More with less

Insights from residential energy demand assessment using PIER

Energy Modelling Series

Prayas (Energy Group)

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Prayas (Energy Group), Pune

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Executive summary

Perspectives on Indian Energy based on Rumi (PIER) is an open-data, demand-oriented model built upon the open-source Rumi platform, that enables estimation of energy demand in a bottom-up manner. This paper presents the results and insights emerging from an estimation of residential energy demand up to FY2041 using version 1.5 of PIER. The key insights from this modelling exercise are as follows.

1. **Demand assessment:** The bottom-up analysis undertaken in this exercise shows that it is highly unlikely that India's residential electricity demand will increase by more than about 4% per annum up to FY2041 in any scenario. This is unlike the trends seen in the recent past, and different from the results of other studies such as the 20th Electric Power Survey from the Central Electricity Authority. We believe that supply planning based on detailed bottom-up exercises as done in PIER 1.5 is likely to lead to more prudent investment and power purchase decisions.
2. **Role of efficiency:** The model results show that an effective appliance energy efficiency regime can enable many more households to achieve material comforts by owning and using appliances without a commensurate increase in electricity demand. With the current energy efficiency regime from the Bureau of Energy Efficiency, energy demand increases only moderately even with a seven-fold increase in the number of households using ACs and more than a doubling of the number of households using refrigerators. If this can be further strengthened by a stronger implementation regime that ensures that efficiency of appliances sold in the market are close to the notified standards, it can have a bigger impact on residential energy demand. This can help support a significant improvement in quality of life with better affordability, lower investment needs and reduced environmental footprint. It can also partially help with the question of financial viability of distribution utilities, since many residential consumers pay subsidised tariffs.
3. **Electricity load:** Space cooling (fans, ACs and air coolers) remains the major contributor to residential electricity demand. ACs alone contribute to more than three-fourths of the increase in residential electricity demand between FY2024 and FY2041 across scenarios. Space cooling is also the largest contributor to peak residential electricity load which occurs on summer evenings. Increasing use of induction-based electric cooking also contributes to peak load, though its contribution to energy demand is small. These changes result in residential electricity load curve getting significantly 'peakier' over time. Dealing with this would require strengthening the distribution system, and identifying mechanisms to meet the peak load, particularly as the grid becomes increasingly dominated by renewables, in particular, solar generation.
4. **Behavioural aspect:** Results from the various scenarios suggest that how consumers use appliances is a potentially greater determinant of residential electricity demand than how many consumers own and use appliances. This suggests that measures to influence consumers' usage of appliances can be an effective way of managing electricity demand even as more Indian households own electrical appliances.
5. **Modern cooking fuels:** By FY2041, it is expected that 94% of Indian households will use modern cooking fuels such as LPG, PNG, electricity or biogas. However, this means that almost 27 million households – all of them in rural India across seven states – would still be using solid fuels for cooking even in FY2041. This calls for some targeted policy measures to address this issue given the significant health and gender impacts of solid fuel use.

1 Introduction

Perspectives on Indian Energy based on Rumi (PIER) is an open-data, demand-oriented model built upon Rumi, an open-source energy systems modelling platform (Prayas (Energy Group), 2022). PIER enables estimation of energy demand for each demand sector in a detailed bottom-up manner or through coarser means. The first version of PIER was released in Nov 2021[1]. An improved second version of PIER (PIER 2.0) is under development, and is expected to be released later in 2023. The major enhancements being undertaken in PIER 2.0, are extending the time horizon to 2040-41, making the time granularity finer, estimating demand for the transport and industry sectors in a bottom-up manner, and incorporating emerging technologies and energy carriers. This paper presents the results and insights from modelling the demand of the residential sector in the process of building PIER 2.0. As PIER 2.0 is still under development and may undergo some changes, the version of the model used to derive the results in this paper is labelled PIER 1.5. It is expected that the primary findings and insights from this exercise will also hold good in PIER 2.0, though the numbers may vary to an extent.

1.1 Residential model in PIER 1.5

The broad structure of the residential sector model in PIER 1.5 is similar to PIER 1.0. A detailed description of the methodology and set of assumptions used in PIER 1.0 is given in (Prayas (Energy Group), 2021). Appendix I of this paper provides a list of major methodological and input data changes in this version compared to 1.0. A brief overview of the residential model in PIER 1.5 is provided here.

The residential sector energy demand is modelled up to the year 2040-41 or FY2041. It has been modelled separately for 25 "states"[2] in India, with each state further split into urban and rural households. The demand is modelled bottom-up for five energy services namely lighting, cooking, space cooling, refrigeration and television viewing. Each of these services is provided by a set of technologies, namely light bulbs (incandescent, CFL and LED) for lighting; biomass (solid fuels), liquefied petroleum gas (LPG), biogas, piped natural gas (PNG) and electric induction cookstoves for cooking; fans, air coolers and air-conditioners (ACs) for space cooling; direct cool and frost-free refrigerators for refrigeration and televisions for television viewing. The energy required for services that are not modelled bottom-up (e.g. washing machines, water heating, computers, mobile phones etc.) is estimated exogenously[3]. Electricity provides all the unmodelled services, and this energy demand is estimated by calibrating the state-wise modelled bottom-up residential electricity demand for 2021-22 against actual state-wise residential electricity demand for 2021-22 as published in the All India Electricity Statistics (Central Electricity Authority, 2023).

All energy services other than cooking are provided only by electricity, whose demand is useful to estimate at a finer temporal granularity than just at the annual level. Therefore, electricity demand for the modelled energy services is estimated for each hour in one representative day in each of five seasons, namely summer, monsoon, autumn, winter and spring in each year. This

[1] A newer 1.1 version was also published in April 2022 with some minor changes.
[2] Each "state" is either an actual Indian state or a collection of some smaller states or union territories.
[3] Electricity demand for charging vehicles at home will be accounted for under the transport sector in PIER.

enables a better understanding of seasonal and diurnal electricity load in addition to annual electricity demand.

The most critical parameters to estimate the energy demanded for any energy service at a particular time and geography are the number of users of the energy service[4] (e.g. number of households using electric lighting or an AC), the amount of energy service demanded per user (e.g. hours of lighting or cooling-degree hours of space cooling by ACs) and the specific energy consumption (SEC) or efficiency[5], of appliances providing the energy service (e.g. wattage of the light bulbs or kWh of electricity per cooling-degree hour for ACs). The number of households demanding an energy service is projected based on unit level data from the fourth and fifth rounds of the reports of the National Family Health Survey or NFHS (Ministry of Health and Family Welfare, 2021), and growth rates of per-capita GSDP of the respective state in the period between the fourth and fifth rounds of NFHS.

Estimation of the amount of energy service demanded varies by energy service. Hourly space cooling demand is estimated based on geographically disaggregated projections of temperatures and assumptions about the temperature at which appliances such as fans and ACs are used[6]. Reasonable assumptions are made about the usage hours of lighting, televisions and (electric) cooking, while refrigerators are assumed to run through the year. The efficiency for most appliance types is based on assumptions about notifications from the Bureau of Energy Efficiency (BEE) as described later.

1.2 Scenarios modelled

Five scenarios have been modelled as part of this exercise representing a range of future trajectories of the key parameters that determine energy demand viz., appliance efficiency, ownership and usage. The other key parameter that determines energy demand, namely demographics, is the same across all scenarios and is based on the state-wise rural-urban population projections given in (National Commission on Population, 2020). The Likely Efficiency Trend (LET) scenario reflects what is the most likely ongoing trend of efficiency improvement over time through notification of efficiency standards. It also assumes default appliance ownership and usage. Three other scenarios are built corresponding to changed assumptions about each of the key parameters – efficiency, ownership and usage. Thus, the Desired Efficiency Trend (DET) scenario assumes that efficiency standards evolve along a desired trajectory, which involves a slightly faster revision of standards than LET and more stringent implementation of the standards. DET has the same assumptions regarding ownership and usage of appliances as LET. The High Ownership (HO) scenario assumes a higher ownership of appliances compared to LET, while the High Usage (HU) scenario assumes a higher usage of appliances. The other assumptions in both these scenarios are the same as LET. Finally, a High Consumption (HC) scenario is modelled which represents a combination of efficiency, ownership and usage from the LET, HO and HU scenarios respectively. Table 1 summarises the five scenarios.

[4] Based on the percentage of households owning an appliance providing the service.

[5] The model inputs provided are for SEC – the energy required to provide one unit of energy service – which is the inverse of efficiency (energy service per unit of input energy). However, for simplicity, we use the terms efficiency and SEC interchangeably throughout this paper.

[6] This is further adjusted to account for household occupancy.

Table 1: The modelled scenarios

Scenario name	Ownership	Usage	Efficiency
Likely Efficiency Trend (LET)	Standard	Standard	• Efficiency standards revised every four years for all appliances except fans (revised once in six years) • 'Actual' appliance efficiency is 60% of notified efficiency • Gradual shift to higher star-rated appliances
Desired Efficiency Trend (DET)	Standard	Standard	• Efficiency standards revised once in four years for all appliances • 'Actual' appliance efficiency is 80% of notified efficiency • Slightly faster shift to higher star-rated appliances
High Ownership (HO)	Greater uptake of appliances than standard	Standard	Similar to LET
High Usage (HU)	Standard	Cooling appliances turned on 2°C earlier; greater use of lighting and TVs	Similar to LET
High Consumption (HC)	Similar to HO	Similar to HU	Similar to LET

Notes:

- "Standard" ownership refers to past trends of appliance ownership as a function of per-capita GSDP broadly continuing into the future for each state and urban/rural geography, with some modifications to adjust for cases of extremely high or low growth
- "Standard" usage refers to fans, ACs and coolers being switched on at a particular 'trigger temperature'; lighting being used in the evenings and early morning; TVs being used for six hours a day[7]; and a certain per-capita useful heat requirement for cooking.

These scenarios enable us to get a good understanding of the likely range of energy demand from the residential sector in the coming decades.

1.3 This paper

The objective of this paper is to share the insights and conclusions that emerge from this residential demand modelling exercise, with a view to informing policy and planning. Section 2 presents an overview of the model, focusing on appliance ownership, usage of modern cooking fuels, and appliance efficiency. The national level results of the modelling exercise are presented in Section 3. The insights emerging from the model results are discussed in Section 4. Section 5 briefly presents some relevant state-level results and findings from the model. The paper concludes in Section 6 by summarising the key insights that emerge from the modelling exercise. Some additional details are provided in the appendix.

[7] This is consistent with BEE's assumption while defining the efficiency standards for televisions (Bureau of Energy Efficiency, 2022b).

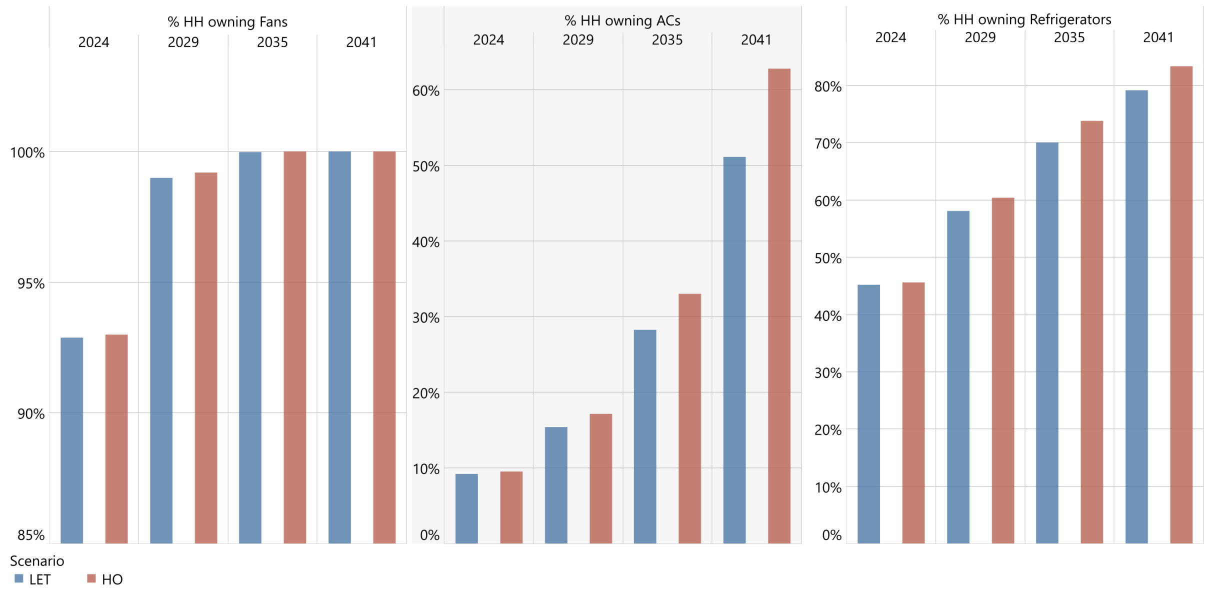
2 The model

2.1 Appliance ownership

Extrapolating recent trends, appliance ownership in India is estimated to increase significantly during the model period (defined as FY2024 to FY2041) even in the 'default' case as represented in the LET, DET and HU scenarios. Following schemes such as RGGVY[8] and Saubhagya[9], it is assumed that 100% of households in India use electricity for lighting through the model period in all cases. As per the model projections, all households in India also possess fans by FY2038 in the default case. In addition, by FY2041, 79% of Indian households own refrigerators and 96% own TVs in the default case. Moreover, 51% of Indian households in FY2041 are estimated to own ACs[10] – which may currently be considered as 'luxury goods' – with the ownership growing at 12% per annum between FY2024 and FY2041. The household AC penetration numbers are 72% for urban households and 34% of rural households in FY2041. Thus, in FY2041, every other household in India is likely to own an AC (compared to just 7% households in FY2021), with every third household even in rural India owning an AC (compared to just 1.7% in FY2021). In other words, even in the default case, Indian households are expected to achieve a reasonable standard of living by FY2041 if one considers ownership of fans, refrigerators and ACs as a proxy for well-being.

In the HO (and HC) scenarios, the share of households estimated to own an appliance is greater than in the default case. For each of the three major appliances – fans, ACs and refrigerators – the charts in Figure 1 show the percentage of households that are expected to own the appliance over the years, under the default as well as high ownership cases.

Figure 1: Household penetration of fans, air-conditioners and refrigerators in the default and high ownership cases[11]



[8] Rajiv Gandhi Grameen Vidyutikaran Yojana
[9] Pradhan Mantri Sahaj Bijli Har Ghar Yojana (https://saubhagya.gov.in/)
[10] Note that, in PIER, all households that own ACs (or air coolers) also own fans.
[11] In all charts and tables in this paper, years refer to financial years. That is, 2024 refers to FY2024, i.e. 2023-24. Scenarios are referred to by their short names (LET, DET, HO, HU and HC). The penetrations are projected from FY2022 though results are presented from FY2024. Hence, the values for FY2024 also differ across scenarios.

As per the projections, not surprisingly, there is little difference in penetration between the two cases for appliances that have a high initial penetration. Thus, almost all households in India are likely to own fans by about FY2035 in both the cases. But for appliances with relatively lower initial penetration such as ACs, the penetration in the high ownership case is over 10 percentage points more in FY2041 (51% in the default case and 63% in the high ownership case). This translates to about 60 million more ACs (23%) being in use in India in FY2041 in the high ownership case, as compared to the default case. The difference between the two cases for the number of fans and refrigerators in use in FY2041 is more than 20 million each[12]. Table 2 presents the number of these appliances in India in FY2041 under the different cases, while Appendix II lists the number of these appliances for each state in FY2024 and FY2041 under both the cases.

Table 2: Number of fans, ACs, refrigerators in India in FY2041 under different scenarios

Scenarios	# Fans (millions)	# ACs (millions)	# Refrigerators (millions)
LET, DET, HU	957	272	357
HO, HC	983	336	380

2.2 Usage of modern cooking fuels

Access to, and use of, modern cooking fuels is one of the major energy access challenges in India. Moreover, household air pollution caused by use of solid cooking fuels is a major public health concern. PIER models four different modern cooking fuel options namely LPG, PNG, induction-based electric cookstoves and biogas. Buoyed by increasing incomes, greater awareness and programmes such as the Pradhan Mantri Ujjwala Yojana (PMUY)[13], access to modern cooking fuels has increased rapidly in India in recent years, and has attained the 100% mark (Petroleum Planning and Analysis Cell, 2023). However, due to challenges around affordability and availability, regular usage of modern cooking fuels stood at only 60% nationally in FY2020, with about half of rural India still using solid fuels such as biomass (Ministry of Health and Family Welfare, 2021)[14].

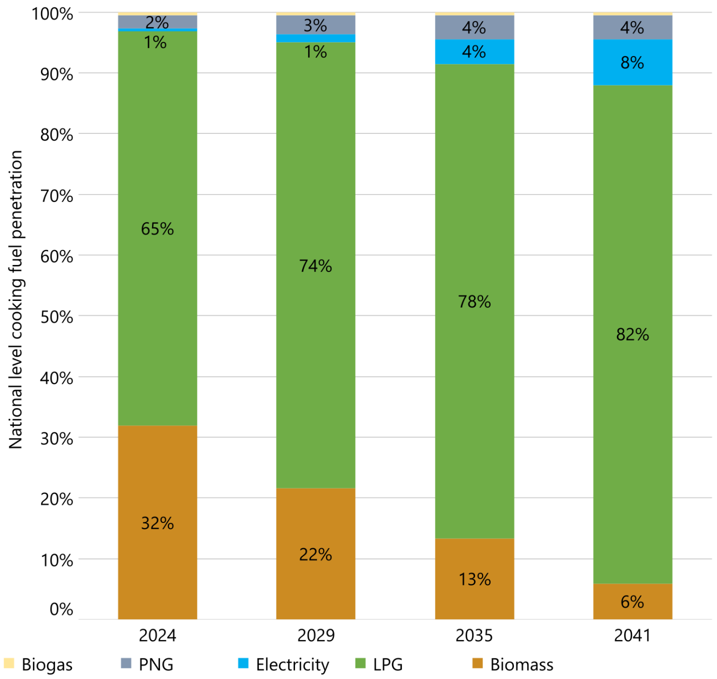
Figure 2 shows the national penetration of cooking fuels over the years in PIER. The share of modern fuels is estimated to increase from 68% in FY2024 to 94% in FY2041 in the default ownership case. Among the modern cooking fuels, LPG is estimated to be the predominant fuel with its penetration going up from 65% in FY2024 to 82% in FY2041. Given India's plans to rapidly increase the geographic area covered by PNG, its penetration is estimated to double from 2% of households in FY2024 to 4% in FY2041. The fastest growth in penetration among cooking fuels occurs with electric induction-based cooking – estimated to increase from a mere 0.5% households in FY2024 to 7.6% households in FY2041. Biogas penetration is likely to remain nearly constant over the period at about 0.5% households.

[12] Despite all the households having fans by FY2041 in both scenarios, there are 25 million more fans in the high ownership case because, it is assumed that each household owns a greater number of fans in this case.

[13] https://www.pmuy.gov.in/index.aspx

[14] 'Stacking' of cooking fuels – i.e. usage of multiple fuels in the same household – is not modelled in PIER. Households are assumed to use the 'primary' fuel for all their cooking needs. All biomass use is assumed to be traditional biomass.

Figure 2: National level cooking fuel penetrations in the Likely Efficiency Trend scenario



Note that, even though only 6% of Indian households are likely to use biomass and solid fuels for cooking in India in FY2041, this represents a significant 27 million households, all of which are in rural India[15]. This effectively means that, according to PIER projections, only 89% of rural Indian households use modern cooking fuels even in FY2041.

2.3 Appliance efficiency

As indicated in Section 1.2, two broad trends of efficiency trajectories have been modelled. In the LET, HO, HU and HC scenarios, the trajectory of efficiency improvements for new appliances with mandatory efficiency standards is modelled broadly based on current practices. Under this, revised efficiency standards are notified by BEE every four years for ACs, refrigerators and TVs, while it is assumed that it would be revised once in six years for fans[16]. Current efficiency notifications for these appliances can be found at (Bureau of Energy Efficiency, 2021; Bureau of Energy Efficiency, 2022; Bureau of Energy Efficiency, 2022a; Bureau of Energy Efficiency, 2022b). Each revised efficiency notification moves the efficiency levels of the various star-ratings of appliances up one notch, in accordance with normal BEE practice[17].

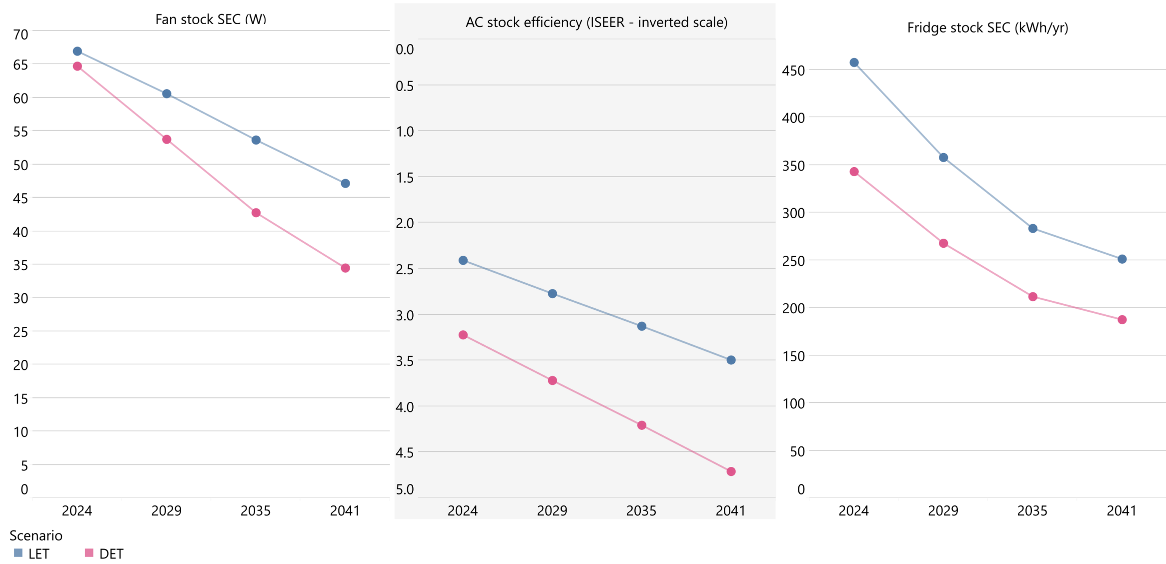
The notified efficiency is based on results conducted under laboratory conditions and may not hold in real usage conditions. There is general consensus among experts that actual achieved efficiencies are considerably lower than the notified efficiencies, though there is little hard

[15] In the high ownership case, this number reduces to a little under 20 million households (4%).
[16] Efficiencies of the stock of other appliances (coolers, lighting appliances and various cookstoves) are assumed to slowly improve. The rate of improvement in the LET is assumed to be a little slower than in the DET scenario.
[17] That is, the efficiency of a 1-star appliance in the new cycle would be what it was for a 2-star appliance in the previous cycle; the efficiency of a 2-star appliance would be what it was for a 3-star appliance and so on. The ratio of the efficiency of the 5-star appliance to the 4-star appliance in the latest BEE notification for that appliance is used to estimate the efficiency of 5-star appliances in future notifications. It is implicitly assumed that such efficiency improvements are technically feasible up to FY2041. The values in the BEE notifications are translated to SEC values using assumptions for factors such as the amount of air delivery required, the size of the room being cooled and the size of the refrigerator.

evidence to quantify the difference. Limited evidence from actual measurement of a small sample of appliances suggests that it may not be very high (Prayas (Energy Group), 2019). Therefore, 'real life' efficiency of appliances is assumed to be 60% of the notified efficiency in LET.

In the second case (DET scenario), a more optimistic trajectory of efficiency improvement is modelled. It is assumed that efficiency standards of all appliances, including fans, are revised once in four years. When they are revised, they are revised similar to the LET scenario. In addition, the 'real life' efficiencies of appliances are assumed to be 80% of the notified efficiency due to better implementation. In this scenario, consumers also shift to higher rated appliances at a faster rate than in the LET scenario.

Figure 3: National average efficiency of the stock of various appliances in the different scenarios



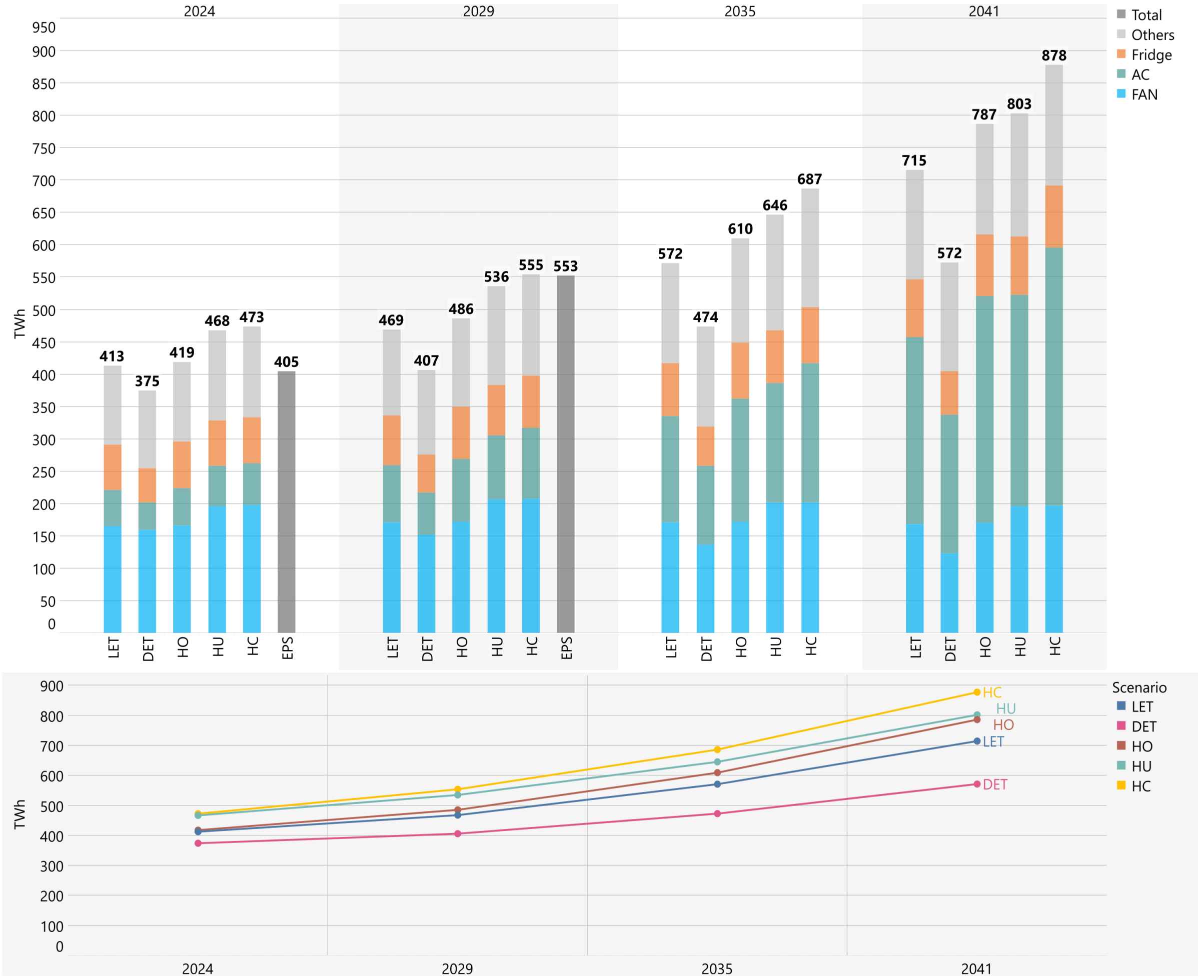
Note that the notification of standards is relevant only for *new* appliances. Overall efficiency of the stock of appliances in a particular state-geography-year is calculated as the weighted average efficiency of pre-existing and newly purchased appliances. Appliances also have an assumed lifetime, after which they get replaced by a newer appliance. Figure 3 shows the projected national weighted average efficiency of the stock of the three most critical appliances: fans, ACs and refrigerators. SEC values are depicted for fans and refrigerators (W and kWh / year respectively), where lower values indicate higher efficiency. For ACs, ISEER[18] values that are shown correspond to efficiency, i.e. a higher value indicates greater efficiency – hence this chart is shown in inverted scale. The average AC in India in FY2041 has an ISEER of 3.5 under LET but is nearly 33% better at 4.7 in DET. Similarly, the average fan and refrigerator in India in FY2041 consume 47 W and 281 kWh / year respectively in LET as against only 34 W and 187 kWh / year respectively in DET[19].

[18] Indian Seasonal Energy Efficiency Ratio, a unitless value, indicating the heat energy dissipated per unit of input energy.
[19] To put this in context, the average fan consumed about 70 W before they were brought under mandatory efficiency standards.

3 Model results

3.1 Electricity demand

Figure 4: Projected national residential electricity demand under the various scenarios



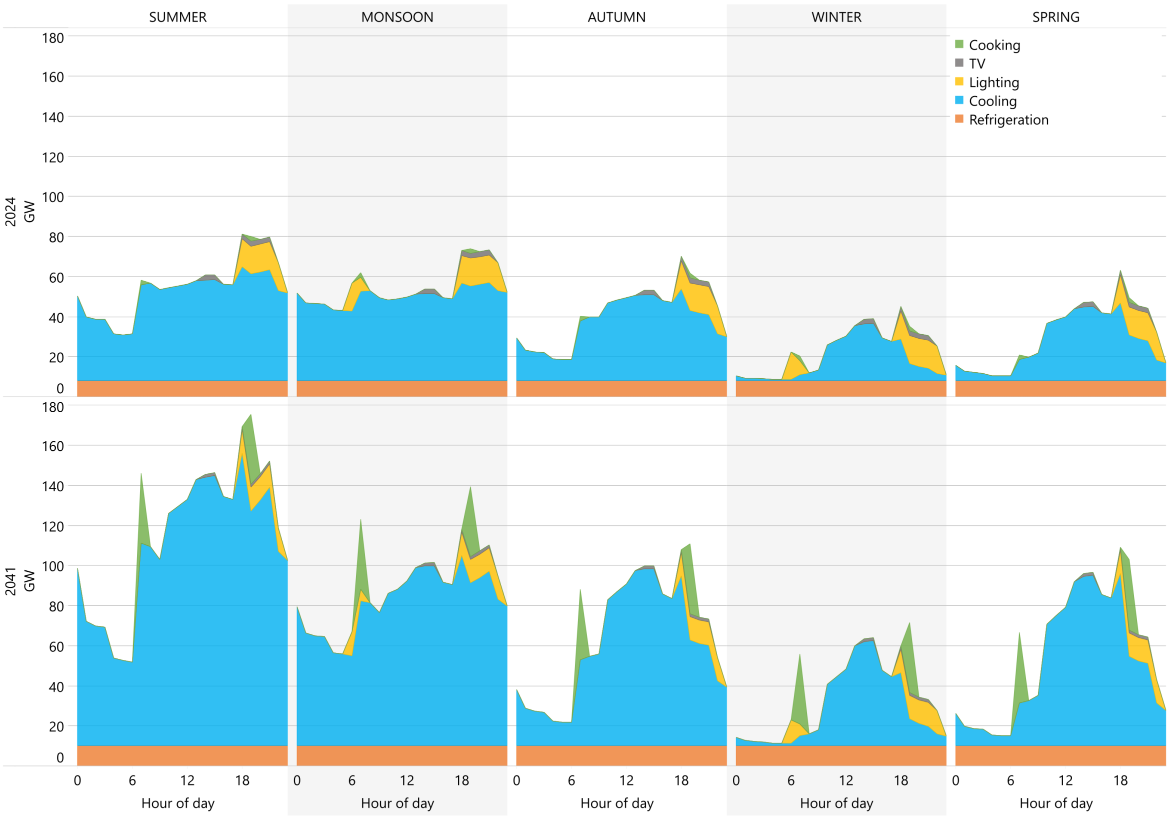
The electricity demand results of this modelling exercise at the national level are shown in Figure 4. In the first chart, the projected demand is shown separately for the three most important appliances (fans, ACs and refrigerators), and the demand for the rest is clubbed together into "Others" which includes lighting, cooking, televisions, air coolers and unmodelled energy services. For two years (2024 and 2029), the graph also shows residential electricity demand as projected by the 20th EPS of CEA (Central Electricity Authority, 2022). The second chart in the same figure shows the demand growth under each of the scenarios for easier comparison.

In LET, residential electricity demand is projected to increase from 413 TWh in FY2024 to 715 TWh in FY2041, growing at 3.3% per annum. In DET, when efficiencies improve faster, the projected demand increases from 375 TWh in FY2024 to 572 TWh in FY2041, growing at only 2.5% per annum. At the other extreme, in HC, it is estimated to increase from 473 TWh to 878 TWh over the same period growing at 3.7% per annum – a higher growth rate than the other scenarios but still significantly lower than the growth rate of 7%-8% observed in the past decade. As discussed later, these seemingly low growth rates are due to regular revision of efficiency standards, replacement of older appliances by newer (more efficient) ones after their lifetime, a gradual shift to higher star-rated appliances, and gradual saturation of penetration of some appliances.

From Figure 4, it is clear that efficiency plays the most significant role in determining demand across scenarios, as compared to ownership or usage. The FY2041 demand in DET is as much as 20% (143 TWh) lower than LET. In contrast, the demand in FY2041 is only 10% (72 TWh) higher in HO and 12% (88 TWh) higher in HC, compared to LET. It is interesting that HU (803 TWh) results in slightly greater demand in FY2041 than HO (787 TWh), even though there are about 60 million more ACs and 25 million more fans in HO.

3.2 Electricity load

Figure 5: Residential electricity load-shape for modelled bottom-up energy services in the Likely Efficiency Trend scenario



The PIER model produces temporally disaggregated results for electricity services that are modelled bottom-up, which allows one to infer the load-shape of residential electricity demand. The national residential demand load shape estimated for the modelled bottom-up services is depicted in Figure 5 for the years FY2024 and FY2041 for LET. Since the energy demand from unmodelled services is less than 15% in most years, the broad inferences are likely to remain valid even after considering the unmodelled energy services.

Unsurprisingly, residential peak load occurs on summer evenings when cooling demand is highest. The all-India residential load for the modelled services is estimated to be about 81 GW in FY2024 summer evening in the LET scenario, which more than doubles to 175 GW by FY2041, growing at 4.6% per annum. This growth rate is higher than the growth rate of electrical energy demand in the scenario indicating that residential demand is likely to get 'peakier' over time.

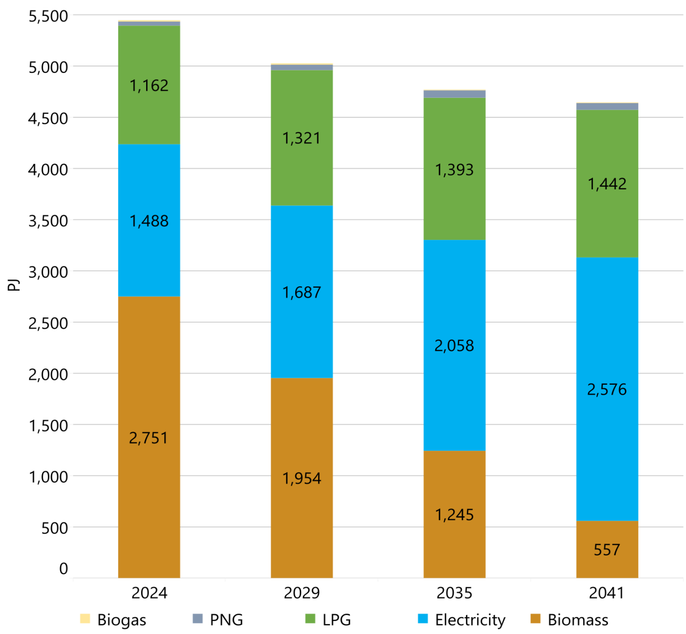
Conversely, early winter mornings are expected to have the lowest residential load. In FY2024, it is about 8.7 GW from the modelled energy services, which increases to about 11.3 GW by FY2041. In these time slots, there is hardly any other (modelled) load other than refrigeration whose load is constant throughout a year.

3.3 Total residential energy demand

Energy required for cooking constitutes a huge part of total residential energy demand. This is more so when many households are dependent on solid fuels for cooking because traditional biomass cookstoves have very low energy efficiency compared to modern cooking options such as LPG, PNG or induction cookstoves.

As a result, the shift from inefficient biomass cookstoves to efficient modern fuels results in a *reduction* in total energy required for households in India over the years, as projected by PIER. In LET, the estimated energy demanded by households *decreases* at 0.9% per annum from 5,448 PJ in FY2024 to 4,650 PJ in FY2041. This is despite the fact that the number of households increase during this period, and that households own and use more electrical appliances. This is depicted in Figure 6.

Figure 6: Total residential energy demand (PJ) by energy carrier in the Likely Efficiency Trend scenario



Of the energy carriers, biomass naturally sees a major reduction in use – decreasing by nearly 2200 PJ from 2751 PJ (177 million tonnes or MT) in FY2024 to just 557 PJ (36 MT) in FY2041. In contrast, the use of electricity increases from 1488 PJ to 2576 PJ. The use of LPG too increases from 1162 PJ (24.6 MT) to 1442 PJ (30.5 MT), while PNG's contribution increases from 37 PJ (0.98 billion cu m or BCM) to 65 PJ (1.73 BCM) over the same period. Within cooking, though LPG remains the dominant modern cooking fuel, other options such as PNG and electricity increase faster than LPG, with PNG consumption going up at 3.4% per annum and electricity use increasing at 17.3% per annum.

4 Insights from the model results

4.1 The role of energy efficiency

As discussed in Section 2.1, even in the default appliance ownership scenarios (LET, DET, HU), there is significantly greater ownership of appliances in India by FY2041 compared to the present. 51% of Indian households own ACs by FY2041 compared to just 7% in FY2021. Similarly, 79% of Indian households own refrigerators, nearly all households own TVs and all households own fans by then.

Table 3 shows how fast the numbers of the three most important appliances[20] – ACs, refrigerators and fans – grow in the country between FY2024 and FY2041 in LET, and how electricity demand from these appliances grows. As expected, the appliances with low initial penetration grow faster – thus, the number of ACs and frost-free refrigerators increases at more than 10% per annum. The fast growth in frost-free refrigerators is due to the combined effect of increasing number of households owning refrigerators and an increasing share of new refrigerator purchases being frost-free. The growth rate of the number of direct cool refrigerators and fans is slower – the former due to increasing migration of new refrigerator purchases to frost-free and the latter due to saturation of household ownership of fans.

Table 3: Growth rates of the number of select appliances and their electricity demand between FY2024 and FY2041 in LET

	Compounded Annual Growth Rate	
Appliance	Number of appliances	Appliance electricity demand
ACs	12.7%	10.2%
Direct cool refrigerators	2.2%	-1.9%
Frost free refrigerators	11.4%	7.5%
All Refrigerators	5.1%	1.4%
Fans	2.8%	0.1%

For all appliances, the growth rate of electricity demand is slower than the growth rate of the number of appliances because of increasing efficiency of newer appliances over the years. This improves the efficiency of the stock of appliances in two ways – (1) the appliances bought by households for the first time with better efficiency, raises the overall appliance stock efficiency, and (2) older appliances that have completed their life (15 years for most appliances) are replaced by newer, more efficient appliances. As a result, the electricity demand from ACs and frost-free refrigerators grows at 10.2% and 7.5% respectively – lower than the growth rate of appliance numbers but quite rapidly. For direct cool refrigerators, their slower growth in numbers and improving efficiency results in the growth rate of electricity demand actually becoming negative – i.e. the electricity demand for these appliances in FY2041 is lower than the demand in FY2024 though there are more direct cool refrigerators in India in FY2041 than in FY2024. With fans, despite an increase of nearly 20 million in the number of fans in the country between FY2024 and FY2041, electricity demand from fans remains nearly flat, growing at only 0.1% per annum.

[20] The number of appliances is the product of the number of households, the penetration of the appliance and the number of appliances per household.

The combined effect of this increase in the number of appliances and improving efficiency is depicted in Figure 7 and Figure 8 for LET. Figure 7 plots the number of households using ACs, number of households using refrigerators, India's total residential electricity demand and per-household electricity demand from FY2024 to FY2041, after normalising their values to 100 in FY2024. Figure 8 shows the trend of annual average electricity consumption per appliance for fans, ACs and refrigerators.

Figure 7: Relative change in appliance ownership & electricity demand in LET (2024 = 100)

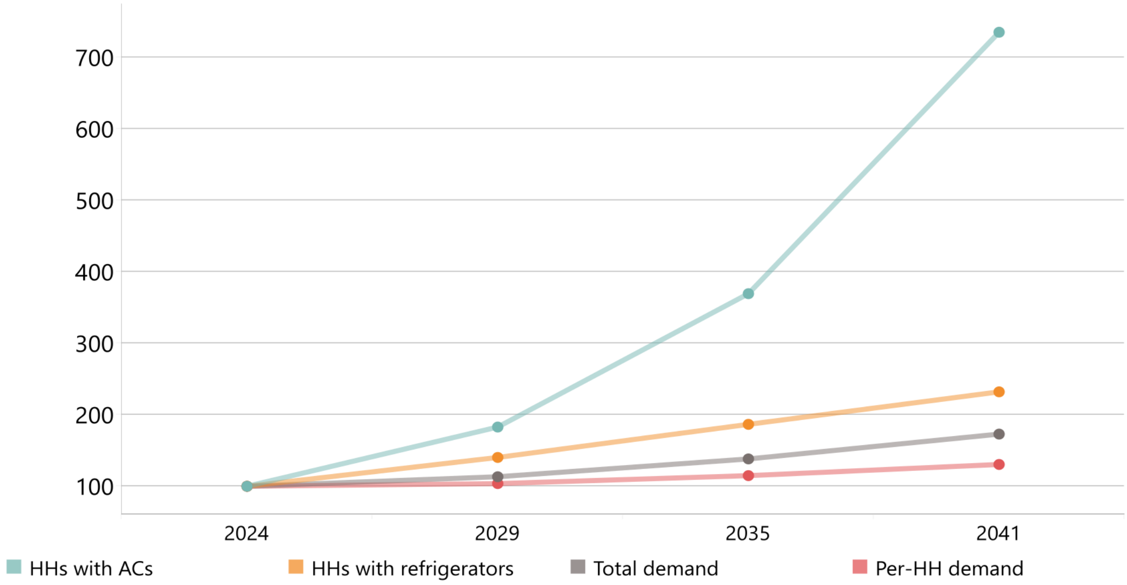
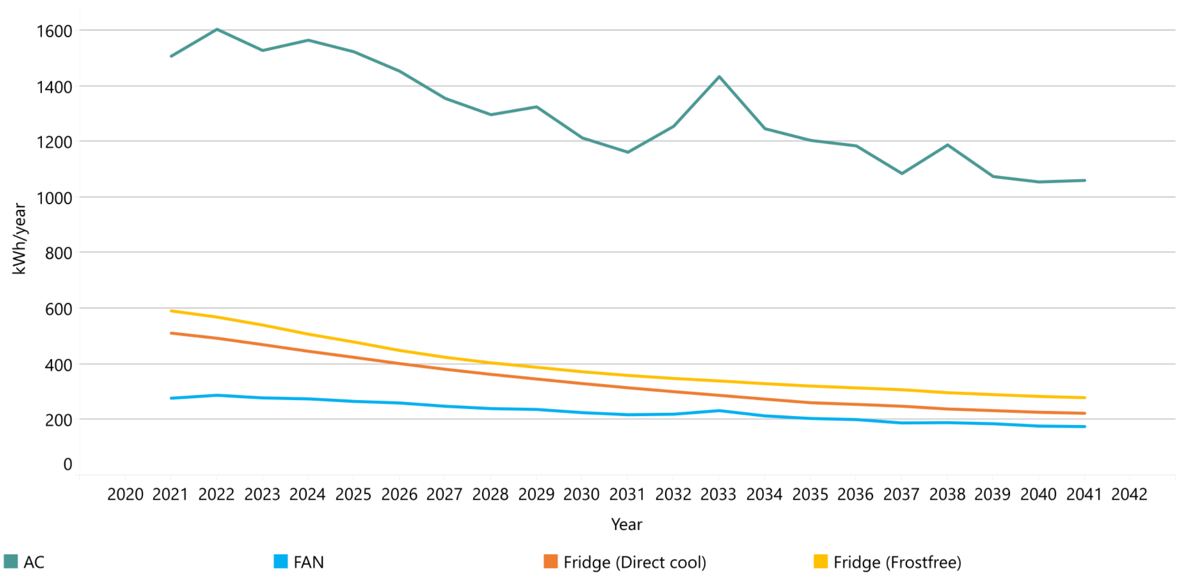


Figure 8: Electricity consumption per appliance per year in LET (kWh/year)[21]



The normalised number of households owning ACs and refrigerators in India in FY2041 increases to a staggering 736 and 232 respectively from 100 in FY2024 in LET[22]. But residential electricity

[21] The figure shows actual consumption per year per appliance. Since this is dependent on the expected temperatures in the year for fans and ACs, their lines are not smooth and have some spikes and troughs.
[22] The actual number of households using ACs and refrigerators increases from 3.1 crore and 15.4 crore respectively in FY2024 to 23 crore and 35.7 crore respectively in FY2041 in this scenario.

demand increases only to 173 and per-household electricity demand increases to only 131 from 100. In other words, more than seven times as many households use ACs and more than double the number of households use refrigerators for only a 73% increase in overall residential electricity demand and 31% increase in average per-household residential electricity consumption in the LET.

The result of such a scenario setup is that the annual residential electricity demand grows at 'only' 3.3% per annum between FY2024 and FY2041. This may seem rather low for a developing country such as India where the expectation is that residential electricity consumption would grow rapidly. However, as discussed above, the model projections are based on significantly increased appliance ownership and use – in other words, significantly greater consumption of energy services. Thus, if India implements its existing energy efficiency regime effectively, the model results show that an increase in owning and using appliances need not be accompanied by commensurate increase in electricity demand.

The projections in this study are considerably lower than what many demand projections estimate. For example, the 20th EPS projections from CEA (Central Electricity Authority, 2022), whose FY2024 and FY2029 values are shown in Figure 4, projects a 6.4% annual growth in residential electricity demand between FY2024 and FY2032, while the PIER projections grow by just 2.8% per annum over this period in LET. The reason for this is probably that the EPS projects future electricity demand largely based on past growth trends. However, we believe this is unlikely to be valid going forward for two reasons: one, the recent past witnessed a great upsurge in households being electrified and hence a surge in appliance purchase which is unlikely to continue at that pace; and two, the recently introduced efficiency regime for ceiling fans – currently the most energy consuming appliance – will reduce consumption from new fans drastically if implemented effectively[23]. As a result, we believe that if India implements an effective efficiency regime as denoted by LET, the growth in its residential electricity demand is likely to be under 3.5% per annum over the next couple of decades while enabling a rapid improvement in its standard of living.

Indeed, if India can improve its energy efficiency regime as indicated by the DET – where fan efficiencies are also revised once in four years, real efficiencies are 80% of notified efficiency and there is a slightly faster switch to higher rated appliances – then India's residential electricity demand can be even lower for the same ownership and use of appliances. In such a case, electricity demand grows only at 2.5% per annum between FY2024 and FY2041, growing from 375 TWh to 572 TWh. In normalized terms, this means that for a seven-fold increase in AC ownership and more than doubling of refrigerator ownership, residential electricity demand increases only by 53% and per-household residential demand increases by only 15% between FY2024 and FY2041. This highlights the role an effective, but practical, efficiency regime can play in enabling material comforts without significant increase in energy demand.

[23] Two other mutually contradictory factors may also play a role in determining the trajectory of future residential electricity demand. Household tariffs for consumption below a certain limit are low in many states, and these thresholds may act as a barrier to increased use of appliances that may take a household past the threshold. In contrast, the increasing trend of many state governments offering certain free units of electricity per month to households might increase consumption. These aspects are not modelled in PIER.

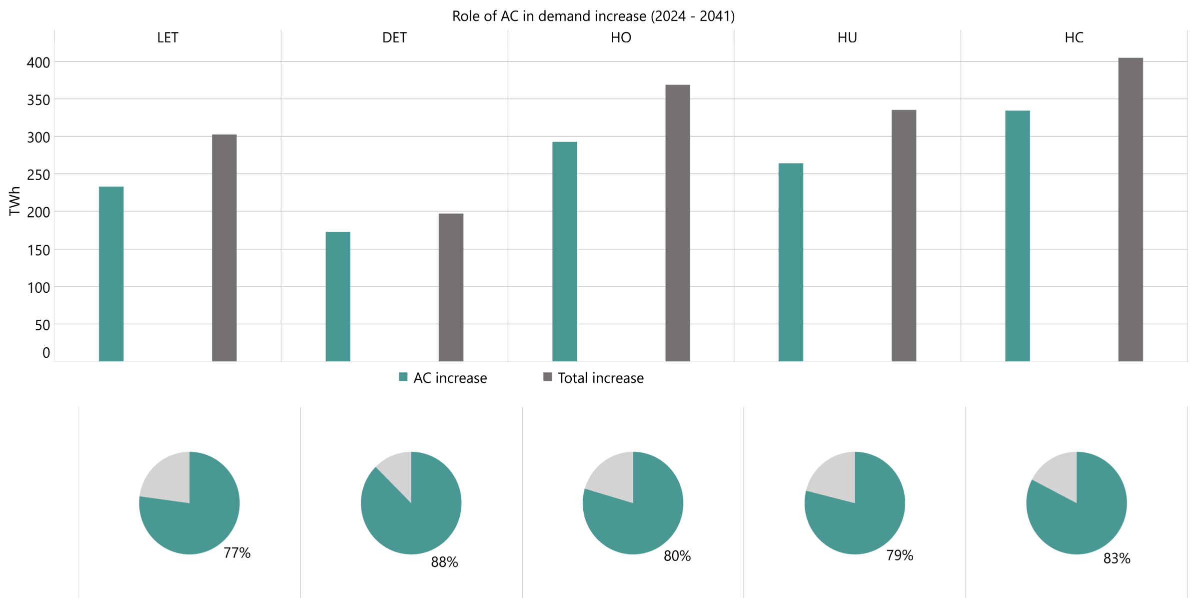
The growth rate of residential electricity demand does not significantly increase even under the other scenarios which model higher ownership and usage of appliances and ranges between 3.2% per annum and 3.8% per annum between FY2024 and FY2041 for the HO, HU and HC scenarios. All these growth rates are significantly lower than those projected by other studies. Therefore, future demand growth rates of 5% - 6% are likely only if appliance ownership and usage grow faster, and efficiency levels improve slower, than even in the High Consumption scenario – which is unlikely.

Interestingly, according to PIER projections, the FY2041 residential electricity demand in HU (803 TWh) is a little higher than the demand in HO (787 TWh). This holds true across all the modelled years, indicating that consumer behaviour (how they use appliances) is a more critical factor in determining demand than ownership of appliances. This suggests that programs aimed at influencing consumer behaviour can also be an effective way of moderating electricity demand even as households own and use more appliances.

4.2 Role of ACs and space cooling

Space cooling dominates the estimated residential electricity demand projections across scenarios. Nationally, it is responsible for between 61% and 67% of residential electricity demand across the years in LET, and between 64% and 70% in HC. Indeed, across scenarios, ACs alone are estimated to be a huge contributor – between 77% and 88% – to the overall increase in residential electricity demand over the years, powered by the fast growth of AC penetration across scenarios. This is shown in Figure 9.

Figure 9: Share of ACs in increasing residential electricity demand across scenarios



In terms of load, space cooling contributes around 70% of the modelled load in residential summer evenings in FY2024. This share increases to over 80% by FY2041 in most evening hours[24]. Indeed, the maximum contribution to load in a single hour from space cooling is 86% in FY2024

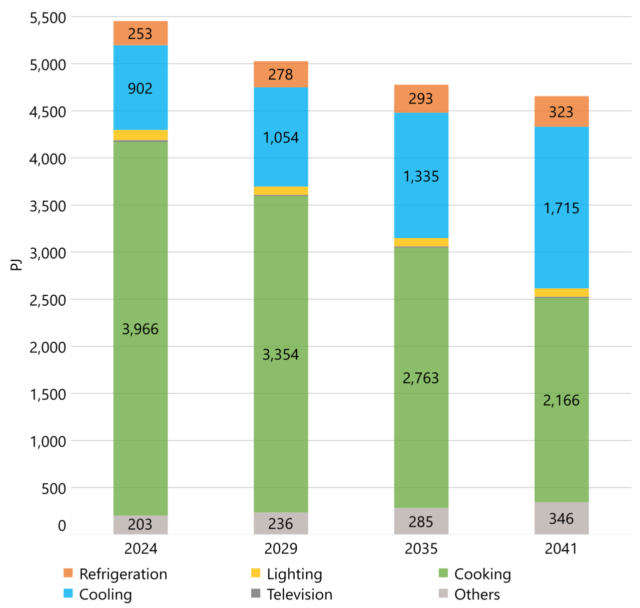
[24] The exception is 7 PM, when induction cooking also contributes significantly to the load. This is discussed later.

and 93% in FY2041. The high share of cooling in residential load can be seen from Figure 5 for LET.

4.3 Role of cooking in residential energy demand

Cooking, as an energy service, dominates residential energy demand, as illustrated in Figure 10 for LET. With a relatively high share of inefficient biomass use, cooking is estimated to take up as much as 73% of the energy consumed in Indian households in FY2024. From 3,966 PJ in FY2024, residential cooking energy demand is expected to fall to nearly half the value (2,166 PJ) by FY2041 due to the shift to modern cooking fuels. As a result of this, and as a result of greater uptake of other energy services, the share of cooking in residential energy demand falls to 47% by FY2041, though it remains the energy service that consumes the highest energy. Space cooling, which has a dominant share in residential electricity demand, is estimated to account for only 17% of residential energy demand in FY2024. But this share is likely to more than double to 37% by FY2041 with rapid uptake of ACs combined with the shift to modern cooking fuels. The predominant role of cooking in residential energy demand does not change much across the modelled scenarios and reflects the energy-intensive nature of cooking.

Figure 10: Residential energy demand by energy service (PJ) in LET



Indeed, as shown in Figure 6, biomass alone is expected to account for more than half (51%) the residential energy demand in FY2024. The shift to modern fuels results in this share becoming just 12% in FY2041. Electricity, which has a share of 27% in FY2024 is estimated to more than double its share to 55% in FY2041, driven by greater ownership and use of appliances and the reducing role of solid fuels. LPG's share is estimated to increase from 21% in FY2024 to 31% in FY2041.

4.4 Impact of electric cooking

It is expected that the use of electricity for cooking – primarily through induction cookstoves – will increase rapidly. This is likely to be driven by a combination of convenience, economics and push from the government (Press Information Bureau, 2023). PIER models such an increase in use of electric induction-based cooking, with the percentage of households using electricity for cooking nationally estimated to increase from a mere 0.5% in FY2024 to 7.6% in FY2041 in LET. As a result, electricity demand for induction-based cooking is estimated to grow the fastest – at 17.3% per annum between FY2024 and FY2041 – among the various modelled energy services, and electricity demand for cooking increases from a mere 1.7 TWh nationally in FY2024 to 25.5

TWh in FY2041, though this accounts for only 3.6% of residential electricity demand in that year in LET.

However, since many households are likely to undertake cooking at more or less a similar time, by FY2041, this small energy demand is likely to contribute significantly to load at specific times. In PIER, it is assumed that cooking takes place in two hours in the day – at 7 AM and 7 PM. Induction-based cooking is likely to lead to a demand of nearly 35 GW in FY2041 in these two hours of the day as shown in the spikes visible in Figure 5 at 7 AM and 7 PM[25]. This is about 20% of the annual peak residential electricity load from the bottom-up modelled services (occurring on summer evenings). Indeed, as shown in Figure 5, PIER results suggest that residential electricity load shapes will have a distinct morning peak by FY2041 in addition to the traditional evening peak. The significant contribution of electric cooking to peak load is seen across scenarios. Thus, while switching to induction-based cooking is desirable for multiple reasons, it is likely to contribute significantly to load at specific hours of the day – even at a national penetration of under 8%. This indicates a need for better network planning and power procurement by distribution utilities (Palit, 2021)[26].

[25] If the cooking load is spread over a larger time, then the load impact would be lower but still significant.

[26] Promoting electricity for cooking may involve other policy issues (e.g. around tariff design) but these are beyond the scope of this paper.

5 State level model, results and findings

5.1 Penetration of appliances and modern cooking fuels

Not surprisingly, there are significant differences across various states regarding penetration of electrical appliances in a country as large and diverse as India.

Figure 11: State-wise penetration of ACs, refrigerators and modern cooking fuels in FY2024 and FY2041 in LET

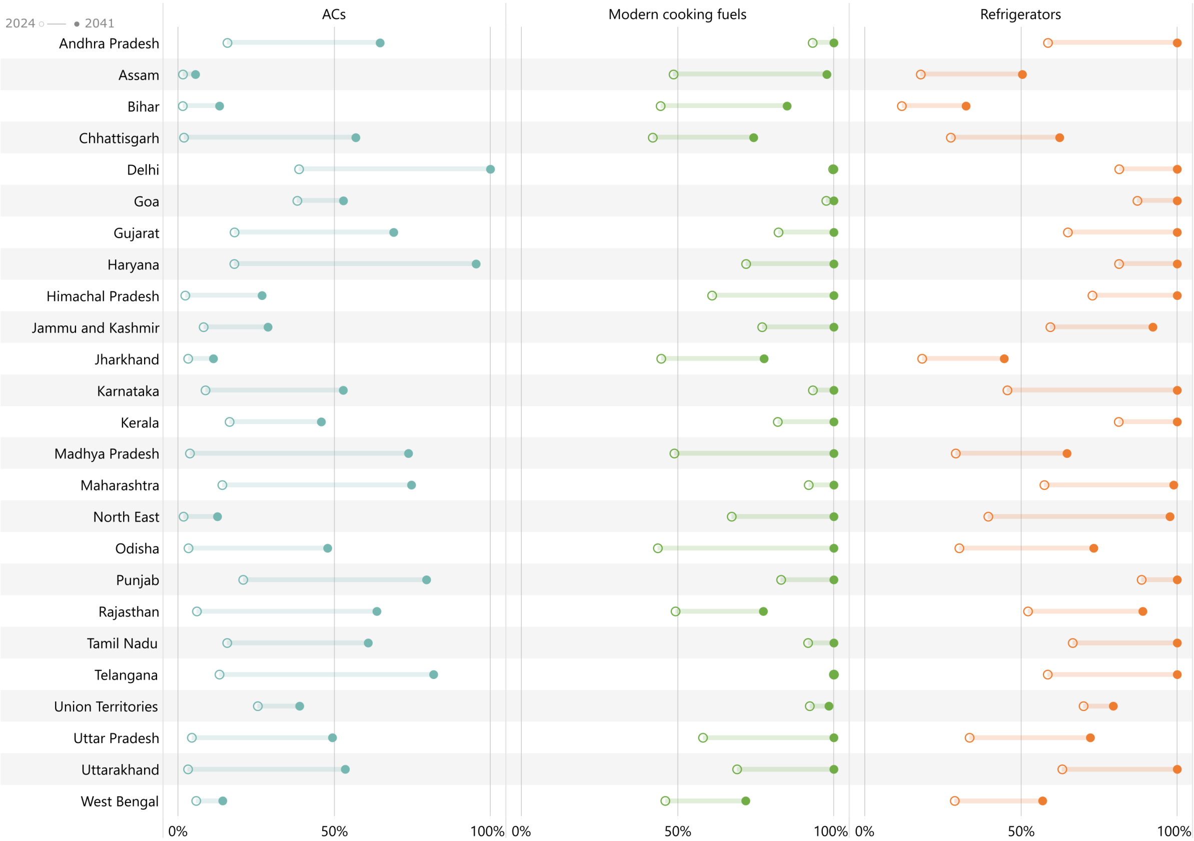


Figure 11 presents state-wise penetration of the three major appliances, namely ACs, refrigerators and modern cooking fuels in LET in FY2024 and FY2041. The following points are noteworthy:

- No Indian state is estimated to have 100% penetration of ACs in rural areas even in FY2041[27]. Indeed, only two states – Delhi and Haryana – are likely to have 100% penetration of ACs even in urban areas by FY2041. As a result, only Delhi has 100% AC penetration by FY2041. Haryana (95%), Telangana (82%), Punjab (80%), Maharashtra (75%) and Madhya Pradesh (74%) are the other states likely to have high AC penetration in FY2041. In PIER, the states with the lowest AC penetration in FY2041 – due to a combination of low penetrations in the starting year, low growth rate of AC penetrations in the recent past and a high share of rural households – are Assam (6%), Jharkhand (11%), Bihar and the North Eastern states (13%) and West Bengal (14%).
- When it comes to refrigerators, as many as 20 Indian states are likely to have 100% penetration of refrigerators in urban households by FY2041. 12 states – nearly half of all

[27] Delhi is the only state in India to be 100% urban in FY2041 – hence, there are no rural households in Delhi in FY2041.

modelled states – achieve 100% household penetration of refrigerators in the entire state. Haryana (FY2030), Delhi (FY2031) and Kerala (FY2033) are estimated to be the earliest to achieve 100% refrigerator penetration. Bihar (32%) and Jharkhand (45%) are the only states in which less than half the households are likely to own refrigerators in FY2041.

- All the urban households in the country are expected to use modern cooking fuels by FY2041. Indeed, they do so by FY2033 itself, with Jharkhand being the last state to do so. As for rural India, 18 of the 25 states are expected to achieve 100% penetration of modern cooking fuels by FY2041. The states that don't achieve it are Assam (98%), Bihar (85%), Chhattisgarh (74%), Jharkhand (77%), Rajasthan (77%), the Union Territories (98%) and West Bengal (72%), with West Bengal having the lowest rural penetration at 54%. This is despite rural West Bengal seeing a growth rate of 5% a year for penetration of modern cooking fuels – one of the highest in the country – because only 20.5% of its rural households use modern cooking fuels in FY2020 as per (Ministry of Health and Family Welfare, 2021). Therefore, the 27 million households estimated to be using solid fuels in FY2041 are spread across the rural areas of these seven states. This suggests that targeted initiatives may be required in these states to address this challenge. Leaving aside Delhi (with no rural households by FY2041), the states which are likely to achieve 100% rural penetration of modern cooking fuels relatively early are Telangana (FY2024), Andhra Pradesh and Karnataka (FY 2027), Tamil Nadu (FY 2029) and Goa, Gujarat and Maharashtra (FY 2030).

5.2 Electricity demand, appliance ownership and role of efficiency

As discussed in Section 4.1, the model results suggest that, if India is able to implement an effective efficiency regime, the increase in residential electricity demand is muted even as appliance ownership increases significantly – thus providing better quality of living with a lower energy, environmental and carbon footprint. We present state-level results on similar lines for many of the 'poorer' states with relatively low initial penetration of appliances such as ACs and refrigerators.

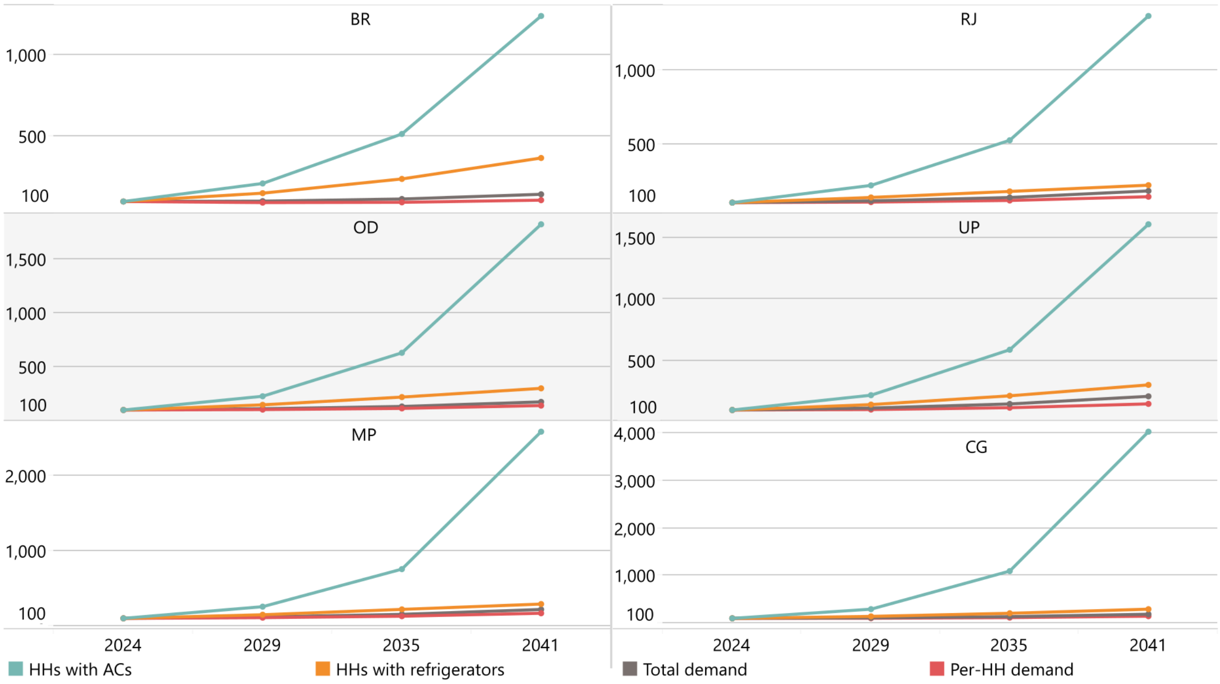
Figure 12 presents normalized graphs for the number of households estimated to own ACs and refrigerators, along with estimated total residential electricity demand and per-household residential electricity demand in LET for six states: Bihar, Odisha, Madhya Pradesh, Rajasthan, Uttar Pradesh and Chhattisgarh. In all these states, less than 6% households are estimated to own ACs in FY2024. By FY2041, in each of these states, the number of households estimated to own ACs increases more than 12-fold[28]. Similarly, the number of households estimated to own refrigerators more than doubles between FY2024 and FY2041 in all these states, with the number more than tripling in a few states. Assuming ownership of such appliances as a proxy for 'welfare', these results indicate that these states experience significant welfare gains over this period.

Figure 12 shows that such increases in appliance ownership do not translate to corresponding increases in residential electricity demand across these states, as estimated annual growth rates of residential electricity demand is below 5% in all these states in LET, with the growth rate being

[28] This is in contrast to the more than 7-fold increase for all of India (Figure 7). Thus, the growth in these states is significantly faster than the national average.

under 4% for four of the six states. This may appear very counterintuitive, given that in many of these states residential electricity demand has been growing at very high rates – sometimes greater than 10% per annum – in the recent past. However, we believe that PIER model results are likely to be a good indication that the (long term) future may not be similar to the recent past. This is because the rapid increase in demand in recent years in these states was mainly driven by a massive household electrification drive which has more or less saturated. Demand in future years would be driven by the ability of households to purchase (a function of disposable income and appliance costs) and use (a function of affordable tariffs and reliable supply) appliances, and by the efficiencies of appliances that get purchased (a function of efficiency standards and market transformation).

Figure 12: Relative changes in appliance ownership and electricity consumption across select states in LET (2024 = 100)



As expected, the growth rates in state residential electricity demand and per-household residential electricity demand are even lower in DET when efficiency of new appliances is better than in LET. Results from PIER indicate that greater acquisition and usage of appliances is unlikely to lead to residential electricity demand increasing rapidly – even in the so-called poorer states – if effective efficiency programs are implemented. However, residential electricity demand in most of these states grows faster than the national average of 3.3% per annum between FY2024 and FY2041 in LET[29].

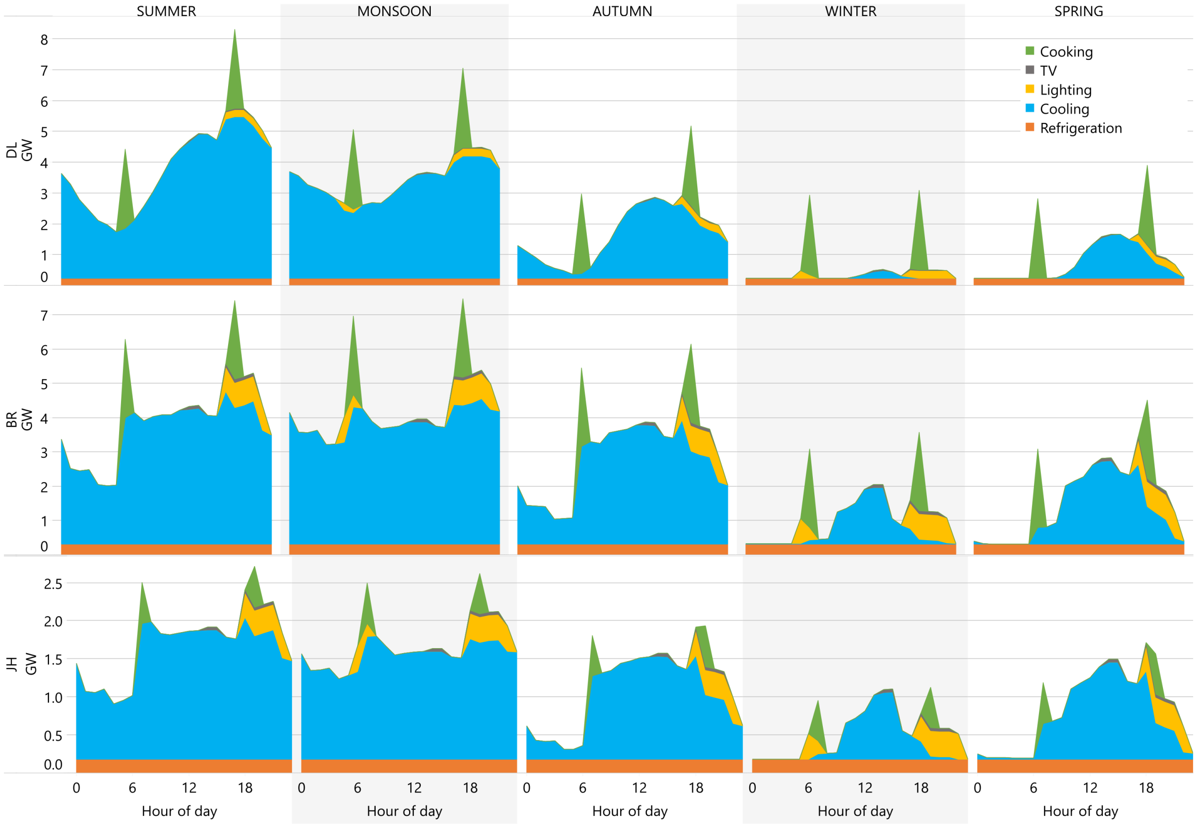
Comparing across scenarios, the demand for these states increases broadly similarly to national demand. The reduction in demand through improving efficiency (in DET) is greater than the increase in demand through increased ownership or usage. In most states, demand in FY2041 is greater under HU than HO, highlighting the role of consumer behaviour. Naturally, the highest demand is seen in HC which combines higher ownership and usage with relatively modest

[29] The exception is Bihar (growing at 2.2% per annum).

efficiency improvement. But even in this case, the growth rate of residential electricity demand in none of these states exceeds 5.5% per annum. Thus, even in these states, the annual growth rate of residential electricity demand is highly unlikely to exceed 5%-6% even in a situation where appliance penetrations increase rapidly[30] and the appliances are used more if the efficiency regime is as per LET. Appendix II provides state-wise residential electricity demand in FY2024 and FY2041 under the LET, DET and HC scenarios.

5.3 Electricity load shapes

Figure 13: FY2041 residential electricity load shapes for Delhi, Bihar and Jharkhand in LET



Similar to the findings at the national level (Section 4.4), induction-based cooking is likely to contribute significantly to residential electricity load at specific hours in many states in FY2041. Delhi is an extreme case in this regard. According to PIER, about 30% of Delhi households would be using induction-based cooking by FY2041 in LET. This translates to a load of about 2.6 GW at 7 AM and 7 PM each day – which constitutes about 31% of the total bottom-up modelled residential load at the peak load hour of 7 PM on summer evenings. The use of induction-based cooking in the morning leads to a distinct morning peak and evening peak in residential electricity load in most states by FY2041, including in states such as Bihar and Jharkhand with relatively low penetration of induction-based cooking in FY2041 (just 5% and 4% respectively). This is shown in Figure 13 which plots the load shapes of the bottom-up modelled energy services in FY2041 for Delhi, Bihar and Jharkhand.

[30] In HO and HC, the annual growth rate of the number of households with ACs in these states ranges between 18% (Bihar and Rajasthan) and 26% (Chhattisgarh).

5.4 State energy demand

As at the national level, the shift away from solid fuels to modern cooking fuels results in a reduction in total energy demand in most states. Total energy demand decreases between FY2024 and FY2041 in all but 5 out of the 25 modelled states in LET because the decrease in energy use from falling solid fuel consumption is greater than the increase in usage of electricity from greater appliance ownership and use. The five states where this is not the case are Andhra Pradesh, Delhi, Maharashtra, Telangana and the Union Territories. Among these, Andhra Pradesh, Delhi, Maharashtra and Telangana achieve 100% modern cooking fuel penetration fairly early (latest by FY2030) after which there is little scope to reduce energy demand by cooking fuel switching. Hence, the increase in electricity demand by FY2041 more than compensates for the decrease in cooking energy demand in the initial years in these states. In the Union Territories, though modern fuel penetration does not reach 100% by FY2041, it remains high (above 90%) throughout the model period. Hence, here too, the scope for reduction in cooking energy demand is limited in comparison to increase in electricity demand due to growing appliance use.

6 Conclusions

The interesting insights and findings of the modelling exercise are summarised below:

1. **Demand assessment:** Electricity demand estimation through bottom-up analysis of appliance ownership and usage as undertaken in PIER shows that it is highly unlikely that India's residential electricity demand will increase by more than about 4% per annum up to FY2041 under any scenario. This is despite significantly greater ownership and usage of appliances – i.e. it is not because Indians are not able to avail of energy services. PIER findings suggest that, unlike the projections of studies such as the 20th EPS (Central Electricity Authority, 2022), future growth rate of residential electricity demand is likely to be much slower than past growth rates even with the current energy efficiency regime. Hence, it would be more prudent to plan for power purchase and investments based on such detailed exercises as they are likely to lead to more prudent decisions and prevent unnecessary resource lock-ins.
2. **Energy efficiency:** An effective energy efficiency regime can enable many more Indians to achieve material comforts by owning and using appliances without a commensurate increase in electricity demand. The BEE already plays a significant role here through periodic revision of efficiency standards, and bringing in more appliances under the ambit of efficiency. If this can be strengthened by a stronger implementation regime that ensures that efficiency of appliances sold in the market are close to the notified standards (Prayas (Energy Group), 2022a; Prayas (Energy Group), 2017), it can have a big impact on residential energy demand. It can lead to a reduction in investment needs and environmental footprint, while improving affordability and quality of life. It can also help to partially address the challenge of financial viability of distribution utilities, since many residential consumers pay subsidised tariffs.
3. **Electricity load:** Space cooling (fans, ACs and air coolers) is the major contributor to residential electricity demand. ACs alone contribute to 77% - 88% of the increase in residential electricity demand between FY2024 and FY2041 across the various modelled scenarios. Space cooling is also the largest contributor to peak residential electricity load which occurs on summer evenings. The increasing use of induction-based electric cooking – which occurs at relatively fixed times of the day – leads to residential electricity load shape having two distinct peaks corresponding to the hours when households do their cooking. These result in the residential electricity load curve getting significantly 'peakier' over the years. Hence, the distribution system will need to be strengthened to support such appliance use. In addition, appropriate mechanisms to meet the load at such times would have to be devised, particularly in view of the ongoing transition to a solar-heavy renewables-based electricity grid.
4. **Behavioural aspect:** Comparison of the results across scenarios suggests that how consumers use appliances is a potentially greater determinant of electricity demand than appliance ownership. This reinforces the finding from PIER 1.0 (Prayas (Energy Group), 2021) regarding use of cooling appliances, and suggests that measures targeted at consumers' appliance usage (e.g. when appliances get turned on, the set point of ACs etc.) can be an effective way of managing electricity demand even as Indian households own and use more electrical appliances.

5. **Modern cooking fuels:** By FY2041, it is expected that 94% of Indian households will use modern cooking fuels such as LPG, PNG, electricity or biogas. However, given India's size, this means that almost 27 million households – all of them in rural areas across seven states – would still be using solid fuels for cooking even in FY2041. This suggests the need for some directed policy measures to ensure that all households can shift to using only modern fuels, given the significant health and gender impacts of solid fuel use.

The PIER 1.5 residential energy model was built based on the most recent publicly available data for appliance ownership, namely the fifth round of the NFHS. It is also based on other available data such as GDP projections etc. Hence the results of PIER 1.5 are subject to the same uncertainties and limitations as those data-sets. Availability of finer grained and updated data – such as may become available from the ongoing NSS consumer expenditure survey – may enable a more refined model that also accounts for aspects such as expenditure fractiles. In addition, better understanding of aspects such as occupancy of houses, heat retention by buildings and behavioural patterns of using appliances can help to refine such models further. To aid in such exercises and better understand residential energy demand, periodic nation-wide representative surveys such as the Residential Energy Consumption Survey (RECS)[31] undertaken in the United States would be extremely helpful.

[31] See https://www.eia.gov/consumption/residential/

Works cited

Bureau of Energy Efficiency. (2021, November). *Room Air Conditioners efficiency notification.* Retrieved June 14, 2023, from http://www.beestarlabel.com/Content/Files/IAC_Notification.pdf

Bureau of Energy Efficiency. (2022, May). *Ceiling fan efficiency notification.* Retrieved June 14, 2023, from https://www.beestarlabel.com/Content/Files/CFN_Notification.pdf

Bureau of Energy Efficiency. (2022a, September). *Refrigerator efficiency notification.* Retrieved June 14, 2023, from https://www.beestarlabel.com/Content/Files/REF_Notification.pdf

Bureau of Energy Efficiency. (2022b, May). *Colour Television efficiency notification.* Retrieved June 14, 2023, from https://www.beestarlabel.com/Content/Files/CTV_notification.pdf

Central Electricity Authority. (2022). *Report on Twentieth Electric Power Survey of India (Volume I).*

Central Electricity Authority. (2023). *All India Electricity Statistics: General Review.* Ministry of Power.

International Monetary Fund. (2023, April). *World Economic Outlook database*. Retrieved June 14, 2023, from https://www.imf.org/en/Publications/WEO/weo-database/2023/April

Ministry of Health and Family Welfare. (2021). *National Family Health Survey*. Retrieved from https://rchiips.org/nfhs/

National Commission on Population. (2020, July). *Population projections for India and states 2011-2036*. Retrieved June 14, 2023, from https://main.mohfw.gov.in/sites/default/files/Population%20Projection%20Report%202011-2036%20-%20upload_compressed_0.pdf

National Sample Survey Office. (2012). *Household Consumer Expenditure across socio-economic groups, 2011-12.* Retrieved June 15, 2023, from https://www.mospi.gov.in/sites/default/files/publication_reports/nss_rep_562_27feb15.pdf

Palit, D. (2021, August). *Transition to electric cooking in India*. Retrieved June 15, 2023, from https://energy.economictimes.indiatimes.com/energy-speak/transition-to-electric-cooking-in-india/5041

Petroleum Planning and Analysis Cell. (2023, January 1). *Quarterly LPG profile report.* Retrieved July 5, 2023, from https://ppac.gov.in/uploads/rep_studies/1676631694_WebVersionLPGProfile01.01.2023.pdf

Prayas (Energy Group). (2017, October). *The Efficiency Of Appliances*. Retrieved June 15, 2023, from https://energy.prayaspune.org/our-work/article-and-blog/the-efficiency-of-appliances

Prayas (Energy Group). (2019, August). *'Refrigerator Electricity Consumption Patterns', part of blog-series on smart meter data collected under the eMARC initiative*. Retrieved June 15, 2023, from https://energy.prayaspune.org/our-work/article-and-blog/refrigerator-electricity-consumption-patterns

Prayas (Energy Group). (2021, November). *PIER: Modelling the Indian energy system through the 2020s.* Retrieved from https://energy.prayaspune.org/our-work/research-report/pier-modelling-the-indian-energy-system-through-the-2020s

Prayas (Energy Group). (2022, April). *Rumi & PIER*. Retrieved from https://energy.prayaspune.org/our-work/data-model-and-tool/rumi-pier

Prayas (Energy Group). (2022a, May). *Watch the stars: How to strengthen compliance with India's Standards and Labeling program?* Retrieved June 15, 2023, from https://energy.prayaspune.org/our-work/research-report/watch-the-stars

Press Information Bureau. (2023, June). *Fast-forwarding India's transition to Electric Cooking*. Retrieved June 15, 2023, from https://pib.gov.in/PressReleseDetail.aspx?PRID=1929584

Appendix I: Details of the PIER 1.5 residential model

The PIER 1.5 model builds upon versions 1.0 and 1.1 of PIER (Prayas (Energy Group), 2022), and updates it using the latest available data. The major changes that have been made in version 1.5[32] as compared to 1.0 and 1.1 are described in this appendix. The entire PIER 2.0 model, along with the workbooks, assumptions and other documentation will be made publicly available on GitHub when it is ready.

1. **Time horizon and granularity:** In PIER 1.5, the model's time horizon has been extended up to FY2041 from FY2031 in PIER 1.1. Model results are provided from FY2024 up to FY 2041. Moreover, the time granularity of each representative day has been made finer. While each representative day was divided into six time slices in the earlier versions, each day is now divided into 24 time slices of one hour each, allowing for finer modelling of electricity load.
2. **Demographic projections:** State-wise urban-rural population has been taken based on the latest projections provided by (National Commission on Population, 2020). Since this projection is only available up to calendar year 2036[33], the population growth rate for each state and urban-rural geography between 2030 and 2036 is used to obtain projections up to 2040.
3. **GDP projections:** Newer national GDP projections from the IMF published in April 2023 are used in this exercise (International Monetary Fund, 2023). These projections are given only up to FY2027. For the years beyond FY2027, the GDP growth rate of FY2027 is used. GSDP for each state is projected based on national GDP projections and past GSDP growth rates, similar to the earlier version of PIER.
4. **Appliance penetration:** In the earlier versions, appliance penetration was based mainly on a regression relationship between monthly per-capita expenditure (MPCE) and appliance ownership as derived from the household consumer expenditure survey by the NSSO (National Sample Survey Office, 2012). However, as pointed out in (Prayas (Energy Group), 2021), this is quite a dated source. In the absence of newer expenditure survey data, in version 1.5, data from the NFHS have been used. Appliance penetration from NFHS-5, applicable for FY2020, was used to project future appliance penetration (Ministry of Health and Family Welfare, 2021). The projection was based on the elasticity of growth rate of appliance ownership for each state and urban-rural geography to the growth rate of per-capita GSDP of that state between the fourth and fifth rounds of NFHS. In cases where these growth rates and elasticities were unusually high or low, they were gradually adjusted to bring them to more 'reasonable' values over the years. One implication of using NFHS instead of NSSO expenditure survey is that NFHS does not have MPCE related data, and hence the expenditure-quintile based classification of residential consumers is not possible in PIER 1.5. Thus, instead of 250 types of residential consumers (25 states, urban-rural geography, and 5 expenditure quintiles) in PIER 1.1, there are 50 types of residential consumers corresponding to 25 states and urban-rural geography in PIER 1.5.
5. **Appliances modelled:** In addition to the changes in appliance penetration, PIER 1.5 models an additional appliance, namely televisions. Televisions of one efficiency level, corresponding to

[32] These changes will also be valid for PIER 2.0. In addition, there may be a few additional changes.
[33] Calendar year n is treated as financial year n+1 – i.e. the population for CY2030 is considered the population for FY2031

3-star rated televisions, have been modelled. With the recent introduction of mandatory efficiency standards for fans (Bureau of Energy Efficiency, 2022), PIER 1.5 models 3-star fans as the representative fan. While the earlier versions modelled only one type of refrigerator (with three efficiency levels), PIER 1.5 models direct cool and frost-free refrigerators separately. For both these types of refrigerators, 2-star, 3-star and 4-star refrigerators have been modelled. There is no change in modelling of AC efficiency levels in PIER 1.5, and 3-star, 4-star and 5-star ACs have been modelled.

6. **Specific energy consumption of appliances:** The modelling of SEC of appliances has been considerably improved in PIER 1.5. Unlike earlier versions, for all appliances, except the five kinds of cookstoves, the efficiency of the stock of appliances in a particular state, urban-rural geography and year is determined based on the efficiency of appliances newly purchased in that geography in that year, and the efficiency of pre-existing appliances. Assumptions are made about the SEC of the initial (legacy) stock of appliances that exist before the initial model year. Older appliances retire based on assumed lifetimes, and newer appliances are purchased to satisfy the appliance penetration requirements. The SEC of newer appliances depends on the scenario and is based on assumptions of how often efficiency standards are amended and how 'real-life' efficiency corresponds to notified efficiency. In addition, for refrigerators and ACs, the share of higher star-rated appliances in purchase of new appliances gradually increases over the years across scenarios. For refrigerators, there is also a simultaneous, gradual shift towards frost-free refrigerators from direct-cool refrigerators.
7. **Treatment of household occupancy:** The impact of household occupancy on cooling requirements has been modelled differently in this version to make it more realistic. In contrast to PIER 1.1 where the cooling energy service demand was 'shifted' from day time to evening or night to account for household occupancy, in this version an occupancy factor is assumed for each hour of the day based on which the cooling service actually required is calculated.
8. **Estimating energy demand of unmodelled energy services:** In this version, the energy demand from the residential energy services that have not been modelled bottom-up, is modelled as an exogenous input[34]. All these services are provided by electricity. In the LET, this input for each state is calibrated for the year FY2022 based on the difference between actual residential electricity demand for that state as reported in (Central Electricity Authority, 2023) and the computed demand for the state through bottom-up modelling of energy services[35]. This estimated exogenous demand for the state in FY2022 is split into its rural and urban components based on the relative shares of the rural and urban components for the bottom-up modelled services. For the years FY2023 to FY2041, in LET, the exogenous value is estimated for each state and urban-rural geography by assuming the same growth rate as the growth rate of the electricity demand for the bottom-up modelled energy services for that state and geography. For each state, urban-rural geography and year, the demand for

[34] It was modelled as a 'residual' energy service in the previous versions.

[35] For some states, the bottom-up modelled demand for FY2022 is higher than the reported residential electricity demand. In such cases, the exogenous other residential electricity demand is assumed to be 10% of the bottom-up modelled demand. In some states, the modelled demand is much lesser than the reported demand. In such cases, the exogenous other residential electricity demand is assumed to not exceed the bottom-up modelled demand (i.e. at least half the residential electricity demand is modelled bottom-up).

unmodelled services in DET is assumed to be the same as in LET. In HO and HU, it is assumed to be 15% greater than LET to reflect higher ownership or usage. In HC, it is assumed to be 25% higher than LET to reflect the combined (but non-additive) effect of HO and HU.

Appendix II: Some data points of interest

Data Annexure Table 1: Residential Electricity Demand (TWh)

	Likely Efficiency Trend		Desired Efficiency Trend		High Consumption	
	2024	2041	2024	2041	2024	2041
India	413.4	715.5	374.9	572.2	473.4	878.3
AP	26.6	46.8	23.7	36.8	30.1	57.6
AS	5.1	8.7	4.7	7.2	6.7	11.6
BR	19.0	27.3	17.9	21.8	22.1	33.9
CG	6.6	12.3	6.2	10.3	7.8	15.9
DL	17.9	30.9	16.0	26.5	18.8	34.6
GA	1.3	1.3	1.2	1.1	1.4	1.4
GJ	26.9	47.9	23.7	37.8	29.6	56.4
HP	2.1	2.1	1.9	1.9	2.2	2.4
HR	14.4	26.1	12.9	21.5	15.7	30.0
JH	6.4	11.4	5.9	9.1	7.5	14.4
JK	3.2	4.3	2.9	3.9	3.4	4.9
KA	19.8	35.6	17.9	28.2	24.8	47.5
KL	15.9	19.5	14.4	15.2	18.7	22.9
MH	43.2	83.0	38.6	65.5	51.1	102.3
MP	18.9	41.3	17.6	33.4	22.5	53.0
NE	3.2	6.4	3.0	5.5	3.7	7.8
OD	12.5	22.0	11.6	17.3	14.3	28.6
PB	15.0	20.8	13.4	17.3	16.3	23.8
RJ	21.4	38.5	19.6	30.7	24.4	47.8
TN	34.9	50.7	31.0	39.5	40.3	62.6
TS	17.9	32.1	16.1	25.3	20.9	37.8
UK	3.1	3.9	2.9	3.5	3.5	4.5
UP	47.2	99.7	43.3	79.3	53.2	125.6
UT	2.0	4.6	1.8	3.8	2.3	5.5
WB	28.8	38.3	26.5	29.9	31.8	45.4

Data Annexure Table 2: Number of appliances (Standard case)

	Fans		Air conditioners		Refrigerators	
In Millions	2024	2041	2024	2041	2024	2041
India	599.5	956.8	35.7	272.3	153.8	357.3
AP	32.6	52.2	3.0	17.1	9.9	21.7
AS	14.5	25.7	0.1	0.9	1.5	6.1
BR	44.1	65.1	0.4	5.0	3.1	11.3
CG	10.0	16.0	0.1	5.4	1.9	5.6
DL	11.6	20.6	2.5	10.6	4.5	8.1
GA	0.8	0.9	0.2	0.3	0.4	0.4
GJ	31.4	48.3	3.4	18.1	11.0	22.9
HP	2.8	4.6	0.0	0.7	1.4	2.2
HR	13.9	23.2	1.5	11.6	5.6	9.4
JH	12.8	28.6	0.3	1.8	1.7	6.4
JK	4.9	9.9	0.3	1.5	1.9	4.2
KA	36.0	58.8	1.9	15.8	8.2	22.1
KL	20.6	28.8	1.8	6.6	7.8	11.0
MH	59.0	93.3	5.2	40.5	18.3	42.3
MP	30.7	49.7	0.8	19.7	5.7	16.4
NE	4.7	11.3	0.1	0.8	1.6	5.6
OD	20.4	30.8	0.5	8.3	3.8	11.5
PB	14.0	19.8	1.7	8.2	6.6	9.1
RJ	31.4	46.9	1.1	15.4	8.9	19.5
TN	43.6	57.8	4.1	19.2	15.6	27.7
TS	22.6	32.8	1.7	14.0	6.9	15.2
UK	4.5	6.5	0.1	2.0	1.7	3.1
UP	79.4	139.7	2.4	40.4	16.8	51.0
UT	2.6	7.2	0.4	1.5	0.9	2.6
WB	50.8	78.5	1.9	7.0	8.1	21.5

Data Annexure Table 3: Number of appliances (High ownership case)

	Fans		Air conditioners		Refrigerators	
In Millions	2024	2041	2024	2041	2024	2041
India	606.0	983.4	37.1	335.9	156.8	379.7
AP	33.1	54.6	3.1	21.2	10.2	21.7
AS	14.8	26.6	0.2	1.5	1.5	7.1
BR	44.9	66.2	0.4	7.3	3.1	13.0
CG	10.0	16.1	0.1	7.2	1.9	6.1
DL	11.7	21.5	2.5	10.9	4.5	8.1
GA	0.8	0.9	0.2	0.3	0.4	0.4
GJ	31.8	49.4	3.6	21.4	11.3	22.9
HP	2.8	4.6	0.1	1.1	1.4	2.2
HR	14.0	24.1	1.5	12.4	5.7	9.4
JH	13.0	29.2	0.3	2.7	1.7	7.3
JK	4.9	10.2	0.3	2.1	1.9	4.4
KA	36.6	62.3	2.1	21.3	8.5	22.1
KL	20.8	29.9	1.9	7.2	7.9	11.0
MH	59.5	95.7	5.3	47.7	18.5	42.8
MP	31.0	50.8	0.8	24.0	5.9	21.3
NE	4.8	11.5	0.1	1.1	1.6	5.7
OD	20.6	31.6	0.5	11.2	4.1	15.2
PB	14.1	20.3	1.7	9.4	6.6	9.1
RJ	31.6	48.2	1.2	19.5	9.0	21.3
TN	43.8	58.9	4.3	24.4	15.9	27.7
TS	22.7	33.7	1.8	15.5	7.0	15.2
UK	4.5	6.6	0.1	2.6	1.7	3.1
UP	80.5	142.5	2.5	53.1	17.1	56.3
UT	2.6	7.3	0.4	1.6	0.9	2.6
WB	51.1	80.5	1.9	9.4	8.3	23.6

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Estimating residential energy demand is critical to enable informed planning of energy supply, particularly in a growing and aspirational country such as India. This paper presents the results and insights emerging from an estimation of residential energy demand up to 2040-41 using version 1.5 of PIER, an open-data demand-oriented energy systems model. The model estimates demand in a bottom-up manner for five energy services, namely lighting, cooking, space cooling, refrigeration and television viewing. These energy services account for over 80% of electricity consumed in households. Demand is estimated in a disaggregated manner for each state and urban-rural geography, based on projections of the key drivers of demand such as the number of households owning and using specific appliances, the amount of energy service demanded and the energy efficiency of the appliance. Five scenarios are developed based on varying these critical parameters to estimate the range of possible residential energy demand. The following insights emerge from the exercise:

- Residential electricity demand is unlikely to increase by more than 4% per annum under any modelled scenario despite significantly increased ownership and usage of appliances.
- Energy efficiency is the most critical driver of demand, and the Bureau of Energy Efficiency can play a critical role in moderating energy demand growth while enabling greater ownership and use of appliances.
- Residential electricity demand shape is likely to get much 'peakier' than it is currently. This calls for responses such as strengthening of the distribution network and innovative power procurement planning to meet such peak loads at optimal cost.
- Consumer behaviour regarding usage of appliances is a possibly greater determinant of electricity demand than ownership of appliances.
- While India makes significant progress in usage of modern cooking fuels, about 27 million households spread across rural areas of seven states are likely to continue to use solid fuels even in 2040-41.

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