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Balancing energy transition: Assessing decent living standards and future energy demand in the Global South

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ABSTRACT

Achieving low energy demand in buildings is crucial in climate change mitigation. In the Global South, however, reducing the energy demand blanketly is not advisable due to critical gaps in access to the basic services supporting Decent Living Standards (DLS). Current energy demand scenarios mostly overlook achievement of DLS. Furthermore, model limitations in representing distributional aspects hinder modelling future energy demands to meet DLS. Supported by new evidence from a set of detailed sectoral and integrated assessment models, this research contributes to bridging this gap by exploring future trends in DLS achievement and linkages with energy demand in the Global South, focusing on the residential sector in India. We consider four key dimensions of DLS: sufficient space and durable housing, thermal comfort, access to basic appliances and to clean cooking. The results show that the substantial increase in residential floor area will not guarantee an improvement in DLS levels due to continuing non-durable housing construction. Also, despite an increase in space cooling demand of almost 126–800 % by 2050, only 15 % of the population will have access to residential air conditioning, mostly in urban buildings. In contrast, access to clean cooking will increase to almost 80 % under current policies, with energy demand would decrease by 24–49 % by 2050, while majority of the population will have access to clean cooking due to energy efficiency improvements. These findings underscore the importance for India to adopt high efficiency measures that can reconcile seemingly divergent goals of improving well-being while reducing energy demand.

1. Introduction

Global net anthropogenic greenhouse gas (GHG) emissions were estimated to be 59 $GtCO_2$-eq in 2019, which was 12 % higher than in 2010 and 54 % higher than in 1990 [1]. Carbon dioxide (CO_2) from the combustion of fossil fuels and industrial processes is responsible for the largest share and growth in gross GHG emissions. Although around half of all emissions have come from the world's wealthiest nations, often referred to as the "Global North", since the Industrial Revolution, during the past 30 years countries in the Global South have contributed significantly to global emissions due to their high energy intensity and consumption of fossil fuels to drive their development [2,3]. Simultaneously, primarily in the Global South, more than 3 billion people lack sufficient energy to maintain decent living standards (DLS), including nutrition, shelter, health, socialization, and mobility [4]. Less than 10 gigajoules of energy per person per year are available to 38 % of the world's population, which is insufficient to cover even the most basic demands [5]. Access to energy is essential to development and attaining

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at least DLS by improving well-being, which is expected to further increase energy demand in the Global South [6].

To reduce emissions trajectory in the Global South, the building sector would play a pivotal role as it globally accounts 30 % of final energy use and 26 % of energy-related (CO_2) emissions in 2022 [7]. Due to the increasing rate of urbanization and population growth, the buildings sector's contribution in Global South emissions has been growing [8] and is projected to further grow in the future. Yet, results aggregated from different energy modelling studies show that the largest mitigation potential for buildings (5.4 GtCO2) will be available in developing countries [1].

Due to increasing affluence, access to appliances and buildings floorspace has been rapidly increasing in the Global South, resulting in higher energy demand per capita [9]. The increase in energy demand expands the size of the energy supply system which will further pose challenges in achieving carbon neutrality goals [10]. However, reducing the energy demand of the building sector blanketly is not advisable as the buildings sector plays an important role in enhancing well-being by fulfilling the fundamental need for shelter and offering services to individuals, communities, and societies at large.

As a cornerstone of human existence, housing which is often referred as shelter, is a basic necessity that provides safety, security, and comfort. Proper housing not only shields individuals from the elements but also fosters a sense of belonging and stability, which are integral to overall well-being [11,12]. In addition, access to basic services such as thermal comfort, clean cooking, refrigeration and labour-saving devices (e.g. washing machines and mixers) is vital to achieving DLS for all [13,14]. While energy is required to provide such basic services, there is growing recognition that beyond a point, greater energy consumption does not necessarily contribute to greater levels of wellbeing and may only indicate social status [15–17]. At the same time, pursuing any net-zero transition or energy demand reduction strategy without factoring in wellbeing risks leaving behind those who are most vulnerable to the climate crisis. Thus, often decision makers rely on computer-based energy models which are commonly used to project future energy demand and GHG emissions.

DLS represent an established framework to assess the minimum energy levels required to ensure universal access to basic services supporting human wellbeing [18]. In contrast with other multidimensional poverty indicators mostly measuring outcomes of human wellbeing, DLS focus on the requirements for achieving those outcomes [19]. However, majority of the energy models do not account for well-being or DLS and primarily exhibit three significant gaps: firstly, they fail to incorporate DLS/well-being indicators [20]; secondly, many lack the necessary granularity to accurately represent distributional aspects in both DLS attainment and energy demands [21]; and thirdly, there is a tendency for studies (for instance, refer to [22,23]) to focus on individual models rather than integrating various models. Bringing together different models would provide a deeper understanding of the modelling uncertainties. Moreover, most models project energy demand based on data which may be incomplete or outdated [24]. Consequently, it remains unclear whether reducing energy demand is achievable without adversely affecting or, ideally, improving access to decent living standards in the Global South under the present policy framework and efficiency trends.

Therefore, this paper provides answer to two of the research questions- 1) 'What are the current trends in DLS achievement and energy demand for basic residential energy services in the Global South?', and 2) 'Why do different models produce different current trends related to Indian residential energy demand and DLS indicators?'. To answer these research questions, this study uses six distinct models that calculate both energy demand and decent living standards to: i) calculate the current trends in DLS achievement and energy demand for basic residential energy services, ii) examine the differences in current trends produced by different models, and iii) assess the range of uncertainty in existing modelling scenarios that calculate energy demand and DLS for countries in the Global South.

Supported by new evidence from a set of detailed sectoral and integrated assessment models, this research contributes to bridging the gap by exploring future trends in DLS achievement and linkages with energy demand in the Global South, focusing on the residential sector in India. Precisely, this paper contributes to answering the research question by: 1) providing an overview of existing energy demand models and methodologies for the residential sector in the Global South, 2) providing data on DLS trends and energy demand projections for the Indian residential sector based on six different top-down, bottom-up and integrated assessment models, 3) based on the results from six different models, analysing the features of present efficiency trends and policy scenarios in India for aspects related to decent living. The use of different models further showcases the uncertainty range of future demand and well-being scenario in countries in global south, and 4) the research findings provide evidence to show that increase in energy demand does not necessarily improve living standards. This research makes the first attempt to analyse the future energy demand and well-being status of Indian building residential sector based on present policy framework and efficiency rates. Analysing the present policy framework would help us understand about the necessary future policy intervention as well as, it also tests the potential possibility of reducing energy demand while improving well-being.

This research has selected India since India's building industry is particularly significant for two primary reasons: 1) India is home to a sizable portion of the world's poor and has one of the top five economies in the world in terms of GDP [25]. According to Global Hunger Index 2022, the nation is among the least developed [26]. 2) India is among the top three nations in the world for primary energy consumption and is one of the top emitters of greenhouse gases [27]. Furthermore, India currently has the world's third largest GHG emissions, which are rapidly growing, though its historical contribution and per-capita emissions remain quite low [28]. It is now the world's most populous country but has a per-capita energy consumption that is only about a third of the global average. Thus, having these diverse socio-economic features presents an opportunity to explore whether reducing energy demand is indeed possible in countries in the global south while improving the well-being.

2. Key features in energy demand and well-being models

Energy demand for the building sector and well-being often do not get considered together. As a result, discussions about building sector-related energy renovation or construction policies often do not incorporate well-being [29]. Defining well-being or "good life" has intrigued thinkers since the Aristotelian times and Buddhist ideas [30], and linking indicators to these in order to set fair targets and assess the level of achievement has been approached by many. Although there are mainly two types of conceptualizations of well-being, namely hedonic and eudemonic, this research focuses on the eudemonic conceptualization. With the eudemonic conceptualization of well-being, scholars argue that societies should be structured in a way that basic human needs are met everywhere in spite of the fact that a lot of external circumstances are beyond our control and thus require a lot of adaptability [31,32].

DLS is often used as a material prerequisites indicator for human well-being [19]. A growing number of studies investigate the energy requirements related to DLS provision focusing on the building sector [33,34]. Thus, in this study, we use different DLS indicators as a proxy for human well-being - precisely to explore how the link to human well-being is considered in residential energy demand modelling. Having access to energy and different energy services is pivotal to achieve improved DLS, still there are not many models especially focusing on Global South countries which accounts DLS while calculating future energy demand. To understand the key features of models which does account both energy demand and DLS dimensions into models, we conducted a search within the Scopus database and as of August 2023, the search yielded a total of 121 studies. We used three specific theme-based keywords:

1) General: climate change, energy, CO_2, greenhouse gases (GHG), emissions, consumption, demand,
2) Building modelling-specific: buildings, shelters, housing, dwellings, scenarios, narratives, pathways, projections, models, simulations,
3) DLS: equity, DLS, DLE, Decent living, poverty, quality of life, wellbeing

We established four essential criteria to identify relevant studies:

1. Models must endogenously calculate future energy demand;
2. Models must document their method and input data in a report or in a scientific journal article;
3. Models must include any DLS components while modelling energy demand;
4. Models must focus on the countries in Global-South. Models with global coverage are included as well if they provide specific results for any country in Global South.

Based on these four criteria, we identified fifteen studies which calculates energy demand along with different dimensions. Our objective was to gather information on whether any DLS indicators are being considered while modelling energy demand in the global south with a focus on the building sector. We therefore stopped adding demand models in the list when they added no new features to any of the categories listed in Table 1.

We focus on four key DLS-related dimensions of residential buildings (Table 1) which were identified by Rao & Min [19] study: housing, thermal comfort, cooking, and basic appliances. Adequate housing is a key priority to provide safe and sufficient space, and shelter from inclement weather [35]. Ensuring basic thermal comfort with modern and clean technologies is crucial to avoid exposure to extreme temperatures and humidity levels, reducing health risks and improving wellbeing [36]. Modern clean cooking stoves contribute to better indoor air-quality and reduced health risks and physical work for carrying firewood, that are associated with using traditional biomass [37]. Appliances, including fridges, and televisions, provide important services such as food conservation (fridge) and information (television).

We have observed that studies predominantly employ two overarching modelling approaches, namely bottom-up and accounting models, to compute energy demand and DLS measures. The most widely addressed DLS dimension in these models pertains to housing and thermal comfort. Specifically, approximately 80 % of the examined models incorporate these two DLS indicators when calculating energy demand for various end-use building scenarios (refer to Table 1).

Here, we shed light on the significance of DLS measures and energy demand by examining findings from various studies. For instance, Schueftan et al. [38] delved into strategies to reduce emissions from household wood combustion, evaluating their efficacy in mitigating air contamination. Their study, conducted through a household survey in south-central Chile, focused on modelling thermal retrofitting of buildings under three efficiency scenarios, including improvements to both stoves and the building's envelope. The results pointed to the conclusion that retrofitting houses played a pivotal role in alleviating energy poverty. Conversely, the sole improvement of heating appliances did not yield the same impact on alleviating energy poverty or enhancing indoor comfort. Another study focused on a passive school building discovered that the demand for heating and cooling is markedly affected by factors such as the indoor set-point temperature, occupancy levels, and the heat recovery rate [39].

Similarly, Millward-Hopkins et al. [22] constructed a simple bottom-up model to determine a practical minimal threshold for global final energy consumption necessary to ensure DLS for all. The study reveals that by 2050, global final energy consumption could potentially be lowered to levels equivalent to those of the 1960s, even with a population three times larger. Their conclusion emphasizes the necessity for a widespread adoption of advanced technologies across all sectors and substantial demand-side changes to curtail consumption, irrespective of income levels, down to levels of sufficiency. The study also brings attention to the stark contrast in consumption patterns between the Global South, where the upper classes surpass sufficiency levels, and the persistent poverty experienced by hundreds of millions in the same region. Another study focused India, Brazil, and South Africa in the Global South, calculating the energy embedded in the material underpinnings of DLS through a bottom-up approach. The discrepancy between the energy requirements for DLS and the Integrated Assessment Model (IAM) projected energy demand pathways in a 2 °C world represents the energy demand linked to affluence beyond DLS. Notably, India, being a developing nation with the largest DLS gap exhibits the least 'headroom' under the IAM trajectories, despite already having a lower average demand for DLS. This implies that India's future affluence, driven by income growth, would need to be attained with comparatively less growth in energy demand or come with a higher carbon price tag compared to other regions. Addressing such inequities in international cooperation on technology transfer and diffusion is crucial in future negotiations, particularly if countries like India are expected to pursue ambitious mitigation efforts [6]. Delving into India, Mastrucci and Rao [40] conducted an assessment of the life cycle costs (LCC), life cycle energy (LCE), and CO2 emissions impacts related to addressing the current housing gap. They explored various building materials and technologies while ensuring adherence to indoor temperature and humidity standards. The study indicates that opting for stabilized earth blocks instead of conventional fired bricks has the potential not only to decrease the cost of closing the housing gap but also to mitigate the growth of CO_2 emissions. Introducing additional design features, such as filler slabs for roofing/flooring and roof insulation in place of traditional solutions, could lead to an 18 % reduction in LCC and a 17 % reduction in both LCE and CO_2 emissions.

Chidebell-Emordi [41] presents scenarios for attaining an energy-secure future in Nigeria through the introduction of a context-specific approach to calculate per capita energy requirements using consumption data. The study advocates for a minimum energy poverty line set at 3068 kWh/cap yr (350 W/cap), a level deemed adequate to meet basic needs in an urban household. Monyei and Adewumi [23] directed their attention to the demand-side potential for operating cloth washers and cloth dryers at the Medupi power plant in South Africa. The study employed scenario development and a modified genetic algorithm. Notably, the research underscored the paradox of increasing investments in electricity generation amid a rising issue of electricity poverty. Furthermore, the obtained results deviate from conventional evaluations, revealing a growing disparity in electricity per capita across different provinces.

3. Methods

To assess the inclusion of well-being and also to present the trend on DLS and energy services in India, we use six different models (refer to Table 2). We use a set of multiple models to analyse the trends on access to DLS and energy demands in the residential sector. These six models namely High efficiency building (HEB), Perspectives on Indian Energy based on Rumi (PIER), Sustainable Alternative Futures for India

Table 1
List of DLS parameters involved in energy demand models.

Study	Year	Geographical scale	Main method	Domain	DLS dimensions			
					Housing	Thermal comfort	cooking	Appliances
Millward-Hopkins et al. [22]	2020	Global	Bottom-up model	Activity-levels, material requirement or services	✓	✓	✓	✓
Rao et al. [6]	2019	India, Brazil, South Africa	Accounting model	Embodied energy intensities of DLS dimensions	✓	✓	✓	✓
Li et al. [42]	2022	China	multiregional input-output approach	Households energy footprints	✓	×	×	✓
Kikstra et al. [4]	2021	Global	Accounting model	Embodied energy intensities of DLS dimensions	✓	✓	✓	✓
Liaw et al. [43]	2023	Brazil	System dynamics model	Internal room temperature variation	×	✓	×	×
Pereira-Ruchansky, L. and Pérez-Fargallo, A. [44]	2023	Uruguay	Bottom-up simulation (engineering approach)	Buildings structure and energy consumption	×	✓	×	×
De la Paz Pérez et al. [45]	2023	Cuba	Automated simulation and cost-benefit analysis	Buildings structure and energy consumption	×	✓	×	×
Nutkiewicz et al. [46]	2022	17 cities in India, Brazil, South Africa, Kenya, Indonesia	Computational energy model	Buildings structure	✓	✓	×	×
Monyei and Adewumi [23]	2017	South Africa	Scenario simulation	Electricity consumption in residential buildings	×	✓	×	✓
Chidebell-Emordi [41]	2015	Nigeria	Analytical and computational energy model	Electricity consumption in residential buildings	✓	×	✓	✓
Schueftan et al. [47]	2016	Chile	Analytical and simulation	Buildings structure and energy consumption	×	✓	✓	×
Estefania et al. [48]	2023	Ecuador	Simulation	urban and buildings	✓	×	×	✓
Mastrucci and Rao [40]	2018	India			✓	✓	×	×
Flachetta and Mistry [49]	2021	Sub-Saharan Africa	Geospatial energy modelling	Buildings structure and energy consumption	×	✓	×	✓
Wang et al. [50]	2015	China	Numerical and analytical	Buildings structure and energy consumption	✓	✓	×	×

Table 2
Overview of the investigated models.

Model abbreviation	Model full name	Reference	Geographical coverage	Temporal resolution (timestep)	Overall approach	Main methods	Dimensions
HEB	High-efficiency Building model (HEB)-2.0	[54]	Global	Annual, Hourly	Bottom-up (engineering approach)	Other	Housing, thermal comfort
IMAGE	IMAGE 3.3 - Residential Energy Model Global	[63,64]	Global	Annual	Hybrid	Simulation	Housing, thermal comfort, cooking, appliances
MESSAGE_CHILLED-STURM	MESSAGEix-Buildings (CHILLED and STURM modules)	[58]	Global	5–10 years	Bottom-up (engineering approach)	Simulation	Housing, thermal comfort
MESSAGE-ACCESS	MESSAGEix-Buildings (E-USE-ACCESS modules)	[59]	Global	5–10 years	Structural econometrics	Simulation	Cooking, Appliances
PIER	Perspectives on Indian Energy based on Rumi (PIER) 1.5	[56]	India	Annual, Hourly	Bottom-up (engineering approach)	Accounting	Thermal comfort, cooking, appliances
SAFARI	Sustainable Alternative Futures for India	[57]	India	Annual	Hybrid	Simulation, System dynamics	Housing, thermal comfort, cooking, appliances

(SAFARI), MESSAGE-Access, MESSAGE_CHILLED-STURM, and Integrated Model to Assess the Global Environment (IMAGE) are selected by circulating an online survey among the "Energy Demand changes Induced by Technological and Social innovations (EDITS)[1]" consortium. More details about the survey and models can be found in Mastrucci et al. [51] study. The models were selected based on four main criteria: their capability of linking DLS-related service levels to residential energy demand, their granularity in household and building characteristics, the inclusion of India as separate model region, and the availability of a reference scenario representing the continuation of current trends, in line with the Shared-Socioeconomic Pathway SSP2"Middle of the road" [52]. While all selected models use bottom-up or hybrid approaches, different methods were included to better understand the differences in the insights they can provide. Comparability of results was ensured by thoroughly checking the definitions of input and output parameters and basic assumptions and setup across the models. Additional calibration was carried out on floorspace, access to energy services, and final energy to better align the model data for the base year, to the extent possible. We use the reference scenario of these six models to understand the future energy demand of three end use energy services, namely thermal comfort by space cooling, cooking, and appliances which accounts most of the Indian residential energy demand. The reference scenario of each of these six models accounts the present efficiency and policy framework of India to project the future energy demand and DLS indicators. Prior to the analysis, we have checked that the basic socio-demographic and economic drivers underlying the reference scenario in the different models reasonably align to those of SSP2 [53].

Each of these six models are described below to provide an overview on how we calculate energy demand and DLS indicators in this paper:

HEB: HEB model calculates the yearly energy demand and CO2 emissions of the residential and tertiary building sector until 2060 [54] In this study, HEB model is used to calculate the yearly service energy demand and floor area profile for Indian residential building sector. HEB uses both macroeconomic (such as GDP, population growth) as well as socio-technical data (such as renovation rate, per capita floor area, share of slum in the total residential floor area, rate of urbanization) to calculate end-use energy demand for space cooling, heating, and hot-water services in rural and urban residential building sector [55]. This model uses a bottom-up approach to account the service energy for different types of building (such as single family and multifamily buildings, advanced renovated building etc.).

PIER: PIER (v 1.5) is an open-data, demand-oriented model built upon Rumi, an open-source energy systems modelling platform.[2] PIER estimates energy demand in India for each demand sector, including the buildings sector, in a detailed bottom-up manner or through coarser means. Building sector energy demand is estimated up to 2040–41, based on bottom-up modelling of five energy services namely, lighting, cooking, space cooling, refrigeration and television viewing. Demand is estimated separately for 25 "states" in India, each of which is further divided into urban and rural areas, based on criteria such as historical appliance penetrations, per-capita GDP growth and temperature [56]. Temporally, electricity demand is estimated at an hourly basis for one representative day of each of five seasons in each year.

SAFARI: SAFARI is a system dynamics model that enables scenario building to assess pathways for achieving developmental goals at a national scale for India. The sectoral growth in SAFARI is primarily driven by 'well-being' goals such as food and water security, housing, healthcare and education access for all and the macroeconomic consistency of the model scenarios is ensured by soft-linking to a computable general equilibrium (CGE) model. The residential buildings module is enabled to dynamically compute the housing shortage in India based on income classes, housing stock-turnover based on lifespan and floor space area calibrated to decent living standards benchmark [57]. This module additionally computes the operational energy for residential buildings resulting from space cooling, appliance use and cooking. Further, this module has multiple levers pertaining to appliance use/efficiency, choice of construction materials, and urban planning which enables a robust scenario analysis.

MESSAGE_CHILLED-STURM: MESSAGEix-Buildings ([58]) is a modelling framework to assess energy demand and CO_2 emissions of residential and commercial buildings in future scenarios at national, regional and global scales. The modules CHILLED and STURM (abbreviated here as MESSAGE_CHILLED-STURM) use bottom-up methods to estimate heating and cooling demands (CHILLED) and building stock turnover and energy efficiency investments (STURM). The modules are linked to the integrated assessment model (IAM) MESSAGEix-GLOBIOM [59] to account for interlinkages between the demand-side and supply-side systems. The models have high granularity to represent key heterogeneities in residential buildings, including housing type, vintage, energy efficiency standards, and heating fuels, and households, such as location (urban and rural) and income levels. Outputs of MESSAGE_CHILLED-STURM include projections for floorspace, building stock composition, energy demand, and CO_2 emissions.

MESSAGE-ACCESS: ACCESScooking is a bottom-up model of household cooking and heating fuel choices and their implications for residential energy demand [60]. ACCESScooking employs a structural econometric approach to estimate the determinants of household cooking fuel use calibrated to historical household survey data. The calibrated model is used to simulate future fuel consumption patterns endogenously, given changes in future fuel prices and household characteristics. Microsimulation of household characteristics is informed by survey data and is driven endogenously by SSP drivers. Shadow commodity prices from the MESSAGE-ix modelling framework are then introduced to model the distribution of fuel use across the simulated population [59]. ACCESScooking provides both access to specific stoves, considering stove stacking [61] and household fuel consumption across a set of commodities that map to those required by the MESSAGE-ix modelling framework.

IMAGE 3.3: IMAGE is an integrated assessment model developed to describe the relationships between humans and natural systems, including energy use, land use, and greenhouse gas emissions [62]. The energy module of IMAGE 3.3, is recursive dynamic (i.e. no-foresight) and represents the global energy system, disaggregated across 26 global regions. It projects supply and demand of primary and secondary energy carriers needed to provide energy services for different end-use sectors. The model projects (useful) energy demand for each end-use sector based on relationships between energy services and activity. For the residential sector, the model has relationships describing projections of floorspace, building stocks, renovation rates, household size, electrification rates, appliance ownership, and useful energy demand for heating (space and water), cooling, cooking, and lighting [63,64]. The model also disaggregates between urban and rural households, and five income quintiles.

The list of six models provides a comprehensive representation of different modelling techniques as well as comprehensive coverage by incorporating different layers of granularity, such as granularity in terms of housing stock, socio-economic parameters (for example, income, education, household size, GDP, etc.), and geographical factors (for example, climate zones, urban/rural areas, states) (refer to Fig. 1). In this study, with the help of these models' granularity, we use each of them to explore how future energy demand and associated DLS may appear, considering the present trends of energy consumption,

[1] Experts from a range of fields are brought together by the Energy Demand changes Induced by Technological and Social innovations (EDITS) network to frequently discuss and participate in the multifaceted field of energy demand research. The EDITS community collaborates by sharing methodological information, investigating novel modelling approaches across demand-side models, and having a shared interest in related issues. https://iiasa.ac.at/projects/edits.

[2] https://energy.prayaspune.org/our-work/data-model-and-tool/rumi-pier.

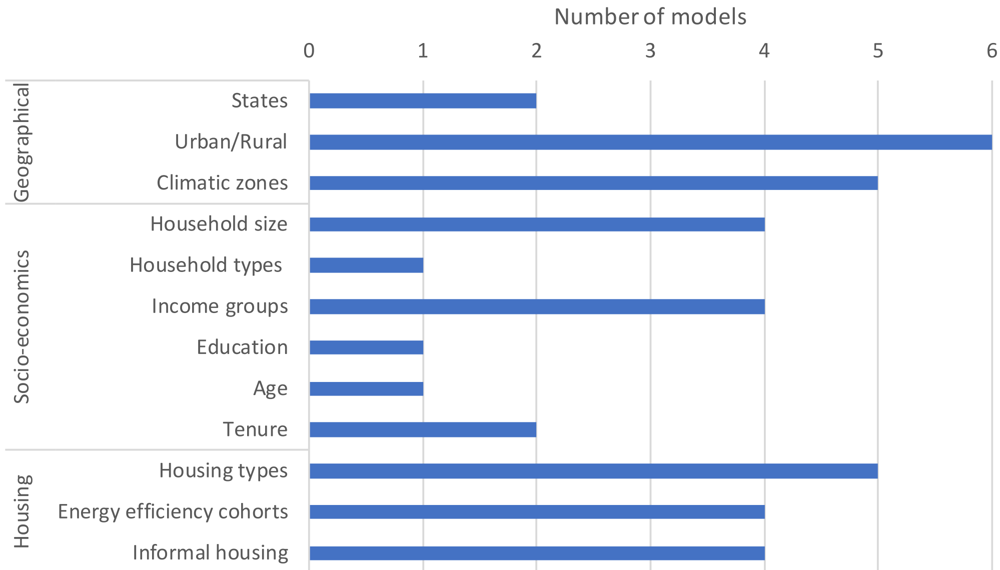

Fig. 1. Granularity in different dimensions of the investigated models.

population growth, GDP, and access to electricity and appliances. The use of different models also enables the consideration of potential uncertainty ranges pertaining to each end-use and DLS parameter, which then provides further insight into how the use of different modelling methodologies can lead to varying data ranges. Furthermore, this uncertainty range also helps to understand the potential impact of existing policies and the need for future policies. For each DLS dimension, and based on data availability and completeness (Table 2), we show results from selected models among the six in this study to assess the range of uncertainty and highlight the different insights that different methods can provide.

4. Results and discussion - model implementations and data trends of energy demand and DLS aspects

4.1. Housing

Floor area is a key element for both DLS and energy demand [54,65]. It is essential to know and understand both the present and project future floor area to calculate residential energy demand. Furthermore, floor area projections also enable to assess the DLS conditions, as shelter being one of the key parameters in the DLS [66]. We use HEB, MESSAGE_CHILLED-STURM, IMAGE, and SAFARI models to present future residential floor area trends based on the present population growth rate and per capita floor area. The purpose of using four different models to project floor area is to explore the modelling uncertainty in terms of projection, precisely in terms of the modelling methodology used by different models.

As per the modelling results of HEB, the total residential floor area of India is projected to increase by 77 % in 2050 compared to 2025 (refer to Fig. 2). This increase in floor area is mostly due to increase in urban floor area, precisely around two times which is about 4 billion m^2 in 2025 to 13 billion m^2 floor area, increase is projected in the urban residential floor area by 2050. Although, in terms of floor area share, rural floor area has a higher share than the urban floor area, the increase in residential floor mostly expected due to immense increase in urban floor area (refer to Table 3).

Similar trends are obtained by using IMAGE, MESSAGE_CHILLED-STURM and SAFARI models, although with different rates of floor area increase. Precisely, as per IMAGE data, the total residential floor area is expected to increase by 42 % by 2050 which is rounding about 9 billion m^2. MESSAGE_CHILLED-STURM and SAFARI results show higher

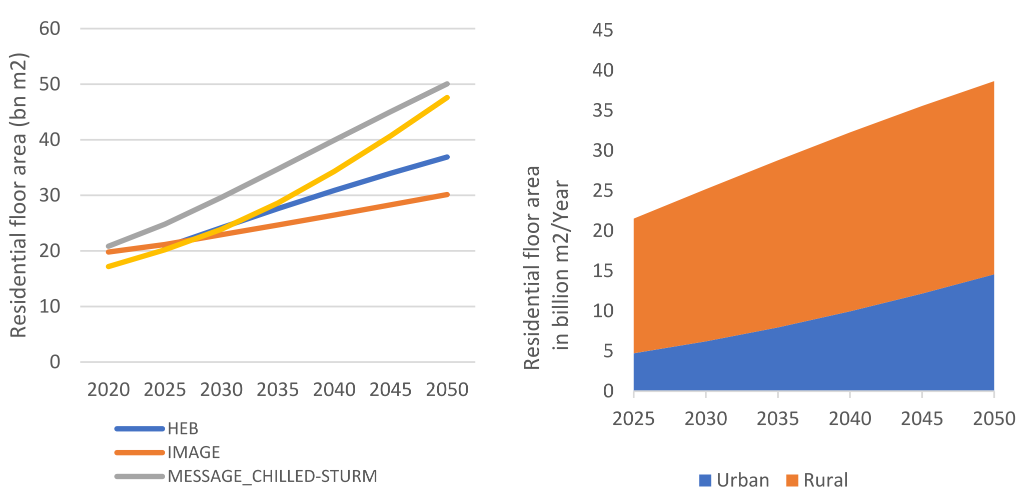

Fig. 2. Floor area projections of India under reference scenario of HEB, IMAGE, MESSAGE_CHILLED-STURM, and SAFARI (left panel) and breakdown by urban and rural in HEB model (right panel).

Table 3
Floor area and Population trends in India following reference scenario.

	2025	2030	2035	2040	2045	2050
Urban floor area (in billion m^2) from HEB	4	5	7	9	11	13
Rural floor area (in billion m^2) from HEB	17	19	21	22	23	24
Total residential floor area from HEB (in billion m^2)	21	24	28	31	34	37
Total residential floor area from MESSAGE_CHILLED-STURM (in billion m^2)	25	30	35	40	45	50
Total residential floor area from IMAGE (in billion m^2)	21	23	25	26	28	30
Total residential floor area from SAFARI (in billion m^2)	20	24	29	34	41	48
Total slum floor area from HEB (in billion m^2)	0.9	1	1.2	1.4	1.6	1.8
Total population living in informal settlements from MESSAGE_CHILLED-STURM (in millions)	161	183	198	206	206	199
Total population living in informal settlements from MESSAGE_CHILLED-STURM (share)	11.0 %	12.0 %	12.5 %	12.5 %	12.2 %	11.5 %
Total population living in non-durable housing from SAFARI (share)	12.0 %	10.7 %	10.6 %	10.2 %	9.2 %	8.1 %

increase in floorspace, in the order of 102 % and 136 % respectively, due to different assumptions on per-capita floorspace growth and gradual replacement of existing smaller informal settlements with larger durable housing. All these models use three parameters, namely present per capita floor area, population growth, and rate of urbanization to calculate residential floor area. The variation in data is occurring mostly due to different methodologies and data points are being used by the models. For instance, the housing sector in the MESSAGE_CHILLED-STURM model is represented with a high level of granularity, considering key household and building characteristics, including location (urban or rural), income level, housing type (single-family, multi-family, and informal), construction materials, and energy efficiency standard, where a linear regression model is used to predict the national share of urban population living in slums depending on the logarithm of national per-capita GDP [4]. Similarly, SAFARI consider detailed segmentation of the housing stock, including rural and urban durable and non-durable housing. On the other hand, HEB model assumes the growth in floor area in the residential sector depends predominantly on the population growth, and the share between rural and urban floor area is calculated based on the urban and rural population along with the rate of urbanization in India [54]. This data range provides a good uncertainty range for the floor area and both the models show a steep increase in the total residential floor area.

However, increasing in future floor area doesn't mean that individual well-being will be improved by having more access to shelter. For instance, although the total residential floor area is projected to increase by 2050, the floor area for informal settlement is also projected to increase by almost 110 % by 2050 compared to 2025 (refer to Table 3), and the population living in the informal settlement increases by 94 % in 2050 compared to 2015 population. Thus, increase in floor area does not necessarily result in the increase in DLS standards. Furthermore, if we assume that housing for all goal needs to be met, then the total residential floor area increases substantially which may result in substantial increase in the total energy demand as well. For instance, by using SAFARI model we calculate this scenario, and data shows that if 'Housing for All' goal is met, then residential floor area is projected to increase by almost 136 % by 2050 which accounts to total residential floor area to be about 56 billion m^2 in 2050 (refer to Fig. 2). Thus, the estimated future reduction in the share of population living in non-durable housing in SAFARI is more optimistic compared to MESSAGE_CHILLED-STURM (Table 3). This results in higher total floor area projections due to the gradual replacement of smaller non-durable housing. SAFARI model calculates residential buildings module with the objective of estimating the material, energy and emissions consequences of meeting the 'Housing for All' goal, and also, it dynamically checks for, and addresses housing shortage based on BAU trends of sanction rates for economically weaker section (EWS) and low-income groups (LIG) of the population. Sufficient housing size is captured exogenously via floorspace area assumptions for different income categories. For EWS/LIG, the floorspace area is assumed to be 40 m2 per house as per decent living standards as per Rao and Mastrucci [6]). Although, article 21 in Indian constitution precisely acknowledges the right to have access to shelter, presently in India around 20 million people have no access to shelter [67]. The Government of India has introduced a new scheme since 2015 where affordable housing will be provided to the urban poor with a target of building 20 million affordable houses to make sure access to shelter for all people. Despite this policy schemes, there are still large number of people living in informal settlement and have no access to shelter.

4.2. Thermal comfort by space cooling

Thermal comfort is a key parameter in determining the total energy demand of the building sector. Unlike the countries in global North, space cooling is the dominating end-use in the building sector in global south countries. Furthermore, thermal comfort is also considered a key component for achieving DLS. The need for cooling to keep people comfortable might be the major recent driver of energy and greenhouse gas emissions as the economies and populations of the world's hottest regions expand and temperatures continue to increase.

In order to represent cooling demand, we use HEB, MESSAGE_CHILLED-STURM, SAFARI and IMAGE models to project the future cooling demand of residential building sector if the present efficiency rate continues. Here, PIER model has not been used as PIER produces data only till 2041 and on a yearly basis. As per the calculations based on SAFARI model, we found if present trend continues, then with the increase of floor area and population, the cooling demand of the residential building sector is expected to grow by almost 800 % in 2050 compared 2020 (refer to Fig. 3).

The cooling trend in India has been upward, and space cooling would dominate India's electricity demand growth, and peak electricity demand growth by 2037 [68]. Our data shows similar trend in cooling growth. To understand the data range for space cooling, we further use the HEB, IMAGE and MESSAGE_CHILLED-STURM models to generate cooling data for the reference scenario. Similar to SAFARI model, MESSAGE_CHILLED-STURM also show a steep upward trend-precisely,

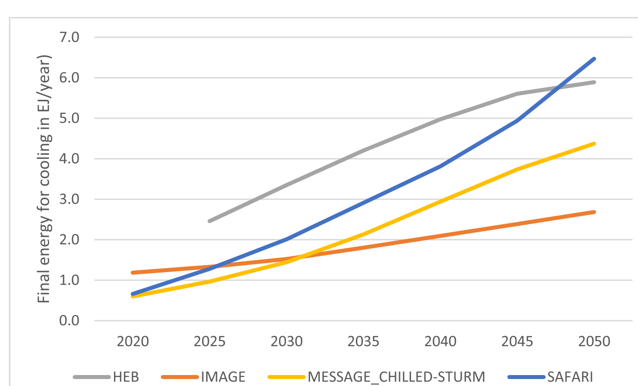

Fig. 3. Space cooling under reference scenario in India in 2050 by using the HEB, IMAGE, MESSAGE_CHILLED-STURM, and SAFARI models.

the data shows an increase of 630 % in 2050 compared to 2020 cooling demand. The cooling demand increase in the IMAGE model is relatively smaller at 126 %. Although, all four of the model's findings show a steep upward trend in space cooling demand, the difference in magnitude is mostly resulting due to different modelling techniques and data sources. This is the reason we show cooling trends by these four models to emphasize how different data and methodologies can cause different magnitude of projections. For instance, for cooling, MESSAGE_STURM, SAFARI and IMAGE models disaggregate between the use of fans and air-conditioning, while the IMAGE model also includes the possibility for air-coolers. However, HEB model does not calculate appliance access especially related to air conditioning. The HEB model calculates cooling demand based on the cooling intensity of different types of buildings, floor space, and population. The cooling intensity changes in the HEB model as it assumes a 1.5 % renovation rate for residential buildings in India annually after 2027, resulting in a less steep increase in cooling demand [69]. All these four models have a representation of urban and rural households, and also include a representation of income groups [57,64]. IMAGE calibrates data to sectoral (residential) energy demand and based on floorspace and calculated cooling intensity, determines cooling demand. SAFARI's reference scenario reflects the current trend of steeply increasing uptake of air-conditioners in the middle- and higher-income groups. While the efficiency trajectory in both these models are comparable, the projections for total stock of air-conditioner units vary significantly due to this difference in approach. Fig. 3 presents results from these two models and provides insights on the possible data range for space cooling in Indian residential building sector provided the present efficiency rate continues.

The objective of this modelling exercise is to provide a 'what-if' insight on how space cooling demand may unfold if present efficiency rates continue. This data range provides solid background to form efficiency policies to reduce future energy demand for space cooling. However, although the cooling demand has showed an upward increase up to 800 % by 2050, considering the present trend, the majority of the people would still not be able to access to residential air conditioning (RAC) by 2050, as shown by the results of the IMAGE model (Fig. 4).

Our estimates show that despite having an increase in future cooling energy demand, access to RAC will remain low in future if current trends continue. Precisely, our modelling results show, only about 15 % of the population will have access to the RAC by 2050 which is around 10 % increase in access to RAC compared to the current trend. However, access to fans will reach to 100 % by 2050 considering the current trend. Access to RAC presently is much more in urban areas, precisely around 18 % of the population have access to RAC in urban residential sector, compared to only 6 % having access to RAC in Rural residential sector (refer to Table 4). PIER model calculates that this access to RAC would increase substantially by 2040 in both rural and urban residential sectors. Precisely, population access to RAC in the rural sector would increase by 15 % by 2040, whereas the increase in urban area is expected to be around 40 % more by 2040 (refer to Table 4). Here, access to RAC only shows people accessibility to acquire thermal comfort and doesn't indicate that RAC is the only way to achieve thermal comfort. These data trends rather lay out the reference scenario trend in order to formulate further future scenarios where cooling demand and associated emissions can be reduced while achieving the DLS. This is only possible by improving the appliance efficiency standards and by changing usage behaviour.

Nonetheless, the increasing access to RAC would result in substantial increase in cooling demand. Thus, in order to maintain the thermal comfort while increasing access to RAC, India's Bureau of Energy Efficiency (BEE) launched the labelling program for RACs in 2006. However, despite the labelling system, with the current efficiency standards,

Table 4
Percentage population having access to different appliances in the future years based data calculated by using PIER model reference scenario.

	2025	2030	2035	2040
Percentage population having Access to RAC in rural residential sector	6 %	8 %	12 %	22 %
Percentage population having Access to RAC in urban residential sector	20 %	30 %	44 %	61 %
Percentage population having Access to Refrigerators in urban residential sector	73 %	87 %	94 %	98 %
Percentage population having Access to Refrigerators in rural residential sector	45 %	56 %	68 %	77 %
Percentage population having Access to Televisions in urban residential sector	88 %	93 %	97 %	100 %
Percentage population having Access to Televisions in rural residential sector	73 %	82 %	90 %	95 %

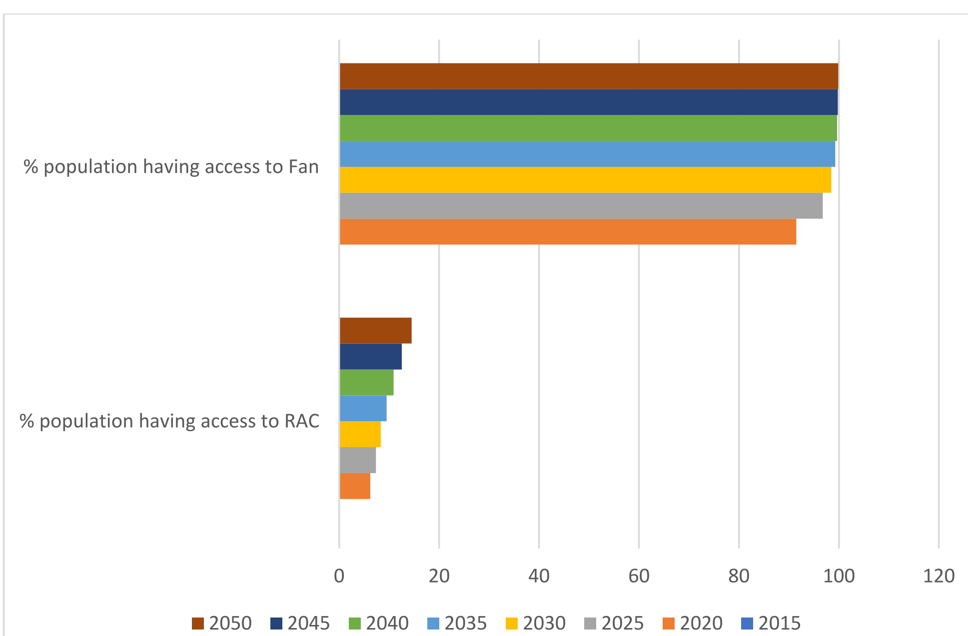

Fig. 4. Percentage of the total population in India having access to residential air conditioning and fan. Data from the IMAGE model.

the energy demand for cooling would go up significantly. One reason for that could be that the initial labeling launched in 2006 was not efficient enough, and hence, in 2016, BEE has revised the standards for certifying the star-rating in a way that the five star label rating obtained in 2010 became only three star label rating in 2015 and in 2018, it became one star according to the new India's Seasonal Energy Efficiency Ratio (ISEER) methodology [70,71]. However, it is important to note that since the initial investment in purchasing a five star RAC is around 37 % which is around INR 12000 (equivalent to 150 USD in 2023), higher compared to one star RAC, majority of the Indian consumers prefer not to buy high-efficiency RAC, thus, the average market share is mostly dominated by three star RAC compared to 23 % for the five star RAC [72]. Due in large part to the ceiling fan's lower cost (which is around 20 USD in 2023) as well as the benefits of the Indian government's Standards and Labelling (S&L) programme, sales of CF, which accounted for almost all five-star items, have increased [70].

To ensure DLS, all models could exogenously force access to cooling appliances. However, none of the models currently include a minimum energy demand threshold which has to be met. Thus DLS, is determined *ex-post*. An important thing to note concerns the different calibration methods models employ to determine and project cooling demand. While some models may calibrate to specific data for these energy services, others calibrate to total sectoral energy demand (for instance from IEA statistics for the residential sector) and then estimate the demand for specific energy services in the residential sector. This highlights a clear area for harmonization between models, methods, and datasets. Thus, meeting DLS through access to RAC is subject to over prosperity of the nation.

4.3. Cooking

Access to and use of clean cooking solutions are complex socioeconomic and behavioural processes to model. Intrahousehold dynamics, budget constraints, supply limitations and appliances all modify the selected modes of cooking service provision. Households under severe budget constraints often hedge their cooking solutions, retaining traditional modes of service provision in case the cost of operating modern modes of provision increases. Similarly, households under budget constraints stack their modes of cooking service provision, combining traditional stoves with modern alternatives such as liquid petroleum gas (LPG) stoves and electric hot plates or induction stoves. The interplay between these alternatives is directly influenced by changes in fossil fuel and electricity prices driven by domestic and international energy policies, highlighting the complex relationship between climate mitigation, public health, and poverty alleviation efforts.

To calculate the cooking-related final energy demand, we use the models IMAGE, SAFARI, PIER and MESSAGE_ACCESS (refer to Fig. 5). As per PIER and SAFARI modelling results, the cooking demand is expected to decrease even in the reference scenario by 24–49 % by 2050 compared to 2020. However, as per the MESSAGE_ACCESS, with the present efficiency trends, the cooking demand is expected to increase by 8 % in 2050. In IMAGE, SAFARI and PIER the final energy decreases until 2040 driven by improved access to more efficiency clean cooking stoves and phasing down of traditional biomass. In contrast, in MESSAGE_ACCESS energy demand for cooking is lower due to different accounting of traditional biomass and slightly increase over time under population growth. The range of variation in total final energy demand for cooking of 46 % in 2040 across the three models. This data difference is again caused due to different modelling methodologies. For instance, ACCESS-cooking models the full distribution of households using microsimulation, capturing the complex dynamics of multiple stove ownership at the household level. Ownership of each stove type is modelled using a logit model, drawing on a range of household characteristics based on relationships identified through recent household survey microdata. This approach enables a nuanced understanding of how socio-economic factors influence stove ownership and stove stacking across the entire population. However, it is a static model that may not accurately represent changes in technology and behavioural patterns in the distant future. Whereas the models SAFARI and PIER calculate fuel consumption based on exogenously determined efficiencies and useful energy demand norms for cooking. Moreover, the assumption of constant demand for useful energy may not capture fluctuations in energy needs due to socioeconomic factors. Furthermore, PIER considers historical clean cooking fuel use penetrations and their relationship with per capita gross domestic product, approximating trends if these relationships were to continue. While it describes heterogeneity across states and wealth groups, PIER does not model stacking of cooking options and assumes that each household only uses its 'primary' fuel.

This is important to note that there is no 'best' modelling approach to calculate end-use demand, rather different modelling approaches provides different insights [24]. That is why we are using multiple models to show the different data range for each of the end-use energy demand as well for the DLS indicators. This data range further show the need for a coherent scenario or set of scenarios where data inputs and assumptions are aligned which would minimise the uncertainty regarding future energy demand and DLS predictions.

The data for access to clean cooking from both IMAGE, PIER and SAFARI models show that almost the entire Indian Population will have access to clean cooking by 2050, which is a major improvement compared to the present standard where around 60 % of the population have access to clean cooking. This substantial improvement in access to clean cooking mostly resulted from one standout policy run by the Indian government since 2016. While 53 % of Indian households had

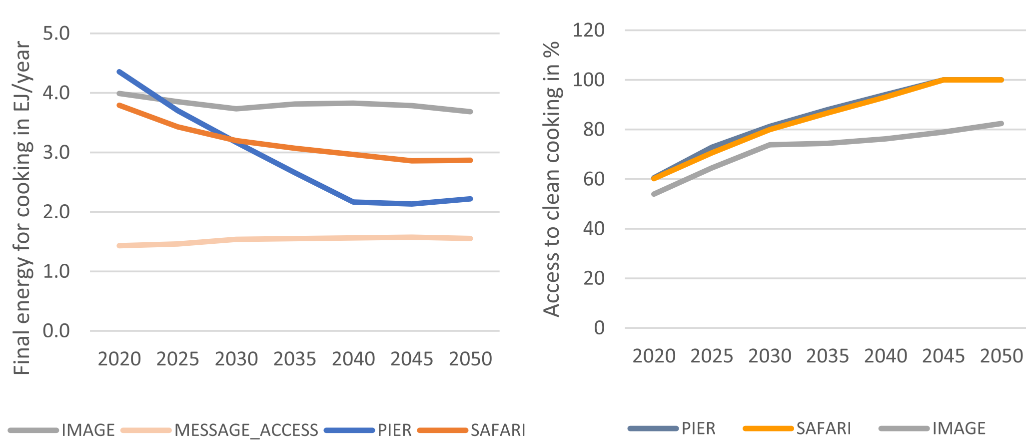

Fig. 5. Final energy demand for cooking and % population access to clean cooking by using IMAGE, PIER, SAFARI, and MESSAGE-ACCESS reference scenario.

access to LPG in 2011, only 28 % used it as their primary method of cooking [73]. The Pradhan Mantri Ujjawala Yojana (PMUY), which offers free LPG connections to all BPL families in accordance with the Socio-Economic Caste Census (SECC), is the government's most recent and greatest endeavour to provide access to clean cooking energy in the nation. Despite making significant progress in addressing the issue of connection affordability and some improvements in the consistency of fuel availability, the programme falls short in addressing the issues of affordability of the ongoing cost of fuel and raising consumer awareness of the health effects [74].

4.4. Appliances

Appliances provide important services in buildings, including food conservation, washing, drying, communication, and lighting. Access to these appliances is a key component of DLS, commonly measured as the share of households having the appliances, also called appliance penetration. Energy use from appliances, in particular electricity, can represent a significant share of household energy demand, especially in developing countries.

Results from the PIER model show that, considering the present rate of economic and population growth, access to appliances such as televisions and fans will reach almost 100 % by 2040 in India (Fig. 7). More expensive appliances such as RAC and refrigerators will also see a rapid growth in terms of access, but many households will still not be able to afford them. Broader access to these appliances could substantially improve the standards of living in India, but would also results in almost 500 % increase in electricity demand by 2050 compared to 2020 (refer to Fig. 6). Modelling evidence from SAFARI shows a similar increasing trend on appliance energy demand if the current efficiency trends continue in future as well (refer to Table A1).

Similar to thermal comfort, the difference between the magnitude (85 % in 2050) between IMAGE and MESSAGE_ACCESS is mostly caused due to use of different methodologies and databases by the models. The models in this study estimate energy demand from appliances bottom-up using either an engineering approach (PIER, SAFARI, IMAGE) or structural econometrics (MESSAGE_ACCESS). In an engineering approach, energy demand for appliances is estimated based on their penetration, use and efficiency. In turn, these typically depend on projected changes in a combination of variables such as floor space, income levels, economic activity, service needs, technological evolution, energy prices, access to quality supply, aspirations and preferences. There is significant heterogeneity in trends of some of these variables along the temporal, spatial and consumer type dimensions. In an engineering approach, energy demand for appliances is estimated based on their penetration, use and efficiency. In turn, these typically depend on projected changes in a combination of variables such as floor space, income levels, economic activity, service needs, technological evolution, energy prices, access to quality supply, aspirations and preferences. There is significant heterogeneity in trends of some of these variables along the temporal, spatial and consumer type dimensions. In structural econometrics models like MESSAGE_ACCESS, estimate appliance energy demand capturing socio-economic heterogeneity through stimulating the distribution within the population based on household-size, income, and location of the household [75]. We present this contrast in methodologies to understand the data uncertainties for each of the end-use demand.

In all the models, the link between appliance penetration and energy demand is through exogenously specified parameters which can change over time and space. For instance, in PIER and SAFARI, these parameters are appliance efficiencies for different efficiency levels and hours of use. In IMAGE, energy consumption per appliance is specified for each appliance type.

Despite the use of different modelling techniques and databases, all the models are showing a substantial increase with appliance energy demand by 2050 if the present efficiency standards continue, and this increase does not guarantee improvement of decent living standards. Thus, to model the access of different appliances, we use PIER model reference scenario and found that population having access to electricity is about 100 %, access to refrigerator and Television will substantially increase as well (refer to Fig. 7).

Population having access to refrigerator is much higher in the urban residential sector where 70 % of the population have access to refrigerator compared to the rural residential sector, where around 40 % of the population has access to refrigerator (Refer to Table 4). For appliance usage, we use only PIER model, as all the other five models do not produce data on different appliances for the reference scenario. PIER model calculates that population having access to refrigerator in both rural and urban sector would increase significantly, where almost the whole population living in urban residential sector will have access to

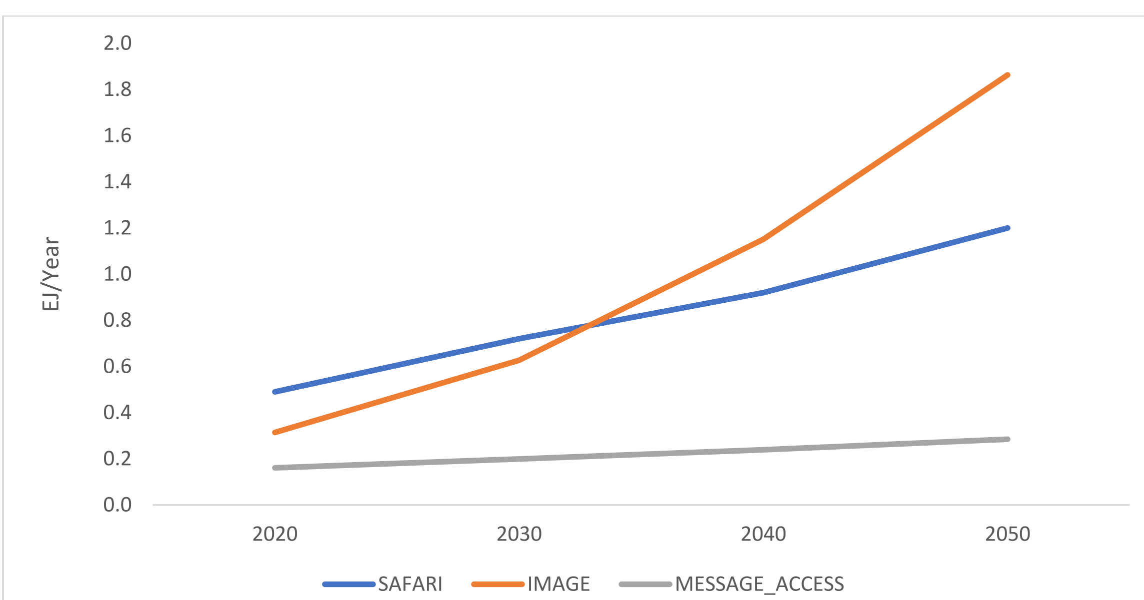

Fig. 6. Residential energy demand of India for appliance usages considering present efficiency standards by using SAFARI, IMAGE and MESSAGE_ACCESS model reference scenario.

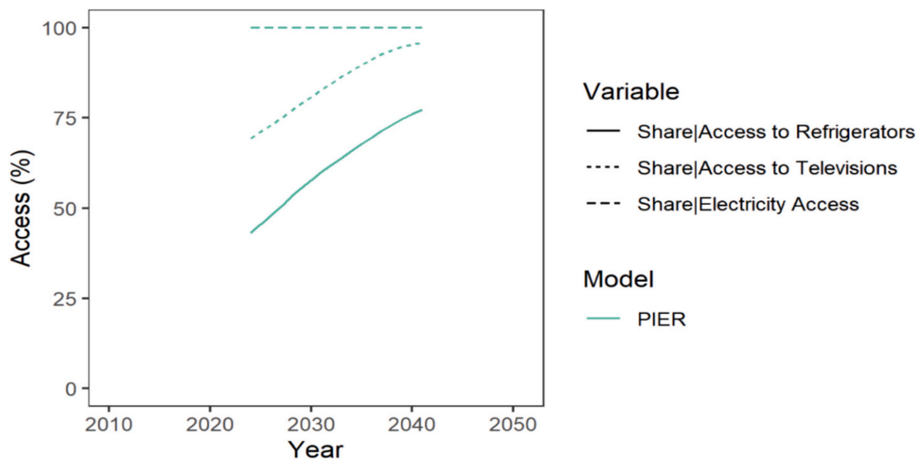

Fig. 7. Percentage population access to appliances In India.

refrigerator, and majority of the population (around 78 %) living in rural area will have access to refrigerator by 2040. In contract to the refrigerator trend, population having access to television is almost the same in rural and urban residential sector, which is expected to increase to almost 100 %, i.e. almost the entire population in both the rural and urban residential sector will have access to the television by 2040.

Similar to RAC, the price of a five-star refrigerator is expensive compared to single star, and as a result, the market share for five-star refrigerator accounts around 25 % only, whereas around 32 % of the market share is accounted by one- and two-star refrigerator (Sing et al. 2019). Also, majority of refrigerator is owned by Indian Urban population (around 75 %), whereas Television ownership is almost same in urban and rural population [76].

5. Conclusion

India stands at a crucial juncture where sustainable practices and responsible consumption can significantly influence the trajectory of its future energy demand and well-being. Implementing energy-efficient design principles, adopting high-efficiency building standards, and integrating renewable energy sources are essential steps toward achieving a balance between providing improved living conditions and minimizing energy consumption. Our research underscores the potential need for India to adopt sustainable and innovative actions that can reconcile these seemingly divergent goals.

With the growing economic growth and population, it is evident that Indian building energy demand would increase substantially, and our models also show the magnitude of this growth. However, empirical evidence from our modelling exercise suggests that increase in energy demand may not always convert fully to improving DLS indicators. For instance, the cooling energy demand is expected to grow by 126–800 % in 2050, but population who will have access to RAC by 2050 is expected to be around 15 % only, which shows a potential inequality, i.e. only 15 % of the population will contribute 150–800 % increase in the thermal energy demand, while rest of the population will still struggle to maintain the basic thermal comfort level, especially in the absence of strong passive cooling measures. By analysing the data obtained from different models, we have further understood, that a way-out from this inequality and high demand future could be easily avoided if we choose for energy-efficient services over conventional sources of energy. For instance, due to access to clean cooking fuel, despite significant increase in population, Indian residential cooking energy demand would decrease by 24–49 % by 2050, while majority of the population will have access to clean cooking.

The data trends presented in this study further show how the use of different methodologies can generate a different range of numbers for the same question, which is: “What are the current trends in DLS achievement and energy demand for basic residential energy services in the Global South?” However, the use of these different models provides a good uncertainty range for the energy demand and DLS indicators. It is important to note that the empirical evidence and discussion in this paper also explain why different models produce different sets of results, which provides additional insights into modelling methodologies. This could be immensely helpful for future modelling work. This research also discusses extensively that it is important to understand there is no single best modelling approach. Considering the complexities and data constraints in modelling energy demand and well-being for countries in the Global South, using multiple models to understand future demand and DLS projections is always advisable.

5.1. Limitation of this research

The findings of this research provide insights into the data uncertainty and methodological features of different modelling approaches. The various data ranges presented in this study emphasize the need for a coherent set of scenarios that incorporate both DLS and energy demand. The different scenarios and models used in this study clearly indicate the need for a coherent modelling scenario to understand future trends in Indian residential demand and its associated DLS. While some models may calibrate to specific data for these energy services, others calibrate to total sectoral energy demand (for instance, from IEA statistics for the residential sector) and then estimate the demand for specific energy services within the residential sector. This highlights a clear area for harmonization between models, methods, and datasets.

The reference scenario of this study provides a solid basis to develop further modelling evidence, particularly related to DLS indicators. Moreover, by discussing different modelling logics and methodologies, this study underscores the need for a coherent database for India that includes data on all end-uses as well as DLS parameter-specific data. Without a coherent database, different models use various data sources and modelling logics, ultimately producing a range of outputs, which can lead to confusion in policymaking.

Additionally, like any quantitative models, the models used in this study are also subject to assumptions and limitations related to the use of data and methodologies. These individual modelling limitations are documented in the model publications cited in Section 3 for each of the models. In this study particularly use reference scenario only for the projections. Thus, new technology uptake or new innovations are not considered in the projections. This study, like many existing energy models, does not include situations such as war, migrations, epidemics, etc., in its projections. This is a common criticism of energy demand modelling. However, the findings of this study remain relevant for two reasons: 1) By examining the projections of energy demand and DLS (desired lifestyle standards), it is evident that an increase in energy demand does not necessarily lead to an increase in DLS. Conversely, a decrease in demand may actually improve DLS in some cases. For example, although the energy demand for cooking decreases over time, more people have access to clean cooking through the Pradhan Mantri Ujjawala Yojana, a current policy initiative. 2) By considering different ranges of projections, this study helps relevant stakeholders to understand why different models produce varying data, thereby emphasizing the need not to rely on a single model.

Through an analysis using various models, we have highlighted the significance of promoting energy-efficient appliances and implementing effective policies as pivotal strategies that can contribute to achieving a harmonious convergence of decent living standards and low energy demand.

As India and many other countries in Global South continues to strive for economic growth and improved living conditions, the findings of this study show the need for incorporating advanced technologies and facilitating policy support as crucial elements in promoting sustainable building practices. Therefore, for our future research, we plan to harmonize key parameters related to energy demand, DLS, and climate change policies to provide a coherent set of scenarios that can further investigate how the Indian residential sector can reduce emissions while improving well-being.

CRediT authorship contribution statement

Souran Chatterjee: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Alessio Mastrucci:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Leila Niamir:** Writing – original draft, Formal analysis. **Kaveri Ashok:** Writing – original draft, Methodology, Investigation. **Ashok Sreenivas:** Writing – original draft, Methodology. **Srihari Dukkipati:** Writing – original draft, Methodology. **Vassilis Daioglou:** Writing – original draft, Methodology. **Oreane Edelenbosch:** Methodology. **Setu Pelz:** Writing – original draft, Methodology. **Benigna Boza-Kiss:** Writing – original draft. **Poornima Kumar:** Writing – original draft. **Diána Ürge-Vorsatz:** Methodology.

Declaration of competing interest

Souran Chatterjee reports financial support was provided by Japan Ministry of Economy, Trade and Industry. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A1
Final energy demand of different end-uses calculated by different models.

End-use energy demand	Models	Unit	2020	2030	2040	2050
Appliance energy demand	SAFARI	EJ/yr	0.5	0.7	0.9	1.2
	IMAGE	EJ/yr	0.3	0.6	1.2	1.9
	MESSAGE_ACCESS	EJ/yr	0.16	0.19	0.23	0.28
Cooling energy demand	PIER	EJ/yr	–	1	1.6	–
	IMAGE	EJ/yr	1.18	1.52	2.09	2.68
	SAFARI	EJ/yr	0.66	2.01	3.81	6.47
	MESSAGE_CHILLED-STURM	EJ/yr	0.60	1.44	2.93	4.31
	HEB	EJ/yr	–	3.34	4.97	5.89
Energy demand to clean cooking	MESSAGE_ACCESS	EJ/yr	1.43	1.54	1.56	1.55
	PIER	EJ/yr	4.36	3.16	2.17	–
	SAFARI	EJ/yr	3.79	3.20	2.97	2.87
	IMAGE	EJ/yr	3.99	3.73	3.82	3.68

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