Meta-study of residential energy studies in India

Rajat Gupta1,*, Sanjoli Tuteja1, Jyotirmay Mathur2 and Vishal Garg3
1Low Carbon Building Research Group, Oxford Brookes University, Oxford, UK
2Centre for Energy and Environment, Malaviya National Institute of Technology, India
3Center for IT in Building Science, International Institute of Information Technology, India

*Email: rgupta@brookes.ac.uk

Abstract. Residential energy (electricity) use in India is expected to grow four-fold by 2030, yet there is paucity of data that is essential for developing energy policy or programme. This paper undertakes a meta-study of residential energy studies in India to characterise their scope, data collection methods and findings. An in-depth review of literature was undertaken using Google Scholar, Web of Science, Scopus and ScienceDirect to identify relevant journal publications, conference papers and reports. A series of expert workshops were held to identify any data gaps and stakeholders’ needs. The identified studies were characterised using a meta-data framework that included criteria such as climate, dwelling form, income group, methods and study duration. An online searchable platform (REACT) was created to make the identified studies more accessible using the meta-data criteria. Of the 29 studies identified, only 16 were published in peer-reviewed publications (10 in journals and 6 in conference proceedings). About 11 studies focussed on dwelling-level energy use, while the remaining used econometric data and statistical modelling at a macro-scale. To develop evidence based energy policies, it is vital to gather empirical data on residential energy in different climatic zones. Robust data sharing policies should be implemented to avoid duplication of effort.

1. Introduction

India’s aggregated primary energy demand is expected to grow by 2.3 times in the next two decades due to sustained economic growth in the building, transportation and industrial sectors, reaching energy consumption of 40 EJ [2]. Currently, the residential and commercial sectors account for 30% (22% residential and 8% commercial) of total electricity use, and consumption in these sectors is rising at 8% annually [3]. Due to growing demand for floor space, and to accommodate emerging service industries and urban migration, India expects a doubling of floor space by 2030 [4]. The increase in energy intensity per unit area of floor, combined with an increase in floor area, has placed heightened pressure on energy demand for buildings. Rising GDP and greater affordability of consumer goods has increased the purchasing power of Indian consumers, resulting in dramatic changes in patterns of energy consumption. Contemporary commercial and residential buildings contain many more electrical appliances as compared to the earlier practices [7].

Residential electricity consumption is expected to grow four-fold by 2030 due to an ever-increasing GDP, increase in the number of urban households, alongside a greater penetration of electrical appliances [1]. It is due to higher penetration of appliances and increased usage that has led to a higher Energy Performance Index (EPI) in buildings. However, although the use of energy-consuming appliances is increasing, energy consumption due to building envelope characteristics is expected to remain a significant element in total energy consumption. The building envelope which consists of external walls, fenestration and roofs plays a major role in making buildings comfortable, both thermally...
and visually. When a building does not meet comfort criteria, occupants rely on mechanical and electrical comfort and lighting systems. Reliance on energy driven systems can only be reduced when the building envelope responds favourably to the local climatic context.

In 2001, the Indian Government introduced the Energy Conservation Act. As an outcome of this act, as the first building energy efficiency related codes in India, the Energy Conservation Building Code (ECBC), which came into effect in 2007. Currently, ECBC applies to buildings that have a connected load greater than 100 kW or contract demand greater than 120 kVA [8]. In principle, the ECBC-2007 also applies to large residential complexes, when their connected load or contract demand exceeds the thresholds. In the next version of the code, ECBC-2017, it has slightly been redefined to exclude all buildings that are not intended to be used for private residential purposes. As single family and multi-family households are expected to show the highest growth rates between 2005 and 2050, the BEE has also initiated development of a separate code for residential buildings a draft version for which was released at the end of 2018. However, various studies have shown that there is paucity of data on residential energy use and indoor environmental conditions, which are essential for developing any residential energy policy or programme [5, 6].

This paper presents the methodology and results of a meta-study on residential energy studies in India to characterise their scope, data collection methods and findings. The study was conducted as part an Indo-UK research programme on residential building energy demand reduction in India (RESIDE) project. The four-year (2017-2021) research project aims to measure, model, map and manage energy demand reduction, temporally and spatially, in urban dwellings in India, in order to produce and share new data and knowledge, low-cost solutions and an accessible evidence base for supporting the development of a national residential energy code (www.reside-energy.org).

2. Methods
A detailed review of relevant literature was conducted to identify existing research. Also a series of expert workshops were held to understand the data needs of various stakeholders related to measuring residential energy in India.

2.1. Literature review
An in-depth review of literature was undertaken to evaluate the existing empirical evidence on residential energy, load profiling and thermal comfort studies in India, covering both published and grey literature. Literature was searched using Google Scholar, Web of Science, Scopus and Science Direct to identify relevant journal articles, conference proceedings and reports. To explore the breadth of these research areas, specific terms such as “residential” “energy consumption” and “thermal comfort” were used. This paper focuses on summarising the findings from studies on residential energy only. About 29 studies on residential energy were identified out of which 10 were published in refereed journals, 6 were published in conferences, and the remaining 13 were in the form of reports and books. The scope of the review was limited to studies focusing on residential energy use in the urban areas of India.

2.2. Stakeholder workshop
Three stakeholder engagement workshops were organised during year one of the project, with an aim to bring together relevant domain experts (academia, consultants) and residential energy data users (Government bodies, industry). The purpose of these events was to bring together relevant organisations to discuss the challenge of gathering data on residential energy use (and thermal comfort), identify what datasets and data gaps exist, and build consistency in gathering data on residential energy and/or thermal comfort studies in India. The events also enabled discussions on other aspects such as appropriate methodology for conducting large-scale residential energy survey. The three events were held at two different locations in India and attracted nearly 63 participants (Table 1) from 32 organisations covering the domains of policy-making, academia and industry (Figure 1).
Table 1: Overview of RESIDE stakeholder workshops.

| Sr. no. | Event                  | Location held | Date       | Total number of participants |
|--------|------------------------|---------------|------------|-----------------------------|
| 1      | Stakeholder workshop 1 | New Delhi     | 01-Nov-17  | 15                          |
| 2      | Stakeholder workshop 2 | New Delhi     | 04-Apr-18  | 24                          |
| 3      | Stakeholder workshop 3 | Hyderabad     | 03-Nov-18  | 24                          |

**Figure 1**: Participation of organisations from various sectors in RESIDE stakeholder workshops.

The discussions and feedback from experts from relevant domains helped to better understand their requirements, needs, types and uses of empirical data and how these can be met through RESIDE field studies.

3. Meta-study of residential energy studies

About 29 studies were identified through an extensive review of literature and these were classified under two broad categories using the data collection approach adopted (Table 2), as follows:

- Studies using secondary data (collected by other organisations)
- Studies based on primary data collection (new data gathered through field studies)

Table 2: Characterisation of residential energy studies.

| Study approach | Reference                                                                 |
|----------------|---------------------------------------------------------------------------|
| Studies using secondary data | (a) Chunekar and Sreenivas [5]; Khosla and Jhanda [6]; Filippini & Pachauri [9]; Rao & Reddy [10]; Pachauri and Jiang [11]; Ghosh and Kanjilal [12]; Chaturvedi et al. [2]; Bhattacharyya [14]; Parikh and Parikh [15]; (b) McNeil and Letschert [16]; (c) Letschert et al [17]; Boegle et al [18]; Dukkipati et al [19]; EIA 2014 [20]; Gupta [21]; Dubash et al. [22]; Niti Ayog 2016 [23]; (d) Wilhite [7]; |
| Studies based on primary data collection | (a) Murthy et al. [24]; (b) Shrinivasan et al. [26]; Jain et al. [27]; Batra et al. [28]; Kanagaraj et al. [29]; Sachar et al. [13]; (e) Rogers & Suphachasalai [25]; Chatterjee & Singh [30]; TERI [31]; Garg et al. [32]; Rawal & Shukla [33]; |

**Note**: (a) Journal article; (b) Conference paper; (c) Report; (d) Book

The studies based on secondary data generally used national data sets such as the NSSO and Census of India data providing information on households at the national, regional and/or state level. Some studies using secondary data included reviews of previous works in the field of residential energy studies in India, that focused on identifying the future of residential energy use and policy measures to optimise energy demand in India. On the other hand, studies based on primary data usually adopted a bottom-up approach gathering data at the household level. Such studies used engineering or statistical methods for data analysis. The engineering methods were deployed using representative models that are developed using high resolution data, and offered a high degree of flexibility and feasibility for modelling new technologies having no historical consumption data. However statistical methods used more low
resolution data for regression, conditional analysis and neural networking. These methods are helpful in developing correlations between end-uses and energy consumption.

A meta-data framework was developed to characterise the various studies, using key criteria such as climate, dwelling form (house, apartment), type (urban, rural vernacular), income group (low, medium, high), methodology adopted (survey, monitoring, modelling, secondary data), duration (annual, monthly) and unit of studies (dwelling, household, occupants) (Figure 2). These criteria also formed the basis of development of the online search repository.

Interestingly, only 11 out of the 29 studies gathered primary data focusing on evaluating parameters influencing dwelling level energy use. The rest of the studies considered residential energy demand at a macro or urban scale using econometric data and statistical modelling. The review of previous studies done at the household level helped the research team to identify various common criteria to characterise the residential studies that adopted a bottom-up approach to evaluate household energy consumption patterns in Indian context. It also helped to identify the methodologies applied, identify existing data sources and gaps in the data.

The meta-analysis showed that majority (7 out of 9) of the studies focused on residential energy use of households located in the composite climate zone of India. Some of them also covered other climatic zones including temperate climate, warm-humid and hot-dry climatic zone. Cold climate was covered only in one study, that adopted a survey based approach to establish a comprehensive understanding of the status of awareness about energy conservation and use of energy-efficient appliances among users across India [30] (Figure 3).
Figure 3: Climatic zones covered in the residential energy studies collecting primary data

Murthy et al. [24]; Shrinivasan et al. [26]; Jain et al. [27]; Batra et al. [28]; Kanagaraj et al. [29]; Rogers & Chatterjee & Singh [30]; TERI [31]; Garg et al. [32]; Rawal & Shukla [33]

Figure 4: Primary data collection methods adopted the identified studies

In terms of the data collection methods, ‘surveys’ emerged as the most common method adopted by previous studies to collect primary data on various aspects of household energy consumption. Some studies combined surveys with other methods such as monitoring (electricity consumption) using data loggers as well as adopted dynamic modelling to provide future energy use projections (Figure 4).

The key findings from the studies using primary data collection methods such as household surveys and monitoring, are as follows. In 2001, Murthy et al. [24] conducted a survey of 1165 households in four districts of Karnataka (state in southern part of India). The survey revealed the patterns of electricity consumption in AEH (all electric homes) and non-AEH households, the stock of electrical appliances used, the differences in the consumption of electricity in urban and rural areas, the use of other sources of energy for domestic purposes, and the degree of penetration of energy efficient appliances. The penetration of major appliances such as TFLs and lamps, fans, mixer, television and iron were found to be much higher in the AEH households, which were mostly concentrated in the urban areas. Thus, indicating the influence of location and socio-economic factors on household energy consumption patterns.

Similarly, Garg et al. [32] conducted a load research survey of 400 residential and 200 commercial buildings in Gujarat and found that appliance penetration especially for heavy appliances such as air-conditioners, electric water heaters (geyser) and televisions was much higher in the higher income groups as compared to the middle- and lower-income households. The study also showed that, space cooling accounted for nearly 58%, 48% and 41% in high, middle- and low-income households respectively in Gujarat, thus signifying the influence of socio-economic factors on household energy consumption. The survey results also showed that about 91% of the identified air-conditioners and 87% refrigerators were non-energy efficient rated appliances. Research shows that promoting the use of energy efficient appliances such as ACs, refrigerators, TVs and ceiling fans alone can lead to a saving of 52 b/kWh to 145 b/kWh in households’ electricity consumption by 2030 [15].

Filippini and Pachauri [9] estimated seasonal price and income elasticity of electricity demand in the residential sector of all urban areas of India using disaggregate level survey data for about 30,000 households. Area of dwelling unit and demographic characteristics (such as household size and age of the head of the household) were reported to have significant effects on electricity consumption in urban India. Apart from socio-economic factors, the review showed other studies that considered various other factors to access household electricity consumption in India. In 2008, a research conducted by The Energy and Resource Institute (TERI) [31] survey and monitoring of 200 households across four cities (50 homes in each city) was conducted during summer and winter months. The dwelling selection was based on the building archetype i.e building form (attached-detached, low-rise/high-rise, independent bungalows) as well as income classification of the households. Appliance electricity consumption and indoor environmental monitoring was done using data loggers and surveys were conducted to
understand aspects of occupant behaviour that influenced electricity consumption. The available publication (report) however, lacks sufficient information on the methods, assumptions and findings from the study.

Rawal & Shukla [33] conducted a survey of 800 households, in four cities (Ahmedabad, Bangalore, Delhi and Mumbai) covering four climate zones of India, to map current appliance 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, were gathered through a survey. Building energy modelling (using EnergyPlus) was then deployed to quantify comfort benefits and energy savings potentials of better performing building envelopes. The results showed variation in households’ energy consumption based on their location as per climatic zone. Similarly, Gupta [21] utilized a national level panel dataset of 28 Indian states for the period 2005-2009 to show that electricity demand is positively related to temperatures in summers and negatively related to temperatures in winters. The effect of temperature increase on demand in summers was higher in a hotter climate as people adapt with the use of higher cooling equipment whereas there was a higher negative response to temperature increase in winters in colder climates as people adapt using higher heating equipment. Further, the effects of both the hotter and the colder climates on electricity demand were expected to be more pronounced at the higher income levels.

Yet another study [29] monitored energy consumption in sample urban multi-storeyed residential buildings in India. The work was carried out under the Indo-Swiss Building Energy Efficiency Project as background research leading to the development of energy efficiency guidelines for the design of new residential buildings in the composite and warm-humid climatic regions of India. The research was aimed to derive strategies and guidelines for improving energy efficiency of urban multi-storeyed residential buildings located in the warm-humid and composite climate zones of the country.

Only one study used detailed energy monitoring of a three-storey dwelling in Delhi [28]. The gathered data set for electricity, water and ambient conditions at different granularities was released for public use. The study discussed the architectural implications of the sensors in the context of developing countries, especially the unreliability of the electrical grid and internet. To address these challenges, the Sense Local-store Upload architecture for robust data collection was presented.

There were only a couple of studies that explored the social science aspect of energy use such as the influence of culture and occupant behaviour. Shrinivasan et al. [26] studied energy, water and fuel conservation practices in urban India. A culture of deep conservation was highlighted, and the results thus obtained raised questions about the viability of typical solutions such as home energy monitors. New opportunities for design such as point-of-use feedback technologies, modular solutions, distributed energy storage; harnessing by-products and automated load shifting were also identified. Jain et al. [27] carried out a survey of 1724 residents of urban India, exploring the motivations and barriers affecting energy conservation and their opinions about sharing energy consumption data and future technologies for conservation. Urban Indians were found to practice conservation because it is a learned habit and to save money, while comfort and convenience are the major barriers in conserving energy. Participants were found to be interested in automated energy controlling systems, which contrasted previous findings.

4. Developing an accessible searchable repository for residential energy studies

To make the residential energy studies more accessible, the published studies were, for the first time, brought together in the form of an online searchable repository accessible to anyone. The RESIDE Energy and Comfort Repository for India (REACT) (Figure 5) is designed to be an interactive online repository that provides the users with easy access to published works on residential energy (and thermal comfort) studies done in the Indian context to date. The repository can be accessed from the project website here.

REACT allows the users to filter the available studies under a set of selection criteria (Figure 2) and based on this provides a list of the relevant works, including the title and year of publication, author/s
name and contact details and an overview of the abstract. It also provides the DOI or url links for the user to access the full publication.

![Figure 5: A screen-shot of RESIDE Energy and Comfort Repository (REACT)](image)

The filtering criteria embedded in REACT are defined based on the determinants of residential energy (and thermal comfort) that emerged from the extensive meta-study of the existing literature. This allows the user to segregate the available publications on the basis of the following broad criteria:

- Publication type (journal paper; conference paper; report)
- Year of publication
- Climate zone (cold; composite; hot-dry; warm-humid and temperate)
- Dwelling form (house; apartment)
- Dwelling type (modern; urban; vernacular)
- Methodology (survey, monitoring; modelling; secondary data)
- Duration of study (year; month)
- Unit of study (dwelling; household; occupants)

5. Findings from stakeholder workshops

Insights from review of literature were supported by the feedback gathered from experts through three stakeholder engagement workshops organised by the authors.

5.1. Stakeholder workshop 1

The first stakeholder workshop introduced the overall RESIDE project and focussed on challenges of accessing available datasets on residential energy use to bridge the data gaps. The participants provided feedback on the methodological approach of the project regarding survey and monitoring. The discussions highlighted the need to gather data on energy consumption of households that are representative of the housing stock (existing/new) in India—construction types/materials, built forms (single/multi-family) and tenure. It was agreed that utilities/energy supply companies could not only be a source of household electricity data, but also benefit from the project findings. Data gaps pertaining to the energy consumption of common services (such as lifts) in multi-storey apartment buildings was highlighted, however given the focus of RESIDE on individual dwellings, this would be an area for future research. The capacity building of students and staff in the survey partner institutions was seen as a positive aspect of the project.

5.2. Stakeholder workshop 2

The purpose of this workshop was to seek feedback from experts regarding the requirements, needs and uses of empirical data on residential energy and how these can be met through the RESIDE field studies. The interaction with various experts revealed that there was a lack of formal framework and policy for
data collection and sharing of information, and making data available publicly. The discussions reaffirmed the influence that the socio-economic and cultural backgrounds of the residents can have on the energy consumption patterns and therefore should be considered as an important determinant while collecting data. Intermediary organisations (such as local community groups, resident association, housing societies) can play a significant role in spreading awareness and encouraging residents to participate in such large-scale studies. The accuracy of the data loggers used in the study is important to ensure the credibility of the data.

5.3. Stakeholder workshop 3

This workshop saw a focused discussion on the methodological approach developed for the energy and thermal comfort survey of 2000 homes in India. The participants discussed the potential for including green certified residential buildings in the study to access the performance gaps (if any) in these buildings. The importance of capturing building architectural/physical features during the study such as the presence of mosquito nets on the windows, number of exposed/semi exposed building surfaces, common areas, courtyards etc was highlighted, as these would affect the indoor environment, consequently influencing household energy use.

Overall the stakeholder workshops reinforced the absence of good quality data on residential energy use in India, and the significance of empirical studies in developing policies to target residential energy use. The workshops also helped to identify important factors that should be considered while gathering energy consumption data at dwelling level, such as the changing trends in the use of appliances in different types of income groups in India. It was highlighted that the field study methodology should account for the climatic and cultural variation in different cities in India. For example, the measurement of relative humidity is as important as indoor temperature in the Indian context and should be included in dwelling environmental monitoring. Success of such large-scale empirical studies can only be made possible by spreading awareness and encouraging participation of residents from all socio-economic and cultural backgrounds of the society. Capacity building of educational institutes and students through their participation in such studies will go a long way in shaping up the future research and its level of implementation in practice and policy measures.

6. Discussion

India’s residential building stock plays a significant role both in influencing the country’s commitment towards addressing future energy demands and fulfilling the commitment to address climate change at a global level. As the Indian government accelerates its development efforts through policies such as “24x7 Power for All” and “Housing for all by 2022 (PMAY)”, this will lead to higher penetration of electricity within the energy mix of urban households [11]. This is why empirical datasets on the use of residential energy on a large-scale are required for capturing these energy consumption transitions.

A deeper understanding of household energy (electricity) consumption patterns is also necessary for developing energy efficiency policies. However the meta-study and engagement with stakeholders revealed that there is absence of empirical studies on residential energy, end uses and load profiles. This was confounded by the lack of consistency in the existing studies in terms of selecting the determinants of residential electricity use.

It was also realised that electricity consumption patterns across different residential building types in different climatic zones of India were not available, and where data-sets were available, they were of low resolution and insufficient to develop representative energy models. Sensor based monitoring of household electricity was found to be emerging. However the unreliability of the electricity grid and Internet calls for bespoke solutions to be developed for measuring electricity consumption in dwellings. Furthermore, due to the dependence on secondary sources, estimates related to impact of new technologies in the building envelope were less robust.

Although the influence of socio-cultural factors was found to have a significant influence on energy use and conservation behaviours of occupants, limited number of studies were found to focus on this
aspect. A holistic examination of residential energy therefore requires an interdisciplinary approach involving the fields of engineering, sociology, anthropology, architecture and others. Participation from residents having different socio-economic-demographics should be encouraged. This is what the RESIDE project seeks to address in its field study.

7. Conclusion
This paper has used a meta-study approach to systematically review and analyse existing residential energy studies in India. Through a series of stakeholder workshops, data gaps and data needs of various stakeholders were identified. A meta-data framework was developed to characterise the disparate studies and bring them together in the form of a searchable online platform. Any future published studies on residential energy (and thermal comfort) can also be added and characterised in this platform. This would not only help in recording ongoing and future research in residential energy in India, but also bring recognition to researchers by potentially increasing citation of their studies.

The meta-study has also revealed that the sociology and psychology of energy use in dwellings needs equal attention, as much as measurement of residential energy use in order to better understand the pattern of energy use. It is evident that empirical data on residential energy use and end uses are presently lacking and urgently required for informing policy. To avoid any duplication of efforts in future, robust data sharing policies should be enforced (by the funding agencies), so that data gathered can be shared with interested stakeholders in an anonymous manner.

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