECBC+ envelopes and a 40 % penetration of ECBC+ envelopes in new buildings by 2050 which can provide 12 % reduction in total electrical energy consumption.

COMPARISON OF SCENARIO PROJECTIONS

Figure 16 compares the four projection scenarios by end use. As shown, policy strategies can have a huge impact on future energy requirements. Very aggressive policy and market efforts can compensate for the impacts of population growth, higher comfort expectations and the increased use of electrical equipment, such as lighting, ceiling fans, refrigerators, televisions and other devices (including VCR, DVD players and mobile chargers).

While efficient air conditioners can reduce energy use by 60 %, overall air conditioning usage will continue to rise until 2050. The very aggressive scenario does not account for the development of new, non-conventional cooling technologies, which have the potential to influence future energy use dramatically.

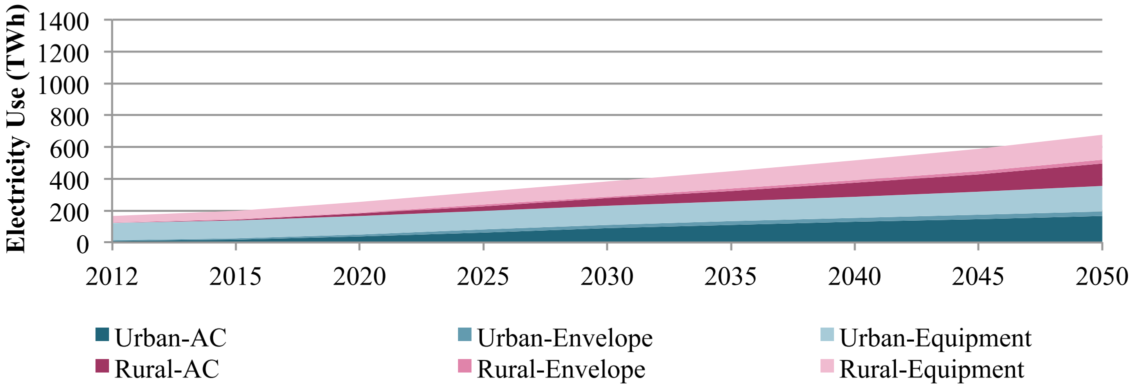


Figure 14. Electricity consumption projection in residential sector – aggressive scenario.

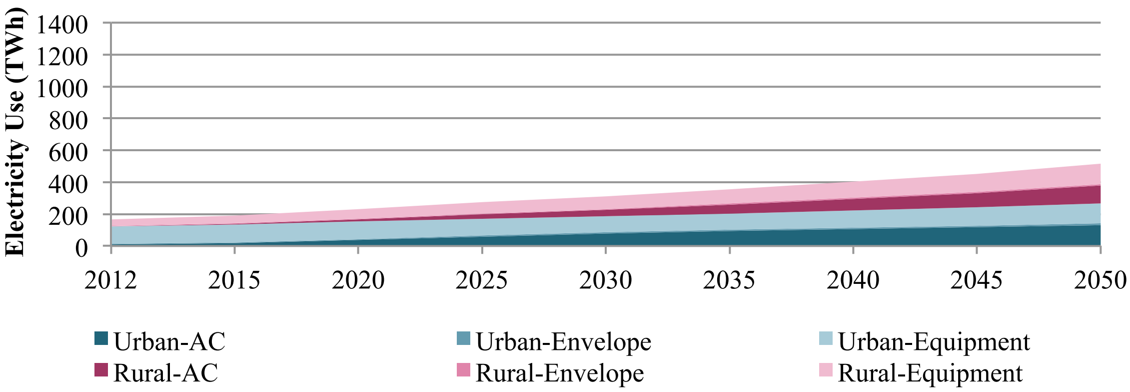


Figure 15. Electricity consumption projection in residential sector – very aggressive scenario.

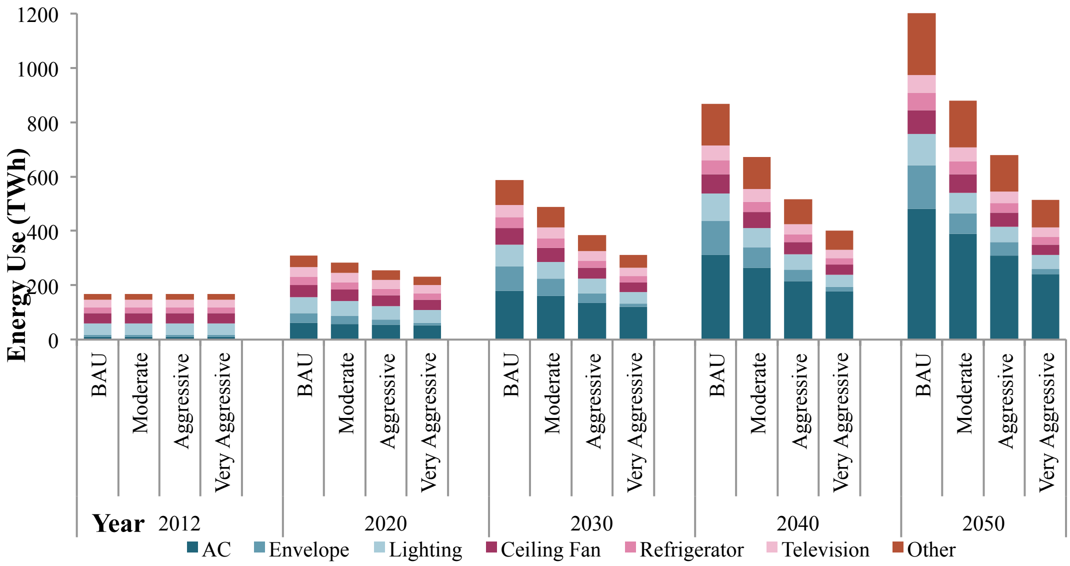


Figure 16. End use comparison of projection scenarios.

Conclusions and policy recommendations

MAIN FINDINGS FROM THE SURVEY

The survey established an essential baseline for estimations of savings potentials in four cities, each representative of a different Indian climate zone. Assessment of the survey data identified the following major trends in residential energy consumption patterns:

- Numbers of air conditioners, dwelling area and numbers of bedrooms are found to be the most significant correlated variables in annual energy consumption. While number of occupants is also an important variable, the correlation between number of bedrooms and number of occupants is strong.
- Levels of appliance penetration are similar for Mumbai and Delhi but vary significantly in Ahmedabad and Pune. Appliance penetration observed in the survey is higher than that recorded by national statistics for urban residences (NSSO, 2011). While this could be due to the small and focused sample size, this does indicate a trend of increasing appliance penetration rates.
- The increase in air conditioners is steadily increasing energy consumption in residences. However, once the number of air conditioners in a household reaches more than three, energy consumption stabilises or reduces. This indicates that usage patterns vary significantly for homes with more than three air conditioning systems. Discussions with experts indicate that additional air conditioning units are frequently not operated, which may be the reason for this. However, the factors influencing EPI stabilisation or reduction should be further investigated in future research.
- The survey results show that 45 % of 1BHK units do not have air conditioning units in contrast with only 18 % of 2BHK and 5 % of 3BHK units. Most households in the survey have air conditioners installed in bedrooms while a few residences also have air conditioners in living rooms. This suggests that dwellings with higher numbers of bedrooms and larger areas have higher comfort expectations.
- Energy consumption within the sample shows wide variations, even among households with equal numbers of air conditioning units and appliances, indicating that occupant behaviour has a significant impact on total energy consumption.
- The survey indicates that occupants prefer to run their residences in temporal mixed-mode operation, using the air conditioning system only when the space becomes uncomfortable. This provides immense opportunity for reducing uncomfortable hours through the use of efficient envelopes, thus lowering space cooling energy consumption.

MAIN OBSERVATIONS FROM THE ENERGY MODELLING ANALYSIS

Building energy modelling has been employed to identify the benefits of efficient envelope and air conditioning usage. The modelling and analysis results produce the following observations:

- Discussions with Indian residents and analysis of survey data provided important information for calibrating the simulation models with the survey data. Three main reasons were identified for the initial overestimation of electric energy use; the temporal mixed mode operation of bedrooms, air conditioning operation hours during the cooling season and the higher thermal adaptation of Indian residents.
- Building energy modelling demonstrated that 15–20 % reductions in uncomfortable hours (based on the adaptive thermal comfort model) could be achieved by increasing envelope efficiency in naturally ventilated buildings in various climate zones in India.
- For air-conditioned buildings, building energy modelling demonstrated that energy savings of 40 % can be achieved in hot and dry, warm and humid, and composite climates by increasing envelope efficiency.

MAIN OBSERVATIONS FROM THE PROJECTION ANALYSIS

The trends observed in the field and building energy modelling analysis, along with information from past studies, have been used to derive residential electric energy projections until 2050.

- Projection scenarios indicate that electricity consumption is predicted to increase by more than eight times under a business-as-usual scenario.
- Using focused policy and market strategies, relative energy savings of 27 %, 44 %, and 57 % can be achieved in modest, aggressive, and very aggressive scenarios, compared to business-as-usual.
- Under the business-as-usual scenario, the annual energy use per household is likely to increase from 650 kWh in 2012 to 2,750 kWh by 2050. With very aggressive policy efforts, increases in projected annual household energy consumption can be reduced to 1,170 kWh per household in 2050.

POLICY AND FUTURE STUDY RECOMMENDATIONS

This study provides a baseline for current residential energy consumption patterns in India and highlights the savings potentials that can be achieved by policy efforts. To achieve savings potentials in the residential sector, the following recommendations for action have been identified:

- The introduction of a specific code focussing on residential building envelope efficiency: as highlighted in the study, thermally efficient envelopes can reduce air conditioning energy use significantly in the air-conditioned building operation mode, as well as increasing comfort in naturally ventilated buildings. A residential code focused on envelope efficiency should be developed to realise the savings potentials of building envelopes and increase comfort.
- The introduction of a residential energy data baseline programme: while this study provides an important baseline for assessing residential energy consumption in four cities, a larger survey, with more detailed information, should be

undertaken to gain a better picture of residential energy consumption. A common database should be created, with built-in quality checks, standard formats and templates to enable the effective sharing of information from different surveys. Use of open and linked (well documented) data can help to spread information on energy consumption patterns in India.

- Currently, most floor space projections are at national level and, while this provides important information for general forecasting, more specific projections should be developed for major cities in India to better plan and design energy-efficiency strategies. With city and county level information factored in, better efficiency plans, appropriate to current urban plans and the purchasing power of communities, could be developed.
- Cost savings achieved from effective building envelopes could be used for investment in air-conditioning systems and the energy saved by envelopes could be used to extend the supply of energy. These benefits should be documented and guidelines developed for such an approach.
- This energy use monitoring should be undertaken in conjunction with monitoring of environment and operational modes. This essential, and currently unavailable, data will assist in developing accurate energy consumption estimates and will significantly reduce uncertainties in future projections. In addition, it will assist in more reliable simulations and predictions of building energy use. Detailed data will also help in assessing savings potentials if energy-efficiency as well as demand-side programmes are targeted at residences. This is required for the development of effective energy efficiency policies.

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