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Overcoming barriers and seizing opportunities for smart meters in developing countries: Insights from a large-scale field study in India

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ABSTRACT

Rapid deployment of smart meters can expedite the decarbonization of the electricity sector by facilitating effective demand-side management strategies, providing essential feedback to consumers for monitoring their consumption, improving energy accounting, and augmenting the financial solvency of the power sector. However, most of the research on the uptake of smart meters has been conducted in developed nations, where there is better electricity infrastructure and distribution services are often privatized. Understanding the factors influencing smart meter uptake is especially important in developing nations where per capita incomes are rising and consumers' energy consumption will profoundly impact the trajectory of global carbon emissions. Here we identify factors influencing consumers' willingness to adopt smart meters in the city of Jaipur in the state of Rajasthan in India. Based on survey responses from >5000 consumers, our study is the first to examine consumers' reactions towards smart meter installations while meters were being installed in their households, by a state-owned Indian distribution company. In contrast to developed countries, we find that consumers in our study area were mostly concerned about the accuracy of smart meters and the consequent impact on their electricity bills, rather than about data privacy and security. We also find that in addition to various socio-economic factors, community mobilization and local political context impact consumers' decision-making. Smart meters provide electricity distribution companies with a unique set of opportunities (e.g., improving their financial condition and increasing the transparency of meter readings) and challenges (e.g., obtaining public confidence and addressing employee concerns). Our findings suggest that policymakers should consider local socioeconomic, cultural, and political circumstances to accelerate the speed and success of smart meter deployment.

1. Introduction

Power consumption by the residential sector in India accounted for 24 % of India's total electricity consumption from April 2019 to March 2020 [1] and is projected to increase as the use of household appliances (e.g., air conditioners, refrigerators and washing machines) grows [2–4]. Empirical studies from Europe have found reductions of up to 27 % of residential energy consumption through efficient energy usage [5,6]. Similar reductions will be critical in populous countries like India and China where domestic energy use is projected to increase as per capita incomes and temperatures rise [7].

Smart meters are a critical tool for reducing power consumption by the residential electricity sector. They can help households monitor their electricity consumption in close to real-time, potentially resulting in a decrease in energy consumption of 3 to 15 % [8–11]. The lack of advanced metering and communication systems in electricity distribution in many developing countries has been identified as one of the biggest barriers to effective Demand-side Management strategies such as time-of-use pricing [12]. Smart meters can provide detailed data about consumers' electricity consumption to utilities, which when combined with new information technologies (such as big data analytics and cloud computing), can help utilities manage demand efficiently [13]. Utilities

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can use these resources to manage peak power demand without adding new generators. Finally, the electricity distribution systems in many developing nations are beleaguered with inefficiencies. Poor financial performance of distribution companies in nations like India creates uncertainty about the ability of distribution utilities ability to pay generating companies on time. This can lead to reduced investments in renewable power generation or increases in power pricing by generators to compensate for the uncertainty [14–17]. By providing infrastructure to facilitate better energy accounting and revenue collection mechanisms and reduced meter reading costs, smart meters can improve the financial solvency of the electricity sector [18].

To fully exploit the opportunities described above, the International Renewable Energy Agency has estimated that over 80 % of households worldwide should have smart meters installed [19]. However, households may be suspicious of smart meters. Research primarily conducted in developed countries has identified several barriers to smart meter acceptance: concerns about additional costs, lack of familiarity with smart-meter technology, lack of trust in electricity utilities and associated data privacy and security concerns, and (unfounded) health concerns due to supposed emanation of electromagnetic radiation from smart meters [20–23] 17/02/2025 18:53:00. Conversely, pro-environmental behaviors and heightened climate change risk perceptions increase smart meter acceptance [24,25]. Some scholars have found that social influence is an important determinant of smart meter acceptance [14,26,27], while others have argued that it is likely less important for smart meter adoptions as this is a private household decision [24,28,29]. Perceived usefulness, perceived ease of use and control over smart meters have been identified as psychological variables influencing intentions to install and use smart meters [30].

Present research on consumer acceptance of smart meters has made valuable progress but important questions remain. Even though household behaviors vary between developed and developing nations [31,32], most research on willingness to accept smart meters has been conducted in the developed world [26,27,33]. Moreover, the social nature of smart energy systems implies that it is critical to pay attention to local circumstances, political processes and social histories to fully appreciate the intricacies of such roll-outs [34,35]. For example, some studies on smart meter acceptance in developing countries highlight the interplay between socioeconomic factors, technological infrastructure, and government policies [36–39]. For instance, in Chile, researchers examined how democratic participation and transparency in decision-making can improve public acceptance [36]. Similarly, research studies conducted in Brazil identified the importance of commodity pricing along with performance expectancy, hedonic motivation and social influence in consumers' decision to adopt smart meters [37–39]. However, these studies also elucidate the importance of context-specific insights since the political economy of the electricity sector is also widely different across different developing nations. In addition, most scholarly work on smart meter acceptance has been based on surveys of potential or existing consumers. Whether and how the actual process of the installation itself impacts the willingness to install smart meters has not previously been systematically investigated [30,40].

Our study, focusing on Jaipur, Rajasthan, is unique in capturing consumer sentiments as a state-owned utility installed smart meters. Based on the variables implicated in past research and theory on technology adoption, this paper examines several factors influencing the adoption of smart meters among residents of Jaipur city in the state of Rajasthan in India. We studied the acceptance of smart meters in the field based on characteristics observable to planners, (i.e., socio-economic demographics and the local socio-political context in which smart meters are introduced) and via direct assessment of consumers' reactions during the actual deployment of smart meter installations to capture the real-life dynamics of a large-scale roll-out of new technology in a large Indian city. Using a combination of surveys and qualitative interviews with key stakeholders (distribution company officials and installation team members), we sought to understand the perspective of various actors towards the transition. This approach illuminates how pre-existing politics and power relations in the electricity sector relate to the smart meter installation process—an understudied but important research agenda [35]. While concerns about data privacy have dominated previous discussions, our findings show that billing accuracy is the primary concern among Jaipur consumers, underscoring the need for localized communication strategies. Furthermore, we investigate how community mobilization and local political dynamics shape consumer acceptance, bridging a critical gap often overlooked in the literature. By doing so, we aim to contribute to a deeper understanding of smart meter adoption in India and other developing countries, with meaningful implications for policymakers and future research.

2. Background

2.1. Smart meters in India

An EU directive defines a smart-metering system as "*an electronic system that can measure energy consumption, provide more information than a conventional meter, and can transmit and receive data using a form of electronic communication*" [41]. In India, standards set by the national government require smart meters to have the ability to send data off-site at configurable intervals, provide time-of-use metering, allow for pre-payment of electricity charges, remotely limit loads and electricity supply connection/disconnection and integrate with billing and collection software [42]. The smart meter deployment mission in India can be conceptualized as an outcome of a 'Green Developmental State' – i.e. the state (both central and provincial governments) is proactively setting up targets, funding, and regulation for energy transition policies in a top-down fashion, rather than responding to a bottom-up process [43,44]. Smart meters and the idea of a smart grid in India were introduced in 2010. In 2012, the central government constituted a national Smart Grid Task Force and Smart Grid Forum and pilot projects were initiated for various utilities [45]. To fast-track implementation, the National Smart Grid Mission (NSGM) was established in 2015. The NSGM established special budgetary support and an institutional framework to support the smart grid development. A governing council headed by the Union Minister of Power (MoP), an empowered committee headed by the Union Secretary (MoP), and a technical committee headed by the Chairperson of the Central Electricity Authority were constituted in the central government. A similar organizational structure in the form of state-level missions headed by the secretary-in-charge of the electricity department was established in the state (provincial) governments. Given the federal structure of the Indian Constitution, state governments have substantial leeway in how to roll out the smart meter program. The ground-level execution of the installation campaign is currently carried out by incumbent utilities (most of which are state-owned).

Compared to developed nations, India has been slow to install smart meters [46]. However, the pace of smart meter deployment has dramatically accelerated in recent years. As of Jan 2024, >222 million smart meters have been approved and 8.6 million have been installed across several cities [47]. The central government has established time-of-day electricity tariff regulations to incentivize state governments and consumers to use smart meter infrastructure [48]. Social media campaigns have been launched to motivate consumers to permit distribution companies to install smart meters in their homes. However, consumer receptivity to smart meter installations has varied across cities, with sporadic resistance in some cities and strong citizen protests and slowdowns in other cities [49–54]. As India pushes towards its renewable energy targets, the implementation of bi-directional solar meters, coupled with the smart meter rollout, has the potential to drive significant progress in decentralized energy generation. A significant advancement in India's energy revolution is the integration of smart meters with bi-directional solar meters under the PM Surya Ghar Yojana (PM Rooftop Solar Scheme) guidelines [55]. The Government of India has also promulgated rules laying down the rights of electricity consumers, in which smart metering is an essential component for prosumers [56].

However, existing empirical research on smart meter acceptance in India is limited. One online survey of 590 social media users in India found that procedural fairness and social influence (i.e. having friends or relatives who have installed smart meters) were important predictors of participants' willingness to install smart meters [14]. These respondents were willing to accept pressure from government authorities to install smart meters, *provided the meters help them with financial savings* (emphasis added). Interviews with industry experts found that insufficient government policies and public resources are some of the major impediments to consumers' willingness to accept smart meter technology [57]. A literature review highlighted privacy and health concerns as significant potential barriers to scale up smart grid technology in India [58]. Reports published on smart meter implementation in various parts of the country also provide useful insights. For example, a survey undertaken by a think-tank in India in six Indian states found that consumers were more likely to be satisfied with smart meters if the installation process went smoothly and energy consumption and bill details were available. In contrast, a perception that smart meters could lead to increased electricity bills and a fear of easy disconnection led to a reluctance to install smart meters [59]. However, the survey also found that many consumers struggle with limited digital literacy, relying on SMS updates that lack detailed billing information. A study of urban Indian households found that energy-consumption information provided through smart meters increased consumers' adoption of energy-efficient behaviors [60]. On the technological side, integrating utility IT systems and meter data management remains a challenge leading to delays and increased costs of smart meter implementation [61].

2.2. Governance of the electricity sector in Rajasthan

The governance of the electricity sector and the political economy of electricity distribution are likely to affect the trajectory of smart meter programs [46]. India mostly has state-owned enterprises (SOEs) serving the role of generation, transmission, and distribution utilities. The service quality of these SOEs is often inadequate, billing processes are opaque, electricity is poorly metered, and there is substantial theft of electricity [62]. We conducted our research in Rajasthan because of prior connections with Discom officials and knowledge of the local area. Rajasthan has three state-owned power distribution companies (i.e., Discoms) working across different parts of the state. These companies suffer from high electricity losses. As in the rest of the country, the determination and imposition of electricity tariffs is a politically sensitive issue in Rajasthan [63].

In India, smart meters are being installed by Discoms at no upfront cost to the consumer. For electricity metering, billing and physical supervision, clusters of 200–500 households are often serviced by a common meter-reader. Since a meter reader maintains one binder for keeping accounts for this whole area, utility officials often call the cluster of households a binder area. The meter-reader visits each household to record the electricity meter reading, distribute bills, and ensure that meters run accurately and are not tampered with by consumers. One meter-reader often serves multiple binder areas.

3. Methodology

This study seeks to answer two interrelated questions:

I. Which key socioeconomic variables (such as education or wealth) influence a household's willingness to install smart meters in India?
II. Given the societally embedded nature of smart meter technology, which procedural factors surrounding the installation process influence a consumer's decision to accept or reject smart meters?

This is a mixed-methods study that combines quantitative survey data and qualitative interviews. Mixed-methods approaches can help combine the strengths of both quantitative and qualitative research, and also overcome the disadvantages of each methodology [64,65]. In our study, the quantitative analysis consists of a regression analysis of a structured survey of 5000 households that experienced smart meter installation in their homes. The qualitative analysis consists of 25 semi-structured interviews of providers (public distribution company and private installer vendor), as well as a survey of consumers who expressed resistance to or fully rejected smart meter installation (Fig. 1).

3.1. Consumer survey of households that experienced smart meter installation

3.1.1. Survey design

The survey was conducted in Jaipur, the capital city of Rajasthan, from November 2020 to September 2021, along with the large-scale rollout of smart meters by the city's public utility (Jaipur Discom). During this period, Jaipur Discom installed smart meters in two adjacent parts of the outer city – Pratapnagar and Jagatpura. The smart meters installed by Jaipur Discom were post-paid (i.e., electricity usage was billed after consumption), as opposed to pre-paid (i.e., where customers must pay electricity fees upfront and recharge the meter when the balance goes to zero). Smart meters were installed by a private vendor selected by the Discom through a public tender process.

Jaipur Discom wanted to understand the factors shaping consumers' resistance to inform the subsequent rollout of installations in other regions within the Discom service area. We designed a questionnaire for consumers, although the Discom reserved the right to include (or exclude) questions. Some questions – such as asking households about their income or appliance ownership were excluded by the Discom because of fear that consumers might become apprehensive about the intentions behind the smart meter roll-out and oppose the installation. Survey questions were derived from existing literature on smart meter acceptance and exploratory interviews with Discom officials. The team members of the private vendor entrusted with the job of installing the smart meters were trained to administer the survey along with the meter installation work by the Jaipur Discom. The survey was conducted face-to-face during the installation of smart meters in homes. Since the survey was administered by the vendor team (on behalf of Discom) and our role was limited to the initial design of the survey and analyses of anonymised data, IRB approval was not required for this study. Jaipur Discom shared the fully anonymized survey dataset with us after the collection was complete. The survey is available in Appendix A.

Apart from the data collected in the survey, information on some variables was directly obtained from the Discom for subsequent regression analysis (see Section 3.1.2).

3.1.2. Regression variables and links to previous literature

The goal of the regression analysis is to determine predictors of consumer resistance to smart meter installation. Our dependent variable is a measure of resistance to installations, determined by the installation team members' interaction with a focal household member. Resistance to installing smart meters was noted on a scale of 1 to 5. Survey team members were given objective criteria on how to gauge this measure (see Appendix A). For example, a 1 indicates that the household was enthusiastic towards smart meter installation, a 2 indicates that the household was indifferent towards the installation, a 3 indicates that a household was reluctant to install smart meters and required persuading, while a score of 4 indicates that installation team members had to call a senior official to convince the household. A 5 indicates that the household did not allow installation. *Non-compliant* households (i.e., with a reaction on a scale of 5) also refused to answer the associated survey questions and were left out of the regression analyses. To address this limitation, we carried out a separate set of semi-structured surveys with non-compliant households (see Section 3.2). For the regression analysis that was applied to all compliant households, the observations

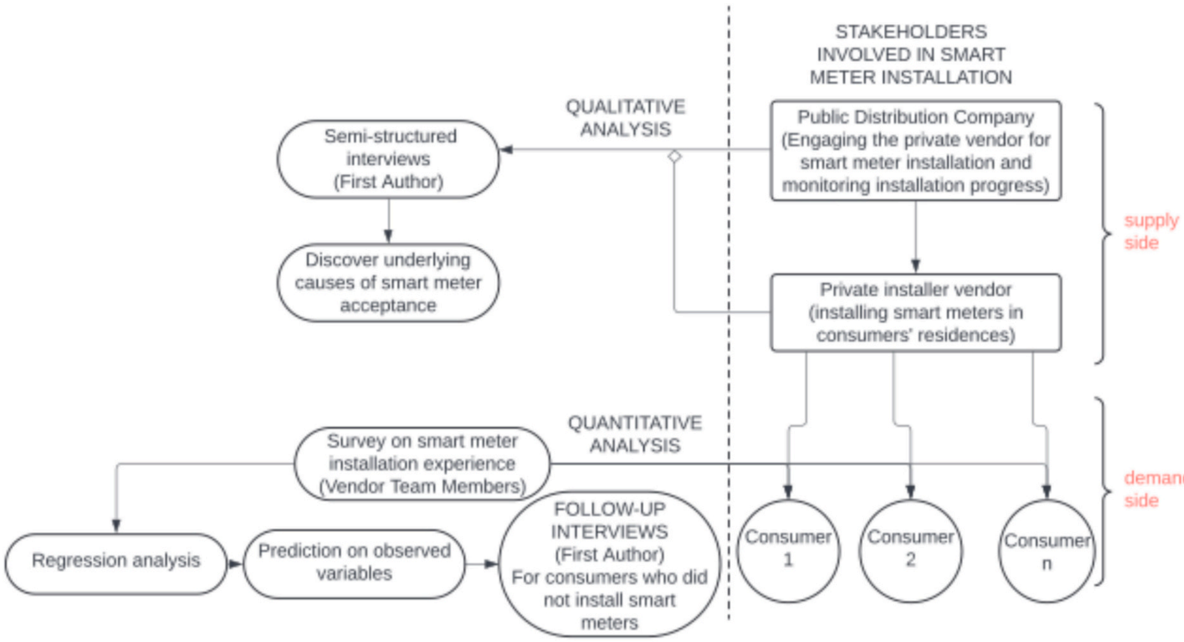

Fig. 1. The study uses a combination of a quantitative analysis of surveys augmented by interviews to discover demand-side (consumer) perspectives, and a qualitative interview analysis to discover supply-side (public utility and private vendor) perspectives on factors influencing the uptake of smart meters by consumers.

under scales 3 and 4 (i.e., households that were resistant to smart installation but ultimately accepted installation) were merged to achieve balanced samples across all categories and to facilitate interpretation of the dependent variable [66]. Hence, in the final analysis, we operationalize consumers' reaction to installing smart meters by a three-scale ordinal dependent variable: *Supportive* (i.e., scale 1), *Neutral* (i.e., scale 2), and *Resistant* (i.e., scale 3 and 4).

Table 1 shows the descriptive statistics of the survey variables for the sample population.

3.1.2.1. Demographic variables (obtained from survey). The demographic variables included in the survey are the number of rooms in the household, the number of household members, and the head of household's education level. Higher education and income have been shown to increase smart meters' acceptance [20,25], although some research studies also debate the significance and direction of this influence [33]. Since Discoms did not ask for household income, the size of a home is considered a proxy for household wealth. In addition, household size has also been found to positively correlate with the decision to install sustainable energy-conserving technology such as rooftop solar in Finland [67].

In choosing the areas to first receive smart meter installation, the Discom appears to have selected locations with a slightly higher average income and education than is typical in Rajasthan. For example, the percentage of urban males (older than 15) in Rajasthan with a college education or higher is 26 % [68], which is much lower than in our survey sample. However, this figure cannot be equated directly with our survey since we noted only the educational attainment of the head of the household (a subset of all urban males). The average family size per urban household in Rajasthan is 4.5 and the average number of rooms per household in Rajasthan is 3.5, compared to our sample average family size of 4.37 members per household and 55 % of households with >3 rooms [69].

Table 1
Descriptive statistics of regression variables in the sample population.

Independent variables ($N = 5315$)	Value
House size	
Small (≤3 rooms)	45 %
Large (>3 rooms)	55 %
Education level of the household head	
Up to upper secondary	52 %
College and above	48 %
Mean number of family members	4.37
Median number of family members	4
Home ownership	
Rented	30 %
Owned	70 %
Presence of government employee in the family	
Yes	10 %
No	90 %
Time living in the same home	
Short (≤2 Years)	40 %
Long (>2 Years)	60 %
Discom mobile application user	
Yes	31 %
No	69 %
Consumer with a complaint recorded in 2 years prior to installation	
Yes	38 %
No	62 %
Working status of meter being replaced	
Satisfactory	93 %
Faulty	7 %
Gender of household member present during installation	
Male	46 %
Female	36 %
Both	18 %
Dependent Variable: Reaction of consumers to installation	
Resistant	16 %
Neutral	55 %
Supportive	29 %

3.1.2.2. Socio-structural variables (obtained from survey). Socio-structural features of the study group are important but have been previously overlooked in smart meter studies [25,70]. Important socio-structural factors included in our study are whether the respondent is a homeowner or tenant, the presence of a government employee in the household, and the duration of their residence at that location. Homeowners and tenants living in the same locality may have systematic differences in smart meter acceptance because they might have different incentives to engage in energy-saving behaviors [70]. Government positions are considered secure and prestigious in Indian society, and the reaction of a government servant to smart meter installation may be more favourable than that of households with no government employees as the installation program is led by a state-owned entity (Jaipur Discom). Finally, previous research has suggested that households staying longer in the same home are more likely to invest in energy-efficient activities [71].

3.1.2.3. Familiarity with technology: use of Discom's mobile application (obtained from Discom). Previous research has highlighted the importance of familiarity with technology and the tech-savviness of consumers as a critical factor in smart meter acceptance [25,29]. In this study, we used whether consumers had installed and used Discom's mobile application ('*Bijli Mitra*') before smart meter installation as a proxy for tech-savviness. Notably, consumers can only access smart meter readings through this mobile application.

3.1.2.4. Trust in utility provider: record of previous complaints (obtained from Discom). Trust in utility providers is an established important factor in smart meter acceptance in other contexts [72]. Trust is often conceptualized along two dimensions – competence and integrity [73–75]. For example, consumers may distrust utilities because of concerns about bias in the electricity consumption reported by the smart meters, or they may fear that utilities are insufficiently equipped to protect their consumption data (competence trust). Consumers may also worry that the utility will sell their data to a third party for monetary gain without obtaining their consent (integrity trust). It is difficult to model integrity trust without detailed surveys, but past experiences with the utility may serve as an indicator of competence trust. Consumers who faced prior operational issues might be conjectured to have lower competence trust in the utility. We collected the complaints lodged with Discom by consumers in the two years before smart meter installations took place (i.e., January 2018 to November 2020) from the Discom's database. Any consumer who had lodged a complaint was assigned a dummy indicator that was included in the analyses as a measure of distrust or dissatisfaction with the utility.

3.1.2.5. Existing meter condition (obtained from Discom). Some scholars have commented that access to free electricity is considered a right in India [76]. According to this strand of literature, meters are deliberately modified or kept faulty by consumers to avoid accurate measurement of electricity consumption. If that is the case, one might expect more resistance from homes that have modified/faulty meters. On the other hand, consumers with defective meters (through no fault of their own) might also have less trust in the utility's competence. Therefore, we included the condition of the meter being replaced (i.e., satisfactory or faulty) in this analysis.

3.1.2.6. Social/neighbourhood influence (obtained from survey). The literature has highlighted the importance of social influence in consumer acceptance of smart meters [20]. In this study, social influence was modelled by taking an average of the observed households' resistance to prior smart meter installation in their neighbourhood. A similar methodology has been used in previous research to model social influence (*peer effect*) in solar rooftop PV adoption [77]. The neighbourhood was defined as the cluster of houses in the same binder area and hence served by the same meter reader. However, modelling in this manner also forced us to drop 1550 observations from the initial sample that were the first homes in their neighbourhood to have smart meters installed, as there was no previous predictor '*peer effect*' variable for those homes. As a robustness check, we conducted a regression analysis after including these dropped observations and dropping the *peer effect* variable and found that it does not change the direction of the result for other covariates (see Table A1, Appendix A).

3.1.2.7. Interaction during installation (obtained from survey). Installation team members were asked to report whether they interacted with the male or female members of the household and how resistant the household seemed towards the installation of smart meters. We dropped 539 observations where the installation team met children rather than an adult in the household.

During the period of the survey (i.e. from November 2020 to September 2021), the Discom installed 46,441 smart meters in the study areas. Surveyors collected data on 7404 households, implying a maximum 16 % response rate. They were instructed to attempt to survey all households and this number does not include households that refused installations. After dropping the observations mentioned above (see Sub-sections 3.1.2.6 and 3.1.2.7), we were left with 5315 usable survey responses.

3.1.3. Regression model

Mixed-effects or multi-level models are indicated for analysis when the observed data are hierarchical, nested or clustered [78]. To address the possibility that responses recorded by the same surveyor, or responses recorded on the same date, or in the same neighbourhood may be systematically correlated with each other, we employ a mixed-effects regression model with random effects for surveyors, meter change dates and neighbourhoods. Applying both random slopes and random intercepts together made the mixed-effect model overtly complex and it failed to converge. Since there is no theoretical reason to assume that the relationship between an explanatory variable (e.g., education) and the outcome variable (i.e. the response to smart meter installation) would be different for different groups (i.e., meter-change dates, surveyors and neighbourhoods) after controlling for other factors, we applied random intercepts but kept the slopes fixed in the regression. Random intercepts allow us to identify differences in the baseline of the outcome variable (i.e., consumers' responses) across the groups considered in our analysis and hence account for unobserved heterogeneity at the group level in the overall mean of the outcome. We used R to analyze the results.

We used a generalized linear and mixed model, which assumes proportional odds. The proportional odds assumption states that the relationship between the predictor variables and the cumulative odds of being in a certain category versus all other categories is constant across all levels of the outcome variable [79]. This assumption is often violated in practice, in which case a partial proportional odds model might be preferable [80]. We found that the assumption of proportional odds was violated for many of our predictors: home ownership, gender of the head of household, existing meter condition, consumers using the *Bijli Mitra* app, and *peer effect* variable. Therefore, we relaxed this assumption for these predictors in our analysis and allowed the coefficients to vary across each threshold [81].

The final model selection was based on parsimony, with results of the likelihood ratio test showing a significant improvement of the model reported below over the alternate models, and lower AIC & BIC values [82–84].

3.2. Qualitative interviews

Although the regression analysis can indicate the associations between the acceptance or resistance to smart meter installation and our independent variables, it cannot identify the underlying reasons behind these associations. To address this limitation and elucidate the findings of the regression results, qualitative interviews were carried out with three sets of stakeholders.

First, Jaipur Discom instructed survey team members to question consumers who were reluctant to install smart meters during the roll-out about the reasons for their opposition.

Second, one of the researchers based in India (RG) carried out semi-structured interviews with Discom officials, installation team members, and local officials of the private vendor company. Interview questions were derived from the relationships observed in the statistical analysis and field observations (Fig. 2).

Finally, since the main data collection only included consumers who agreed to install smart meters, a separate semi-structured survey was carried out with 200 randomly selected consumers who had refused to install smart meters. Table B.1 (Appendix B) provides details on the qualitative interviews and surveys.

4. Results

We first present the quantitative analysis of the consumer survey and follow with the findings of the qualitative analysis of semi-structured interviews.

4.1. Consumer survey results

The results of our preferred regression model (partial proportional odds) with random effects (random intercept with fixed slope) on surveyors, meter change dates and neighbourhood are shown in Table 2. These results are somewhat difficult to interpret because the partial proportional odds model has two thresholds for some predictors since these predictor variables have different effects across different cumulative splits of the outcome variable. A positive coefficient on the first threshold (Panel A) indicates that the presence of the predictor variable is associated with a higher probability of consumers' responses being supportive or neutral, as opposed to resistant (S + N vs R). For Panel B, a positive coefficient implies a higher probability of consumers' responses being resistant or neutral, as opposed to supportive (R + N vs S). Hence a negative coefficient in Panel B implies that the presence of the corresponding predictor variable is associated with higher smart meter support. As an example, the odds of homeowners being supportive or neutral vs being resistant towards smart meter installation are 0.70 (exponential function of the corresponding coefficient − 0.35 in Panel A). Since the odds ratio for this threshold is less than one, homeowner responses are less likely to be supportive or neutral than resistant. Similarly, the odds of homeowners being resistant or neutral vs being supportive is 1.65 (exponential function of the coefficient 0.51 in Panel B). Since the odds ratio for this threshold is more than one, homeowner responses are more likely to be resistant or neutral than supportive. Finally, since both coefficients are significant, we can deduce that homeownership is associated with more resistance and less support.

The presence of a female member during interaction and the presence of a government servant in the household are significantly associated with lower resistance and higher support for smart meters across both thresholds. Similarly, households are more likely to oppose smart meters if their neighbourhood does so, and households with faulty meters tend to be less supportive than households with satisfactory meters.

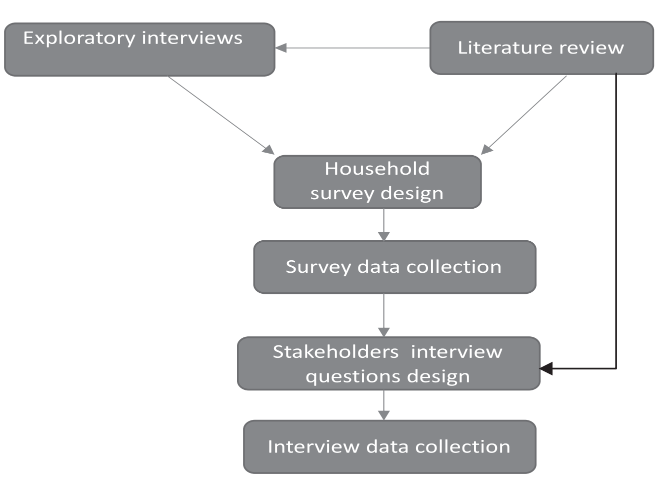

Fig. 2. Research design combines insights from household surveys and stakeholder interviews to triangulate findings and arrive at conclusions. Figure adapted from [85].

Table 2
Regression results of partial proportional odds model. The model has two thresholds, corresponding to comparisons being made across different cumulative categories. A positive coefficient in the first threshold and a negative coefficient in the second threshold signifies higher smart meter acceptance and vice-versa for the opposite case.

Dependent variable: smart meter support	Panel A		Panel B	
	Supportive + Neutral vs. Resistant		Resistant + Neutral vs. Supportive	
	Coef.	p-Value	Coef.	p-Value
Home Ownership: Owned	−0.35	0.000	0.51	0.000
Gender of Household Member Present During Installation: Female	1.69	0.000	−2.41	0.000
Gender of Household Member Present During Installation: Both male and female	0.74	0.000	−1.22	0.000
Presence of Government Employee in the Family	0.3	0.002	−0.61	0.000
Average Binder-wise Resistance Prior to Smart meter Installation	−0.77	0.001	0.58	0.013
Working Status of Meter Replaced: Faulty	−0.62	0.004	0.81	0.005
Discom Mobile App User	0.13	0.202	−0.41	0.006
Panel C: Independent Variables with Unrelaxed PO Assumption				
Education Level of the Household Head: College	0.37	0.000		
House Size: Large	0.61	0.000		
Number of Family Members	−0.29	0.000		
Duration of Stay: Long	0.07	0.202		
Consumers with Record of Complaints with Discom	−0.10	0.162		
McFadden Pseudo-R^2	0.44			

Consumers with Discom's *Bijli Mitra* mobile application have higher odds of being supportive towards smart meters, as compared to being neutral or resistive (coefficient of 2nd threshold is negative and significant). However, this coefficient is not significant in the first threshold (although a positive value does imply higher support). Usage of Discom's mobile application was also mentioned as an important factor in qualitative interviews (Section 3.2), and hence we consider it to be an important predictor of consumer acceptance of smart meters.

Panel C depicts an analysis of predictor variables that satisfy the assumption of proportional odds. As expected, consumers with higher education and larger homes are more supportive towards smart meters, while those with larger households (i.e., more family members) show greater resistance. Since family size decreases with the increase in socio-economic status in India [86], the effect of family size may be driven by constrained household energy budgets and increased sensitivity towards energy-related decisions.

The length of time a family has resided at their address and the record of complaints with the Discom do not have a significant effect on the support towards smart meters.

4.2. Findings from qualitative analysis

4.2.1. Consumers' feedback during smart meter installation

Towards the latter part of the installation drive, smart meter installers were instructed by the Discom to interview households who initially opposed installation but were later convinced to install (i.e., consumers recorded on scales 3 and 4 of the survey) to explain the reasons behind their reluctance. Out of 82 responses recorded, 78 consumers expressed a lack of trust in the smart meter's accuracy and concern about unjustified elevated electricity bills as the reason for opposition.

4.2.2. Interviews with consumers who refused smart meter installation

To understand the perspective of the consumers who altogether refused to install smart meters, a different questionnaire was framed, and interviews were conducted from a randomly selected set of 200 households. This survey was done from February 2023 to July 2023 after the smart meter installation process was almost complete in the study area. The survey questionnaire is available in Appendix B. Almost 60 % (121) of surveyed households that refused installation stated that the installation team never came to install meters in their homes. 30 % (58) of households acknowledged that the team had come for installation, but smart meter installation did not happen due to either logistical problems (installation team wasn't prepared) (30), or they refused the smart meters (28). 10 % (21) of the households refused to participate in the survey.

On further questioning, 15 % (33) of households expressed immediate readiness to install smart meters. 44 % (88) households didn't agree to install immediately but mentioned that they might consider the decision when the team comes again for installation. 40 % (79) of households (including the ones that refused to participate in the survey) declined to install smart meters – citing issues related to trust (*why do we need new meters?*) or the possibility of high electricity bills.

The survey results suggest that the opposition to smart meter installation, among those initially opposed to installation, decreased as consumer acceptance increased in the study area. Since Discom officials and installation team members insisted that they went to all surveyed households, it is difficult to ascertain the exact number of consumers who were approached by installation teams and refused installation. However, several participants in the stakeholder interviews (see Section 4.2.3) also mentioned that many consumers had changed their opinion with time and were now willing to install meters after looking at the experience of other citizens.

4.2.3. Interviews with other stakeholders

Qualitative interviews with other stakeholders included 1) senior and mid-level officials of the Discom, 2) meter readers for the neighbourhoods/binder-areas with the highest and lowest smart meter installation rates, and 3) officials and field functionaries of the private company entrusted with carrying out smart meter installation. These interviews were carried out between January 2021 and June 2023. Rather than being a one-time interaction, interviews with some of the participants took place repeatedly (2–3 times) over two years (2021–23). The questionnaire used in the interviews is available in Appendix B.

The interviews were coded by authors and inductively analyzed to identify main themes, categories, and sub-categories following the approach of the grounded theory [87]. Three broad themes were identified – 1) factors influencing the installation of smart meters, 2) advantages of smart meters and 3) concerns regarding their functioning. Fig. B1, Appendix B shows themes, categories and sub-categories identified based on this analysis.

4.2.3.1. Theme 1: factors influencing the smart meter installation process. The interviewees confirmed the primary findings of the consumer survey. Specifically, the importance of socio-economic demographics (i.e., higher acceptability of smart meters in more educated and wealthier households) and community influence (higher acceptance if neighbors were also willing) were repeatedly mentioned as important factors influencing the acceptance of smart meters.

However, depending on the circumstances, community influence could also lead to more resistance. For example, several interviewees mentioned (false) rumors circulating in their neighbourhood that smart meters were programmed to be prepaid (instead of postpaid), making them much less desirable. Lack of awareness about features of smart meters was mentioned as a problem, but knowledge of mobile phone apps allowing consumers to remotely monitor their smart meters helped convince consumers to permit installation. For example, a member of the installation team said '*the mobile app made people curious about smart meters…young adults in homes took to it instantly and showed the features to their parents….*' Operational issues, such as mismatches in consumers' mapping or problems with supplies of smart meters were mentioned as a reason for poor installation in some places.

Lack of trust in the accuracy of smart meters was mentioned as a main factor leading to the reluctance of consumers to install smart meters. A lack of trust manifested in different ways in consumers' reactions – *smart meters will run fast*; *my bill will increase due to smart meters*; *what's the problem with the earlier meter – it was also installed by Discom*? In his interview, a senior official of Jaipur Discom mentioned the steps taken to win consumers' trust, including setting up demonstration smart meter units in homes so that residents of the area could verify that both smart meters and traditional meters give similar measurements.

Jaipur city shifted from electro-mechanical meters to electronic meters in 2010. Yet, there are quite a few consumers who refused to shift to new electronic meters and are still serviced by old electro-mechanical meters.[1] Some interviewees referred to this social history of meter change in their conversations. A senior official of Jaipur Discom who was interviewed said '*Consumers always oppose change of electricity meters. I was a junior official in Discom when meters were changed earlier in 2010. Back then too, people didn't want to change meters and we faced a lot of protests.*' Another recent experience of people protesting meter change was in Kota, a city about 150 miles from Jaipur and falling within Jaipur Discom's governance. In 2017, Discom's Distribution Franchisee's (a private company managing the electricity distribution in Kota) effort to install smart meters ran into major opposition and the meter installation had to be stopped [88] [89]. Some interviewees and media reports mentioned this incident as a contributing factor to consumers' resistance towards smart meters [49].

Initial lack of familiarity led to early opposition to smart meters which decreased over time. Interviews conducted in 2021 and 2022 mentioned smart meter opposition building up in communities and subsequent strategies deployed by meter installation team members to overcome it. However, interviews conducted in 2023 mentioned that even in the areas where smart meter installation was opposed during the deployment drive, left-out consumers were later coming forward and actively approaching Discom officials to get meters installed.

Smart meter installation in the study area was led by the private vendor hired by the Jaipur Discom. Discom's mid-level field officials were entrusted with troubleshooting wherever the vendor faced problems. Meter readers were not involved in the planning and implementation activity of the smart meter rollout. Yet, a substantial number of meter-readers wished that Discom would have included them in the process and mentioned the *behind-the-scenes* support they provided for convincing uneasy consumers.

One important factor mentioned in the interviews but not relevant to our study area was political mobilization against smart meters. Officials of Discom and the installation company mentioned anti-smart meter protests they faced in other cities of Rajasthan, which were motivated by the political contexts of the cities. Two things differentiated these protests from community-mobilized protests. One, they happened in places where the opposition political party of the state held more sway electorally. Two, these protests were far more difficult to tackle.

4.2.3.2. Theme 2: advantages of smart meters. Discom officials and the installation team members reported that consumers found the ability to track energy usage to be the biggest benefit, especially for absentee homeowners or landlords who were renting their properties.

[1] Unfortunately, Jaipur Discom does not keep records of consumers based on type of electricity meter installed in their connections; therefore, it is not possible to ascertain the exact number of consumers still serviced by electro-mechanical meters.

Most Discom officials considered smart meters to be an effective instrument to improve the financial position of the organization by ensuring timely payments from consumers (due to the ability to disconnect electricity connections of non-paying consumers) and to control electricity theft (by data analysis of consumption). Additionally, many mid-level officials considered the online availability of meter consumption data as a helpful instrument to ward off political pressure (to ignore electricity theft or non-payment of bills, for example). A couple of senior management officials mentioned the possible utilization of smart meters to shift peak demand after time-of-use tariff regulations are implemented.

4.2.3.3. Theme 3: concerns about smart meters. Interviews with meter-readers depicted the paradox and dilemma their cadre is facing with the deployment of smart meters. On the one hand, meter readers were happy with the smart meters to the extent they made their day-to-day job easier. For example, an interviewed meter reader said, '*Smart meters have made the job of meter reading very easy. Earlier, we had to go each home… Not all consumers are nice… many people have dogs which makes our lives very difficult. Now, we only need to collect meter readings of those consumers who don't have smart meters. For the rest, we just need to prepare and distribute the bills and keep a check on their connection….*' On the other hand, smart meters can make the job of meter reading redundant, and meter readers realise that such technological interventions can be detrimental to their cadre by reducing the future hiring of meter-readers.

Many meter readers were circumspect about the benefits of smart meters to consumers. Being consumer-facing workers, they had to face the brunt of maintenance issues related to smart meters. They were also apprehensive that a lack of trust in smart meters might lead consumers to blame meter-readers for high meter readings. Getting re-connected to the grid (after paying pending dues) was mentioned as often a hassle for consumers.

5. Discussion

5.1. Psychological factors influencing smart meters' acceptance among consumers

Trust in smart meters' accuracy was a primary factor influencing consumers' acceptance of smart meters in our study area. A trust deficit seemed to arise from multiple factors: a past legacy of meter change in the region, a lack of clarity on why smart meters were being installed and a variety of rumors. The manifestation of this trust deficit leads to an anticipation of high electricity bills. Discom officials in the study area were aware of this trust deficit and made concerted efforts (such as setting up demonstration units) to convince consumers to accept the installation of the smart meters. Therefore, while better socio-economic status (proxied by larger homes, government jobs, better education, and smaller family size) helps to increase the willingness to install smart meters, it is critical to ensure that the installation process strategically conveys social acceptance of the new technology.

Familiarity with Discom's consumer mobile application increased acceptance of smart meter installation. A positive correlation between smart meter acceptance and familiarity with the technology is in line with previous research [90]. Familiarity with the mobile application can be conjectured to increase perceived ease of use and intention to use smart meters, and hence increase consumer acceptability [25,33]. It can also increase the perceived utility of smart meters which is identified in the literature as a key driver of smart meter acceptance [33]. However, we do not find conclusive evidence that former troubles with electricity supply and lodging complaints with the utility make any significant difference to consumers' acceptance.

Previous research outside of India has noted that consumers perceive smart meters as having higher accuracy, and this is seen as an instrument to *reduce* bill estimation anxiety [72,91,92]. However, we find that smart meters in India *increase* consumers' bill anxiety. Since smart meters can help in detecting electricity thefts due to the granular provision of consumption data, consumers with a tendency to steal electricity are likely to oppose smart meters for obvious reasons. We found evidence of the same in both qualitative interviews and quantitative analysis (*faulty meter variable*).

Bugden et al. [93] found in their study in New York that a longer roll-out of smart meters and smart grids reduces consumers' acceptance with time. However, our research suggests a contrary finding. We found that at first, resistance to smart meters built up as consumers became aware of the roll-out and mobilized against it. However, as time progressed and consumers initially opposed to smart meters observed their successful working around them, their willingness to adopt smart meters increased. The social history of previous installation campaigns also played a critical role in consumers' acceptance.

In contrast to developed nations where privacy concerns or health concerns (perceived radiation effects) related to smart meters are established as key barriers to consumers' acceptance, such concerns did not find any mention in our study area. This finding is also in contrast with [14] who found health concerns an important factor for smart meter acceptance in India, *but their study design primed the subjects* by asking questions about such concerns. Raimi et al. [94] found that providing more information to households about smart meters does not lead to an increase in acceptance, rather it is likely to beget more concerns about privacy, health and cost from consumers. This sentiment was echoed in our research; for example, installation teams found it helpful to avoid highlighting too many features of smart meters in some areas. Privacy or health beliefs didn't enter the public psyche in the study area perhaps because the public debate in India on smart meters has not highlighted these aspects of the technology yet. An alternative explanation could be cultural differences between developed and developing nations. Hori et al. [32] have posited that developing nations tend to respect collective action rather than individual action. A study on smart grids in India points out that, unlike developed nations, households in India often share their energy consumption information and pool resources to meet their energy needs [95]. The importance of neighbourhood influence coupled with a lack of privacy concerns may be interpreted in this light.

Finally, our study has tried to open the black box of interaction between the installation team and consumers and its impact on the consumers' decision-making [40]. We find that idiosyncratic factors, such as whether the team interacts with a male or female member of the household, also had an important bearing on the outcome.

5.2. Societal embedding of smart meter technology and the role of other stakeholders

Smart meter technology may evoke different reactions among different stakeholders: consumers, utility officials and the larger society. The acceptance of smart meters can depend on how these stakeholders come together to orchestrate coalitions that either elicit concerns about challenges or visions of participation [96].

Scholars have suggested creating coalitions for accelerating the energy transition, i.e., multiple groups working together with each other to further the climate-change agenda, even though they have divergent reasons and different priorities for supporting policy [34]. Our research supports the potential of such coalitions to be influential in smart meter deployment in India. Senior management of Jaipur Discom perceived smart meters as an instrument to improve financial solvency and peak load management, mid-management officials considered them a protection against political pressure and they eased the day-to-day work of meter readers. Consumers in the study area were motivated by the possibility of tracking energy usage through smart meters. Although we did not find any deliberate effort of coalition forming in the study area, consciously pursued coalitions can have long-term longevity [34].

However, such outcomes depend on consumers' trust in the smart meter's accuracy. For example, some meter readers in the study area expressed apprehension that consumers might blame them for making up readings due to a lack of trust in smart meters. Since the electricity sector in India is both politically salient and influenced by strong employee unions, it is important to prevent the formation of a coalition of unhappy consumers and disgruntled utility officials which could impede smart meter deployment.

Political mobilization against smart meters stems from the nature of electoral politics in India, in which electricity supply and tariffs play a key role. Being government-owned utilities, Discoms can be perceived as the agents of the provincial state government. Evidence from the interviews suggests that political mobilization against Discom's smart meter installation campaign is driven by opposition to the state government.

Geels et al. [97] mention the tension between a technocratic process (top-driven and target-based approach) and an emergent-adaptive process (focused more on social stabilization at an early stage rather than achieving fixed targets in meter installation) in smart meter deployment across various countries in Europe. We found the process followed in the study area started from a technocratic approach (setting up targets from the top) but was also mindful of the social realities (such as setting up demonstration units to convince consumers). Senior management of the Jaipur Discom decided to let the private contractor lead installation in the study area. Cutting-edge staff i.e., meter-readers were not much involved – a strategy that had both pros and cons. On one hand, the reaction of meter-readers towards smart meters could not be predicted because smart meters have a paradoxical effect on their jobs. But meter-readers also felt left out of the organizational decision-making, which made them apprehensive about the intentions of the Discom towards the future of their cadre.

5.3. Societal embedding of smart meter programs in India – a conceptual model

Geels et al. [97] define smart meter diffusion in society as a function of four dimensions: user environment, policy environment, business environment, and socio-cultural environment. Using the same conceptual framework, Fig. 3 shows the societal embedding of electricity meter technology in India, and the practical implications of these environmental dimensions on the smart meter program.

- **Policy Environment**: The policy/regulatory environment is shaped by the nature of the Indian polity. Electricity is a subject under the jurisdiction of both state and federal governments, as described in the Constitution of India. As our research study points out, state governments, through Discoms, have considerable autonomy to implement the program. However, broader policy framework, funding and electricity sector regulations are still determined by the Central government, and successful coordination between federal and state governments is critical for the success of smart meter programs in India.
- **Business Environment**: Smart meter promotion is mostly the responsibility of state-owned electricity distribution firms or Discoms. According to our research, utility companies are motivated to support the installation of smart meters due to financial incentives, such as the possibility of cost savings from decreased electricity theft, rather than smart meters' utility in decarbonising the electricity sector. The requirement for a corporate environment that aligns the interests of all stakeholders is highlighted by internal concerns of utility staff, who may view these technologies as threats to their jobs.
- **User Environment**: The widespread adoption of smart meters in India faces challenges due to low education and income levels of consumers, which makes them sensitive to electricity bills and heightens their apprehensions about smart meters' accuracy. As our research suggests, prior experience with technology such as Discoms' mobile applications positively influences acceptance, implying that training programs could improve user experience and encourage wider adoption. It also provides an opportunity for Discoms to help consumers monitor their energy consumption more effectively, especially for consumers availing free or subsidized electricity up to a certain consumption limit [98].
- **Socio-Cultural Environment**: Our research indicates that the adoption of smart meters is significantly influenced by community dynamics. When developing and putting into practice smart meter initiatives, it is important to take into account the socio-cultural setting, which includes social history and communal effects pertaining to information infrastructure.

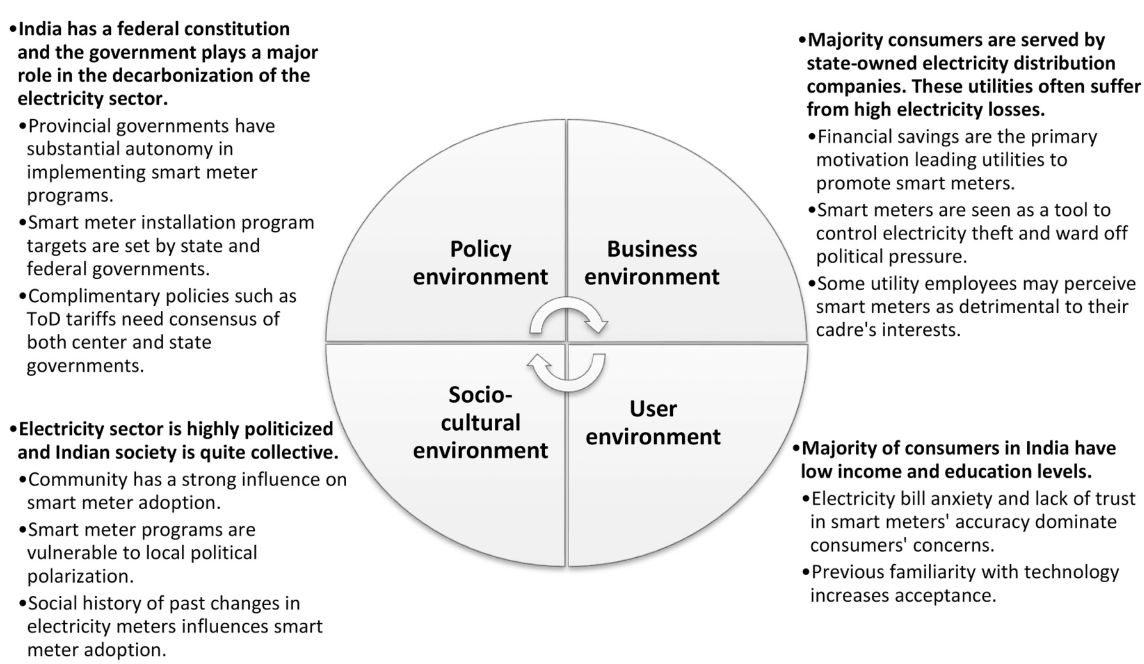

Fig. 3. Societal embedding of electricity meter technology and its implications for the success of smart meter installation programs in India. Figure adapted from [97].

The acceleration of smart meter installation in India will depend on the design of a program which is mindful of above-mentioned societal embeddedness.

6. Limitations and further work

Our research finds that consumers' trust in smart meters' accuracy is an important determinant of their acceptance. Further studies can illuminate the relationship between trust in meter technology and trust in utility companies installing this technology. Although the two may be correlated, scholars have also pointed out how people reify technologies like smart meters in a way that delinks their feelings from the service provider [99].

Research on social opposition to energy transition policies is often troubled by sampling bias – i.e. researchers focus only on areas where there has been social opposition and hence sample on a dependent variable [100]. In contrast, our study area is a sample where no mass protests took place against smart meters, even though there were some pockets of resistant neighbourhoods. Although we unearth some underlying factors that can contribute to large protests (such as electricity bill anxiety), further research in areas with widespread opposition to smart meters can illuminate the pathways through which anti-smart meter protests operate.

The statistical significance of some variables in our quantitative analysis merits further research. For example, why do consumers who have had faulty meters offer more resistance? Is it because a desire to steal electricity leads them to prefer meters that can be more easily manipulated, or because such consumers have less trust in the utility? Similarly, lower resistance posed by women household members during interaction with installation team members warrants more exploration.

Moreover, just installing smart meters may not be enough to induce energy-conserving behaviors [101,102]. Further research can illuminate if and how the installation process impacts the usage of smart meters. More studies are also warranted on how much additional revenue utilities can collect with smart meters compared to existing meters.

Although this study provides important insights into the obstacles and approaches to smart meter adoption in India, several uncharted areas still need more research. Future studies should concentrate on understanding the particular requirements of commercial and industrial customers, investigating the socioeconomic effects on low-income households, and taking note of effective implementations in other areas. Furthering India's energy transition will also require investigating utility stakeholder dynamics and evaluating the contribution of smart meters to the development of net metering and decentralized energy systems.

Finally, we acknowledge that while the findings provide valuable insights into smart meter acceptance in Jaipur, they may not be universally applicable to other regions of India due to differences in consumer behavior, socioeconomic conditions, and energy infrastructures (such as areas serviced by private vs. public distribution companies). Furthermore, the consumer survey's response rate was 16 %, which may have introduced response bias and limited the results' generalisability beyond the study population. Such limitations highlight the importance of exercising caution when generalising findings to a larger population or different geographic regions. The exclusion of non-compliant households (those scoring a "5" on the resistance scale) from the regression analysis could introduce the non-response bias to our results. We discuss how follow-up interviews with such households can potentially address this issue but acknowledge that further research should be done to build on this evidence and explore a diverse set of regions.

7. Conclusions and policy implications

Our study characterizes the critical importance of recognizing and accommodating the local socio-economic, cultural, and political nuances of communities before and during the large-scale deployment of smart meters in India. In stark contrast to the studies conducted in developed nations, our research unveils a distinct set of consumer concerns that revolve around the accuracy of smart meters and anxiety about unfairly elevated electricity bills, rather than data privacy.

Informed by previous research and our empirical findings, strategic policy implications arise. The dynamics of the roll-out, such as perceived acceptance of technology by the neighbourhood, highlight the imperative to design an installation process that tactfully communicates social acceptance of the technology and mitigates potential resistance. Evidence from this study indicates that there are some consistent underlying reasons for anti-smart meter mobilization in India across communities – lack of trust in the meter's accuracy, bill estimation anxiety and the socio-economic context of the area. These issues can couple with factors enabling community mobilization (a strong-knit neighbourhood) or political mobilization (local dominance of the opposition party), leading to sustained anti-smart meter protests.

How to deal with opposition in such cases? Our research suggests a nuanced strategy. On the supply side, targeting areas with educated populations and weaker community ties can facilitate smoother initial smart meter installation. In such regions, awareness campaigns spotlighting the benefits of smart meters can effectively mitigate sporadic opposition. In areas marked by stronger community mobilization, it is advisable to identify and engage community leaders and establish a foundation for future communication efforts. Large-scale deployment without prior engagement of local influencers in these areas is likely to be viewed with suspicion and backfire. In either case, it would be advisable to follow a two-phase installation process where the first wave installation is targeted at receptive and willing households. Our results indicate that following adoption by some members of the community, consumer resistance decreases and it becomes easier to install smart meters in homes of the formerly resistant households.

On the consumer side, utilities can take preventive measures before large-scale deployments – such as educating consumers about their mobile phone app and making replacing faulty meters a priority. Targeted communication strategies for homeowners should be devised to address their specific concerns. For example, awareness campaigns on how homeowners can save electricity bills using the feedback from smart meters can be helpful. The recent introduction of the Time-of-Day electricity tariff by the Government of India is a good step in this direction. Making re-connection to the grid hassle-free after payment of dues is also likely to engender increased consumer trust.

In addition, it can be helpful to consider the impact of smart meter technology on various stakeholders within the utility company while devising the roll-out strategy. This study reveals that the primary motivation for smart meter installation for utility officials is not decarbonization, but rather the co-benefits of smart meters in easing mundane work, ushering transparency in meter reading, reducing electricity theft and improving financial solvency. A coalition of stakeholders can be built with consumers around these goals to accelerate smart meter deployment.

CRediT authorship contribution statement

Rohit Gupta: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Denise L. Mauzerall:** Writing – review & editing, Supervision, Methodology. **Sara Constantino:** Writing – review & editing, Conceptualization. **Gregg Sparkman:** Writing – review & editing, Conceptualization. **Malini Nambiar:** Writing – review & editing. **Elke Weber:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rohit Gupta reports a relationship with Jaipur Electricity Distribution

Company that includes: board membership. The first author (RG) is a PhD candidate at Princeton University while being a civil servant in the Government of Rajasthan, but no competing interests exist between this research study and his professional obligations. Neither he nor other authors have any financial or personal relationship that could cause a conflict of interest regarding this article. 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2025.103996.

Data availability

The authors do not have permission to share data.

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