

Large-Scale Evidence on the Benefits from Off-Grid Technologies^{*}

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Abstract

Evidence on who benefits from off-grid energy, and how, rests largely on single-product studies. We pool 474 standardised customer surveys covering almost 79,000 users of six off-grid technologies and seven appliance types, sold by 164 companies in 31 countries between 2020 and 2023. Nine in ten customers report a better quality of life, with little difference across technologies. Each product works through one dominant channel, usually not lower spending. Gains are largest for first-time users and households without a prior grid connection, although adopters are better educated than the populations they come from. Adoption risk depends more on companies than customers: resolving problems and checking that credit buyers understand their contracts are associated with less dissatisfaction.

JEL codes: O13, O33, Q42, I31

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Over the past 15 years, the number of people without access to grid electricity has nearly halved, enabling millions to benefit from basic energy services such as lighting and refrigeration.¹ Yet substantial gaps remain, particularly for rural households in low- and middle-income countries (LMICs) living in remote areas beyond the reach of centralized grids.^{2;3} Even where grid connections exist, supply can be unreliable, and effective access also depends on households' ability to afford appliances and then electricity.⁴⁻⁷ Off-grid technologies have emerged as a complementary pathway to expand energy access.⁸⁻¹¹ Solutions include solar lanterns, solar home systems (SHS), mini-grids, clean cooking devices, off-grid appliances, and electric mobility (e-mobility) devices. By bundling generation and end-use services, they can reach remote populations while reducing exposure to grid unreliability and payment uncertainty, potentially improving the stability of access to essential energy services.^{12;13}

Despite their rapid deployment, remarkably little is known about the benefits off-grid technologies provide to users, whom they reach, and how they complement grid electrification. This evidence gap hinders policymakers and investors from directing resources towards the technologies and populations for which they can deliver the greatest benefits. At COP29, developed countries committed to mobilizing an additional USD 300 billion annually by 2035 to support low- and middle-income countries in addressing climate change.¹⁴ A central challenge is how to allocate these resources effectively. So far, existing research on off-grid technologies includes case studies evaluating the ex-post impacts or viability of specific energy systems,¹⁵⁻¹⁷ but these typically focus on individual projects or locations, limiting external validity. Complementary work is largely techno-economic in nature, modelling optimal deployment,^{18;19} or focuses on institutional and policy enablers^{20;21} rather than benefits and limitations. By contrast, the economic literature on grid electrification documents substantial welfare gains from energy access,²²⁻²⁴ yet rarely identifies technology-specific effects or the populations most likely to benefit. Nonetheless, evidence points to considerable heterogeneity in electrification outcomes, which likely depend on the circumstances of access.^{5;13;25;26}

Here we provide the first large-scale comparative assessment of user-reported benefits from off-grid energy deployment. We analyse pooled microdata from 474 standardised customer surveys conducted in 31 countries from 2020 to 2023, covering approximately 79,000 product

users across six core off-grid technologies and seven appliances. The data were collected by 60 Decibels, a global impact measurement firm, through survey projects commissioned by 164 off-grid energy companies to assess customer experiences with their products.ⁱ They include standardised measures of user satisfaction, improvements in quality of life, and changes in income. We compare outcomes across technologies and population groups within a unified empirical framework, identifying technology-specific patterns, customer heterogeneity, and common enablers and constraints.

1 Main text

The section moves from what the products deliver to whom they reach and what can go wrong. Our results highlight six stylized facts about the expansion of off-grid energy technologies, which we present below.

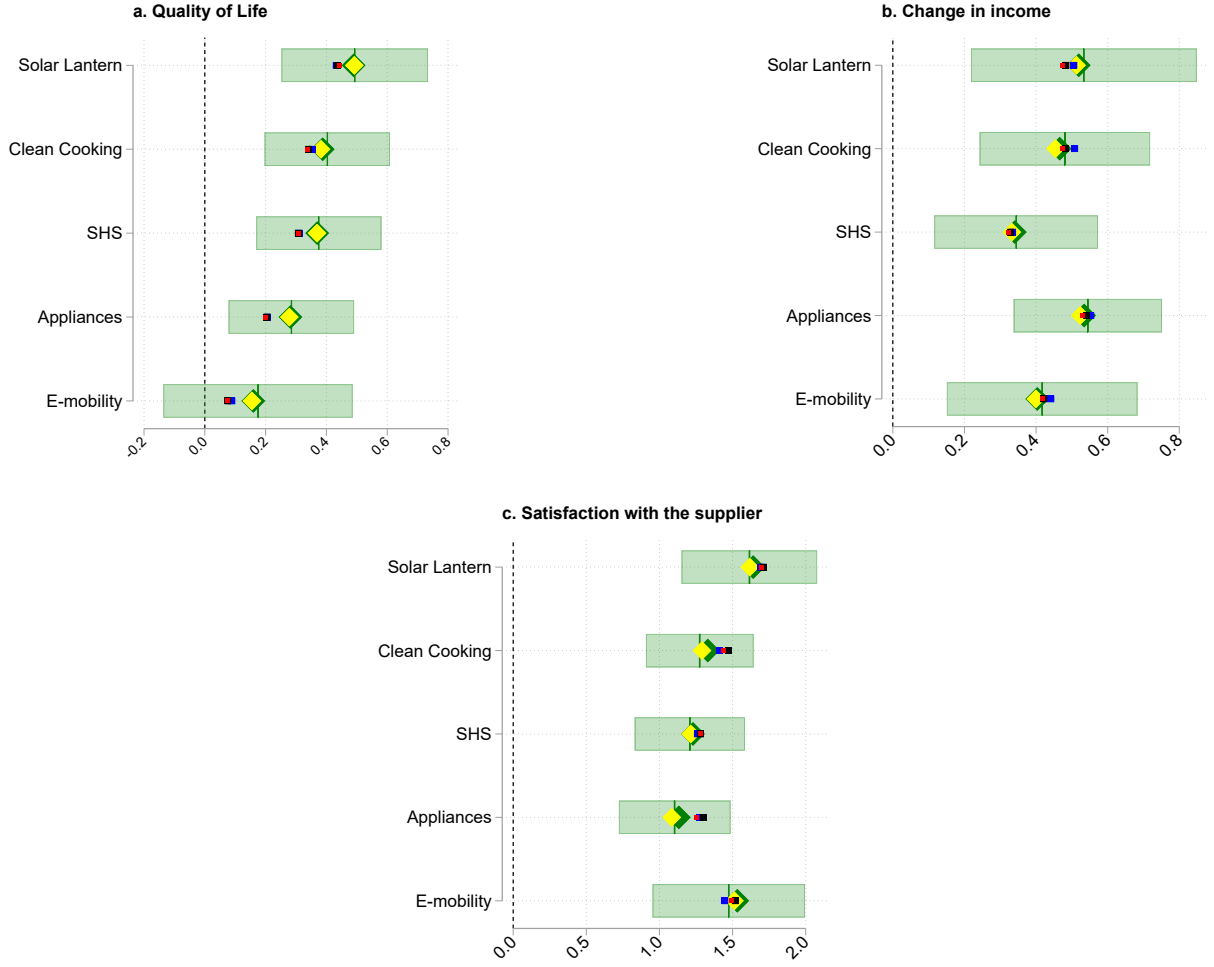
1.1 Perceived welfare benefits are consistently high among adopters

Most users report that off-grid products improved their quality of life, with a mean quality-of-life score equal to 4.44 on a five-point scale and 91.9% of respondents reporting some improvement. Similarly, for those who use the product for productive purposes, the mean change in income score is 4.02 on a five-point scale, with 74.6% reporting an increase in income. On the ten-point scale measuring customer’s satisfaction and likelihood of recommending the supplier of the product, the mean response is 8.04ⁱⁱ (see [Supplementary Information](#) for more descriptive statistics). These three outcomes represent our welfare measures.

ⁱBecause surveys were conducted at the project level, geographic representation is uneven. Most responses originate from Africa (88.1%), particularly Kenya (22.6%), Tanzania (10.9%), Uganda (9.1%), Nigeria (8.2%), and Zambia (7.5%). Additional projects were conducted in Asia (11.0%, including 7.0% from India), with a smaller share of responses from Latin America and the Caribbean (1.0%).

ⁱⁱThe surveys carry two recommendation questions, one about the company that supplied the product and one about the product itself, and no respondent was asked both. We use the supplier question throughout and call it *satisfaction with the supplier*. Supplementary Section B sets out why the product question cannot carry the analysis and reports it separately.

Figure 1: Technology-specific differences in reported improvements in outcomes



Notes: Estimates correspond to the average marginal effect (AME) of each core technology (at 95% confidence intervals), using mini-grids as the reference category. Green vertical bars are the baseline estimates from three-level mixed-effect Tobit regressions that control for country, survey years, and all socio-economic and demographic controls (age, gender, number of people in the household, rural residence, and education). Specification 2 (◆) excludes all socioeconomic controls, except education, and Specification 3 (◆) excludes both education and all socioeconomic controls. The blue (◆), black (◆), and red (◆) squares are the OLS equivalents of the baseline, specifications 2, and 3, respectively.

Figure 1 compares perceived benefits across technologies. To account for differences in project implementation, country context, and respondent characteristics, it presents estimates from a three-level mixed-effects Tobit regression framework. The Tobit model accounts for the lower and upper bounds imposed by the response scales (see [Methods section](#)) while the mixed-effects structure captures variation at multiple levels. The green vertical bars show point estimates and confidence intervals from our preferred specification, while the

diamonds indicate point estimates from alternative specifications (Supplementary Section (SS) [G](#) checks the comparison against alternative estimators and samples).

Results for quality-of-life improvements, presented in Figure [1\(a\)](#), suggest a consistent premium for simpler, portable technologies relative to the mini-grid baseline. In particular, solar lanterns exhibit the strongest effects, delivering the largest quality-of-life gains in the sample (a 0.49-point increase on a 5-point scale). These are followed by clean cooking technologies (+0.40-points) and, subsequently, solar home systems (SHS) (+0.37-points). The ordering should nonetheless be read with care, and the reason is not the number of respondents.ⁱⁱⁱ

Two explanations are usually offered for why simpler products should deliver larger gains: they cost less, sometimes as little as USD 5^{[11](#)}, and they replace something worse. Our data support the second and qualify the first, and they show that what is being replaced is not the same in every case.

If the gain came from gaining electricity for the first time, the products serving the least-grid-connected customers should rank highest. They do not. SHS serve the least-connected customers in the sample, 77.0 per cent of whom had no grid connection, yet rank third. Clean cooking serves the *most* connected, 76.3 per cent of whom had a connection, and ranks second. What clean cooking displaces is not darkness but a polluting fuel, and the next section confirms it: the channel carrying clean cooking is health.

The pattern is therefore better described as the displacement of a poor substitute than as first access to electricity as such. Lanterns and SHS displace kerosene and darkness; clean cooking displaces biomass smoke. Each is a large change from a low base, which is what the randomised evidence on low baseline access describes^{[13;27](#)}, but the base differs by product. Price alone does not organise the ranking either: mini-grids and SHS are the two most capital-intensive systems here and sit at opposite ends of it.

ⁱⁱⁱThis is because, for the respondents of quality of life questions, the estimate rests on 897 lantern customers from 4 companies and 4 projects, against 15,310 SHS customers from 50 companies and 84 projects. Because the customers within a project share a firm, a market and a sales model, it is the number of companies rather than the number of customers that bounds how precisely a technology average can be located. The technologies with the largest estimated premia are also those observed through the fewest firms.

Appliances and e-mobility sit at the other end of panel (a), nearest to the mini-grid baseline, and the reason becomes clear once panel (b) is read beside it. These are the two categories bought to earn rather than to change domestic life: 93.3 per cent of e-mobility customers and 40.2 per cent of appliance customers report using the product for income-generating work, against 4.6 and 11.2 per cent for clean cooking and lanterns. They accordingly record the two highest mean income responses in the sample, 4.28 and 4.21 on the five-point scale, while recording the smallest quality-of-life premia.

The intuition is therefore meaningful. A motorcycle or a water pump changes how a household earns, and the household evaluates it on that basis; a lantern changes how the evening is spent, and is evaluated on that.

Two policy readings follow, and they point in different directions. For households without electricity, expanding basic access appears to deliver large welfare returns before more capable systems are scaled up, since the simplest products here match or exceed the most capable ones on reported quality of life. For households that already have electricity the same logic does not apply, and clean cooking is the instructive case: it ranks second while serving the most connected customers in the sample, so its benefit is not about electrification at all. It is usually attributed to relieving two burdens that fall disproportionately on women, indoor air pollution and time spent cooking²⁸; our results support the first and not the second, which matters for how such programmes are justified.

The perceived change in income in Figure 1(b) is estimated on a subsample of productive users:^{iv} those who usually employ energy access for income-generating activities such as agricultural extension, mobile phone charging, or retail operations.^{27;29;30} While all technologies show positive and statistically significant associations with income growth, the ranking between specific technologies remains imprecise, with overlapping 95% confidence intervals across several pairs.

The reported income response tracks productive use closely, and this bears on how far the

^{iv}Productive users may possess higher baseline motivation or education than the average adopter. The stakes are also higher for these users, as a technical failure in this segment translates directly into financial loss.

result generalises. The ordering of the income response and the ordering of productive use are close to identical.

Two things follow. Income gains in this sample arise mainly through direct productive use rather than through the broader indirect channels, such as time reallocation or human capital accumulation, that the literature also identifies^{27;30}. Those channels may well operate, but they are not what these data isolate, and we do not claim them. And within a technology where productive use is rare, the customers who answer the income question are the minority who do earn from the product. A positive income estimate for clean cooking describes that minority rather than the typical clean cooking customer.

Figure 1(c) turns to satisfaction with the supplier, which equally shows the absence of a clear ordering. Every category is associated with higher satisfaction than mini-grids, but the differences between the others are small and their intervals overlap almost everywhere.

That flatness is informative. Panels (a) and (b) measure what the product did for the household, and they separate technologies because technologies differ in what they deliver. Panel (c) measures what the company was like to deal with, and it does not separate them, which suggests that the quality of the commercial relationship varies more between firms selling the same product than between products. The mini-grid result fits that reading. A mini-grid (the base category) is the one product here sold as an ongoing metered service rather than as an object, so its customers hold a continuing relationship with a supplier who can disappoint them, and it is the only category customers rate materially lower.

Later sections reach the same conclusion from the other direction: what predicts whether a customer is satisfied with the supplier is less the product they bought than the customer services provided by the company and the commercial relationship after sales.

Taken together, the three panels give the first of our stylised facts. Reported benefits are high for every technology in the sample and differ little between them, so the question worth asking is not which product a household buys but what happens to the household that buys a particular technology. The sections that follow take up that question in turn: the channel

through which each product works (Section 1.2), who gains access to it (Section 1.3), how the gains vary with education (Section 1.4), who gains most (Section 1.5), and the risk associated with adoption (Section 1.6).

1.2 Off-grid energy provides meaningful change in daily life

A technology can raise everyone’s assessment of a dimension without that dimension explaining who benefits most. We therefore report two quantities for each mechanism item, shown side by side in Figures 2 and 3. The first is how much customers say the dimension improved, adjusted for who was surveyed (first column). The second is how much that dimension contributes to the welfare outcomes once all of a product’s mechanisms are accounted for, which is what identifies the channel actually carrying the benefit, holding the rest constant (rest of the columns).

For each product, one mechanism carries most of the welfare gain, and it is a different mechanism for each. For SHS and mini-grids the dominant channel is safety and security, contributing 0.528 and 0.627 points of quality of life against 0.048 and 0.101 for energy spending, respectively. Light after dark changes what a household can safely do and store, and that is what separates customers who report a large improvement from those who report a modest one.

For clean cooking the channel is health (0.265), consistent with the removal of indoor smoke rather than with the time or money saved: cooking time contributes 0.044 and cooking spending 0.084, both small beside it. This settles a question left open in Section 1.1 above. The welfare advantage of clean cooking is conventionally attributed to relieving two burdens that fall disproportionately on women – household air pollution and time spent cooking²⁸. Only the first survives here. Customers do report that the stove saves them time, and the improvement column shows it: cooking time scores 4.332 on the five-point scale, barely below health at 4.421. But the time saved is not what separates a customer reporting a large improvement from one reporting a small one, because it is saved by nearly every customer

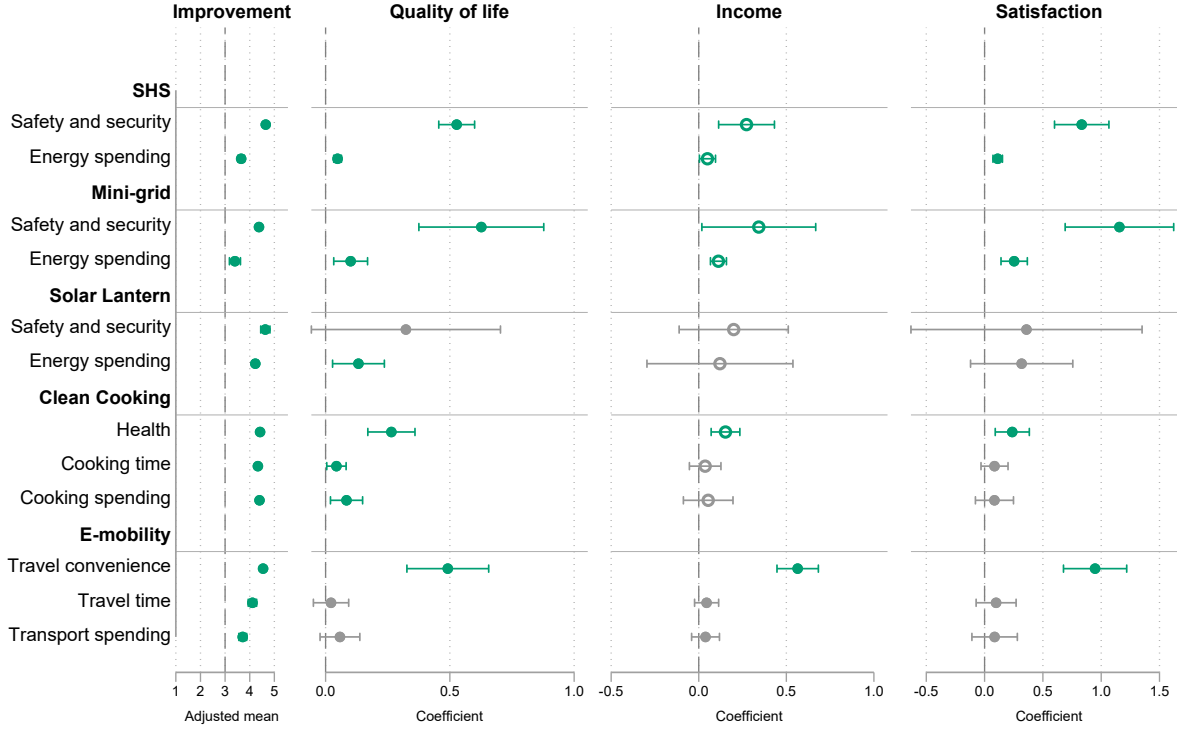
in nearly the same measure. Health varies more across households, and it is that variation the contribution coefficient captures. A clean cooking programme justified on time savings would therefore be defending the weaker half of its case, and one justified on household air quality the stronger.

For e-mobility it is travel convenience (0.492), not travel time (0.022) or transport spending (0.058), which suggests that the gain is the ability to make trips at all rather than to make the same trips faster or more cheaply. Among appliances, solar water pumps work through farm productivity (0.469) and televisions (TVs) through family bonding (0.444), the latter well ahead of the knowledge and awareness channel (0.047) that a TV might be expected to deliver.

Spending is the benefit customers mention most and the one that explains their welfare least. Energy spending scores well on the improvement scale, 3.652 for SHS and 4.228 for solar lanterns on a scale where 3 is no change, and in customers' own words (Supplementary Section E) it is the single most mentioned benefit. Yet its contribution to quality of life is the smallest of any channel for five of the eight products. This holds because cost saving is felt by nearly every customer of a given product in nearly the same way, so it lifts the average while leaving little variation to explain why one customer reports a larger improvement than another. Service quality and safety vary far more across customers, and it is that variation the contribution coefficients pick up. Cost is what brings all customers to the product; it is not what determines how much the product changes their lives once they have it.

The clearest case is the TV (in Figure 3), whose spending item is the only one in the study to fall below the no-change point, at 2.182. TV customers say the product costs them money and still report the second-largest quality-of-life contribution in the appliance panel, through time spent together as a family. The refrigerator is the mirror image: its only significant channel is the family diet, while the time it saves at the market contributes nothing measurable and is, if anything, negative.

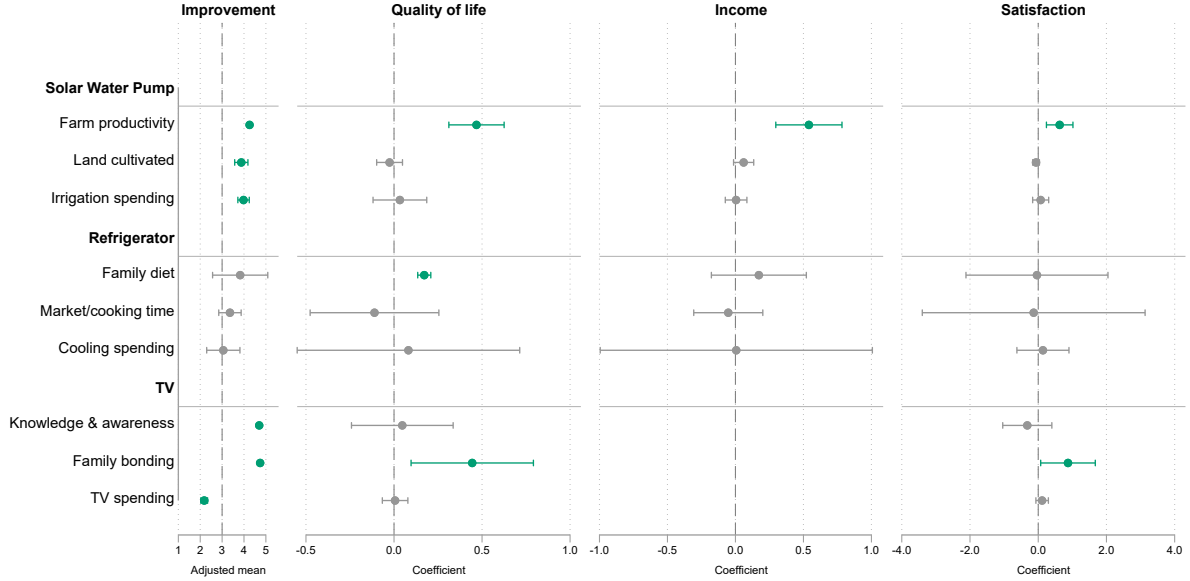
Figure 2: **Channels** - how each core technology improves daily life



Notes. Each row is one mechanism item for one technology. The first column reports the composition-adjusted mean of that item on its five-point scale, where 3 is no change. The remaining three columns report the coefficient on that item in a regression of the welfare outcome on all of the product's mechanism items entered jointly, so each coefficient is the partial contribution of that channel holding the others fixed. Estimates carry country and survey-year fixed effects and the demographic controls listed in Section 2.2, and are predicted at a common demographic profile so that differences between products are not differences in who was surveyed. Standard errors are clustered on company (or robust where a product comes from a single company). A green marker is significant at the 5 per cent level and a grey marker is not. A hollow marker flags an income estimate for a product where fewer than 25 per cent of customers report income-generating use, so it rests on a small and self-selected group of earners rather than on the product's customers at large. Hollow markers are therefore common in the income column and absent from the other two. Quality of life and income are five-point scales; satisfaction with the supplier is a ten-point recommendation scale, so its coefficients are roughly twice the size for the same underlying relationship and should not be compared in magnitude with the other two columns. Section 2.2.2 gives more details on this figure. The same estimates under a two-limit Tobit specification are reported in Supplementary Section C for robustness checks.

The appliances work through the service each one performs. For the three appliances, the pattern is, if anything, sharper than for the core technologies. Solar water pumps run almost entirely through farm productivity, which contributes 0.469 points of quality of life while the land size brought under cultivation contributes nothing measurable, and irrigation spending 0.033. TVs run through family bonding at 0.444, well ahead of the knowledge

Figure 3: **Channels - how each appliance improves daily life**



Notes. Constructed exactly as Figure 2, for the three appliance subcategories with enough respondents to estimate. A green marker is significant at the 5 per cent level and a grey marker is not. Income is not reported for TVs, because too few TV customers were asked the income question. The two figures share a common structure so that the appliance results can be read directly against the core technologies. The same estimates under a two-limit Tobit specification are reported in Supplementary Section C for robustness checks.

and awareness channel at 0.047 that a TV might be expected to deliver. Refrigerators are the weakest case in the study: the family diet improvement contributes 0.172, however, the time saved at the market is negative, and no channel reaches the magnitudes seen elsewhere.

There are two implications. First, the TV result suggests that the welfare value of a TV in these markets lies in shared time at home rather than in access to information, which is the benefit usually claimed for it. A substantial literature identifies TV as a conduit for information and for exposure to new norms^{31;32}. Our estimate does not contradict that evidence so much as locate a different margin. Those studies identify what households learn from what they watch; the knowledge and awareness item here asks customers to assess that channel themselves, and it is the shared time in front of the set, rather than the content, that separates customers reporting a large improvement from those reporting a small one. Olken³³ finds the complement in Indonesia, where TV draws time away from community participation and towards the household.

Second, the refrigerator result is the one where the spending mechanism sits at the no-change point (3.055, not distinguishable from 3): refrigerator customers report no saving on cooling and still report a positive change in quality of life, which is only coherent if the benefit is the food itself rather than any saving, a finding consistent with Ntsiful and Cohen³⁴, who show that refrigeration improves household food security and nutrition, even where the appliance carries a running cost.

The channels that carry welfare also carry satisfaction with the supplier. The channels that carry quality of life also carry supplier satisfaction, and in the same order, which is not obvious in advance: a customer could value a product and still resent the firm that sold it. Because the recommendation scale runs from 1 to 10 while the welfare outcomes run from 1 to 5, the coefficients in that column are roughly twice the size for the same underlying relationship, and the comparison should be read as one of ranking rather than magnitude.

Customers confirm this pattern in their own words. The open-ended responses, reported in Supplementary Section E, point the same way on the dominant channels and diverge on cost, exactly as the two quantities above would predict. Lower energy costs are the most frequently mentioned improvement for clean cooking and solar lanterns, while safety and light dominate the modelled contributions for the lighting products. The qualitative route also rests on more companies than the structured questionnaire does, which is why we report both.

Summary. Across eight products the welfare gain runs through a single dominant channel, and that channel is specific to what the product does: safety and security for the lighting and power systems, health for clean cooking, mobility for e-mobility, farm productivity for water pumps, and shared time and family bonding for TVs. Spending is the exception that proves the rule. It is the benefit customers name most readily and the one that least explains why one customer reports a larger improvement than another, because a price reduction is

felt almost equally by everyone who buys the product. This gives the second stylised fact. Each technology improves daily life through one dominant channel that reflects the service it provides, and for six of the eight products that channel is not money.

1.3 Off-grid energy expands access, but unevenly across populations

Next, we examine who benefited from the welfare improvements documented above. Although the sample of 474 customer surveys is not representative of all adopters in a country, it provides useful evidence on access patterns. The same technologies could reach very different users depending on prices, financing models, distribution strategies, and local market conditions.^{35;36}

Table 1 characterises customer profiles by technology. It is arranged in two main column blocks. The first describes energy access: whether the customer was a first-time user of the product category, whether they had a grid connection before adopting, and the overlap between the two. The second describes the commercial and demographic profile: how the product was paid for, where the customer lives, the sex of the main customer/user, and household education. Each percentage is calculated over the customers for whom that characteristic was recorded, with the denominator printed beneath it. This matters: sex is recorded for 73,552 customers but grid connection for only 15,507, so a single observation count per product would misdescribe most of the table.

Off-grid products reach households the grid has not, but not uniformly. The first block of Table 1 reports that three quarters of customers (76.2 per cent) were using a product in that category for the first time, and two-thirds of those asked (66.5 per cent) had no grid connection before adopting. The third column reports the overlap directly: among first-time users who were asked about the grid, 72.0 per cent had no connection.

That overlap varies far more than either column alone. It reaches 86.7 per cent for mini-grid

Table 1: Profile of off-grid product adopters

Off-grid products	Access to energy (%)			Commercial and demographic (%)				
	First-time users	No grid access	First-time & no grid	Paid upfront	No sec. education	Rural	Female	Interviews
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Core technologies								
Solar lantern	74.0	57.5	55.6	38.7	9.1	83.4	41.8	3,033
	[2,461]	[1,214]	[956]	[865]	[1,838]	[2,073]	[2,962]	
Clean cooking	84.2	23.7	27.5	53.4	9.7	38.0	59.1	11,238
	[10,035]	[744]	[575]	[2,107]	[4,555]	[9,381]	[11,082]	
Solar home systems (SHS)	74.2	77.0	76.0	7.6	19.5	56.9	29.4	38,636
	[23,922]	[9,204]	[6,438]	[9,239]	[26,969]	[23,212]	[34,871]	
Mini-grid	76.5	55.0	86.7	75.4	16.2	80.8	20.0	15,237
	[4,750]	[4,068]	[1,336]	[1,159]	[10,839]	[1,949]	[15,055]	
E-mobility	55.5	—	—	88.1	14.4	67.4	37.8	1,050
	[913]			[329]	[611]	[728]	[978]	
Appliances (pooled)	74.0	42.6	50.8	29.0	10.5	53.8	29.5	9,535
	[4,734]	[277]	[187]	[1,915]	[3,703]	[4,637]	[8,604]	
Appliance subcategories								
Solar water pump (SWP)	88.9	—	—	40.4	12.7	78.6	21.4	4,577
	[2,552]			[1,333]	[1,645]	[1,667]	[4,164]	
Refrigerator	28.5	—	—	1.7	10.4	55.8	44.8	1,841
	[692]			[302]	[328]	[731]	[1,568]	
TV	83.4	56.5	57.1	4.6	9.3	67.3	32.2	1,100
	[349]	[69]	[63]	[280]	[539]	[578]	[1,065]	
Smartphone	61.9	19.0	17.4	—	8.9	21.2	30.3	1,510
	[643]	[100]	[23]		[1,041]	[1,169]	[1,307]	
Solar fan	94.4	55.6	54.5	—	—	7.5	28.7	108
	[107]	[108]	[101]			[107]	[108]	
Solar heater	81.7	—	—	—	0.7	0.0	25.9	175
	[175]				[150]	[167]	[174]	
Solar mill	46.8	—	—	—	—	59.2	61.5	224
	[216]					[218]	[218]	
All core technologies	76.2	66.5	72.0	24.9	16.7	54.9	32.6	78,729
Non-missing obs.	46,815	15,507	9,492	15,614	48,515	41,980	73,552	78,729

Notes: Each cell is the percentage of that product's customers with the characteristic, calculated over those for whom it is recorded. The bracketed figure beneath is that denominator, not the number with the characteristic. Denominators differ from cell to cell because companies chose which questions to ask, so a single count per product would misdescribe the table. A dash means the question was never put to customers of that product. The final column counts all interviews about the product; the final row counts non-missing observations per column across the sample. The seven appliance subcategories decompose the pooled appliance row and do not add to the sample. Products are defined in Table A1 and the characteristics in Table A2. Shares are unconditional; Supplementary Section G.4 re-estimates them with country and survey-year fixed effects.

customers and 76.0 per cent for SHS, but falls to 55.6 per cent for solar lanterns and 27.5 per cent for clean cooking. The lighting and power products are therefore reaching households at the electrification frontier, while clean cooking is largely reaching households that already have electricity and are changing how they cook rather than whether they have power. This is the same division that Section 1.1 identified in the welfare results, where clean cooking delivers its benefit through health rather than through electricity access.

A grid connection is not the same as reliable supply. One figure in the access block looks anomalous and is not. Forty-five per cent^v of mini-grid customers report an existing grid connection, which in a sample of off-grid products invites the suspicion of a coding error. The questionnaire lists grid electricity and a mini-grid connection as separate options, and the pattern is geographic: 77.1 per cent of Indian mini-grid customers report a connection against 5.0 per cent in Kenya, and Indian solar lantern customers are 95.4 per cent connected.

India reached near-universal household connection under the Saubhagya programme, which was launched in September 2017 and reported more than 99 per cent of households identified under the programme were electrified by March 2019³⁷ – time periods preceding the surveys we use in this work. However, the reliability of supply lagged well behind: rural households still report frequent and extended outages, and the pricing and enforcement arrangements that accompanied universal connection left distribution utilities unable to supply reliably^{38;39}. An Indian customer buying a solar product is therefore usually buying backup for an unreliable connection, while an East African customer is usually buying first access. The variable records connection, not electricity actually delivered, and the two markets it spans are different. We therefore report it throughout as *no grid access*, so its direction is never ambiguous, and examine it directly as a source of heterogeneity in Supplementary Section D.2.

^vThe table uses *no grid access* and reports 55 per cent for mini-grid customers, which is analogous to the 45 per cent with a grid connection.

How customers pay is set by the product, not by the customer. Turning to the commercial block, credit rather than cash is the norm. Among the 15,614 customers asked, 75.1 per cent bought on credit and 24.9 per cent paid upfront. The split across products is wide and follows the delivery model rather than anything about the customers: upfront payment covers 75.4 per cent of mini-grid customers, 88.1 per cent of e-mobility customers, and 53.4 per cent of clean cooking customers, but only 7.6 per cent for SHS, 4.6 per cent for TVs and 1.7 per cent for refrigerators.

These are unlikely to be differences in what customers can afford. A mini-grid connection is sold as a service with a connection fee, while a SHS is sold as an asset that pay-as-you-go lending was built to finance. The same household would plausibly pay cash for one and instalments for the other. Payment terms therefore shape which products a household can reach rather than whether it can participate in off-grid markets at all, and a policy aimed at easing upfront cost would change the product mix more than the adoption rate.

Appliance ownership does not follow a simple ladder. Among appliance subcategories, first-time shares range from 94.4 per cent for fans and 88.9 per cent for solar water pumps down to 46.8 per cent for solar mills and 28.5 per cent for refrigerators. This does not order the categories by price, and it is not evidence that households acquire cheap appliances before expensive ones: solar water pumps are among the most costly items here and have one of the highest first-time shares.

What the column records is whether the category was previously available to the household at all. A solar water pump replaces manual or diesel irrigation rather than an earlier pump, so almost every buyer is a first-time buyer of that category. A refrigerator is a category a household may well have had before, powered from the grid or from gas, so a majority of buyers are replacing or upgrading. The share therefore measures novelty of the category in that market, not a rung on an affordability ladder.

Adopters are markedly better educated than the populations they are drawn from. Focusing on the socio-demographic block, some 83.3 per cent of adopters have at least some secondary education, rising above 90 per cent for solar lanterns, clean cooking, smartphones, TVs and solar heaters.^{vi} This is far above completion rates in Sub-Saharan Africa, at 42 per cent for lower secondary and 30 per cent for upper secondary⁴⁰.

The literature reads a gap of this size as evidence that participation in off-grid markets depends on human capital, and specifically on the ability to navigate financing and service arrangements^{29;41}. Our data are consistent with the gap but not with that explanation of it, when it comes to off-grid adoption and usage. We analyse and discuss the details in Section 1.4.

Additionally, a majority of surveyed users (55%) live in rural areas, consistent with the core role of off-grid technologies in serving communities beyond the grid frontier. However, more than 83% of the globally unelectrified population resides in rural areas.¹¹ Unelectrified rural populations are therefore under-represented in our sample relative to their share of unmet electricity needs. This gap may partly reflect the data collection process, but is more likely driven by structural differences in access conditions. Rural areas account for most adoption of solar lanterns (83%) and mini-grids (81%), consistent with their suitability for low-density settings. By contrast, higher-value products such as e-mobility and SHS, as well as appliance-based applications, display a more mixed spatial distribution, suggesting that market depth, logistics, and household purchasing power may constrain penetration in the most remote areas. Clean cooking technologies show the weakest rural targeting (38%), a pattern that warrants attention given the high concentration of indoor air pollution burdens in rural settings.²⁸

Women account for roughly one-third of customers, suggesting that off-grid markets reach women, but not on equal terms with men. This is consistent with broader evidence that women are more exposed to energy poverty and face structural barriers to asset ownership, finance, and participation in energy markets⁴². They are particularly under-represented

^{vi}Solar heaters correspond to only 175 observations, so that particular figure is more likely to reflect sample selection.

among adopters of high-capacity technologies such as mini-grids (20%) and SHS (29%), but better represented where technologies serve traditionally domestic functions, including clean cooking (59%), solar mills (62%), and refrigeration (45%).

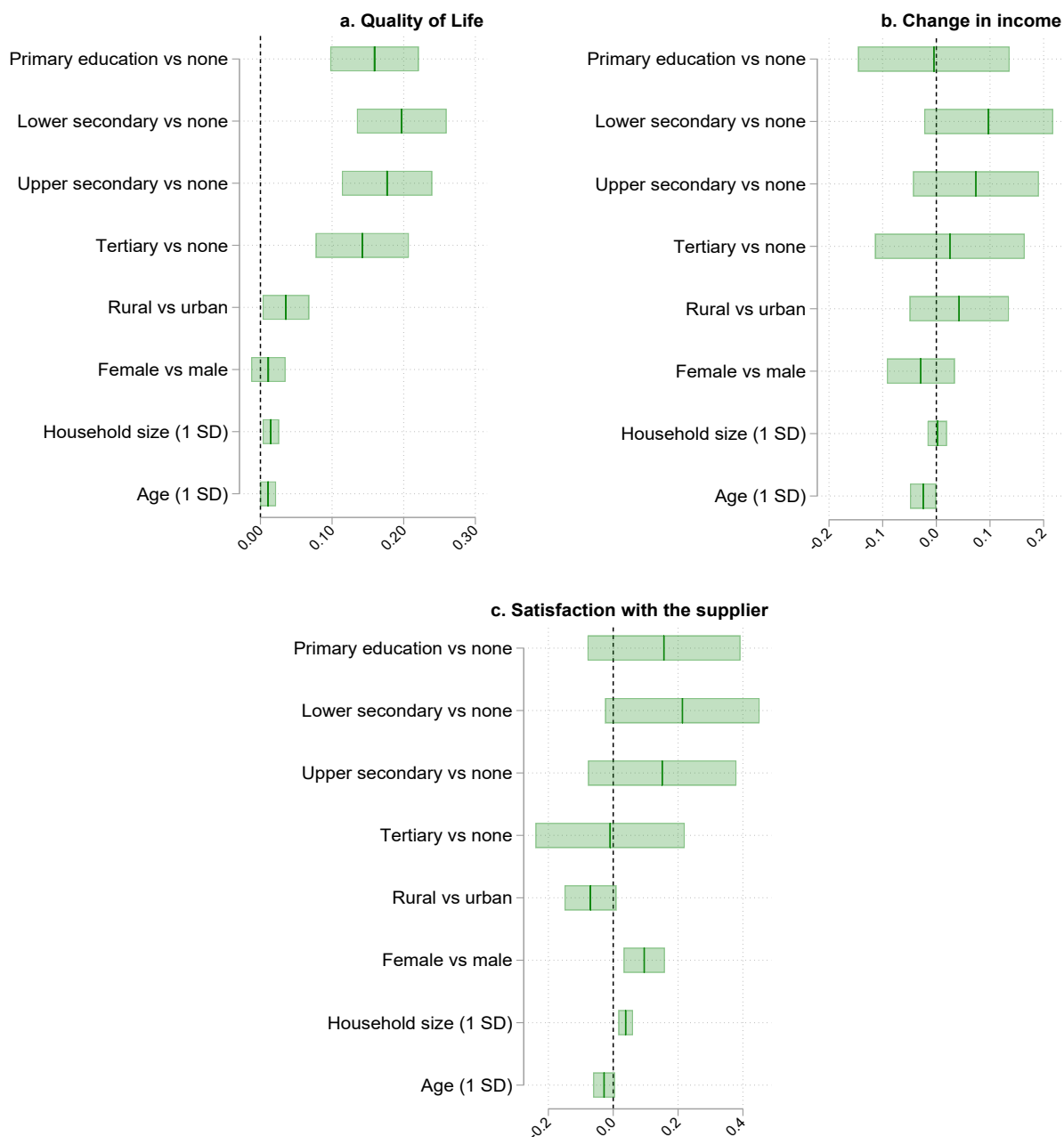
This yields the third stylised fact. Off-grid energy is reaching households the grid has not reached, but within those households it is reaching the better educated. And how a customer pays is decided by the business model of the product, not by what the customer can afford. Thus, payment terms shape which products a household can reach rather than whether it can take part at all. The frontier and the stratification operate through different mechanisms: the first is geographic and technological, the second educational and commercial.

1.4 Education is associated with higher perceived benefits

A lack of education may hinder adoption not only by limiting access, but also by reducing the ability of households to use these technologies effectively and reap their full benefits. Figure 4 examines the association between user characteristics and perceived benefits, conditional on technology ownership, using fixed-effect OLS with country and survey-year fixed effects, so that customers are compared within the same country and survey year. Completion of primary schooling is associated with a 0.16-point increase on the five-point quality-of-life scale relative to no formal education, with comparable effects at higher levels of schooling. Similar patterns emerge for satisfaction with the supplier, although these estimates are less precise, possibly due to smaller sample size. Results remain robust across alternative specifications.

This pattern is consistent with complementarity between off-grid technologies and education. Individuals with more schooling may be better positioned to translate access to energy-using products into welfare gains, for example through higher productivity, improved access to information, or enhanced learning opportunities. However, in this statistical model, the effect of education may also capture other aspects, such as differences in income, since this variable is not available in the data. It may therefore more broadly signal differences in household and individual capabilities.

Figure 4: Sociodemographic differences in reported improvements in outcomes



Notes: Green vertical bars are estimates (at 95% confidence intervals) from fixed-effect OLS regressions, controlling for technologies and country and survey-year fixed effects. Education categories are measured relative to households with no formal education; household size and age are expressed in standard deviations. See the [Methods section](#) for further detail on the estimation strategy.

Effects for other characteristics are modest when statistically significant. Satisfaction with the supplier is higher for women than for men, and improvements in quality of life are larger for rural households, which may reflect differences in baseline access to energy services.

This is in line with the selection that Section 1.3 identified. Adopters are far better educated than the populations they are drawn from, but schooling predicts who appears in these markets and how much they report gaining rather than how well they cope once they have bought. The selection is more plausibly operating earlier, through the income, location and networks that correlate with schooling and determine who a sales agent reaches at all.

This gives the fourth stylised fact. Education is associated with larger reported benefits from off-grid products, and consistently so across outcomes. But it operates on the size of the gain rather than on the odds of the purchase going wrong. It is therefore better read as a marker of the capability and circumstances a household brings to the product than as a skill that protects it.

1.5 Heterogeneity: those who had the least before gain the most

The preceding sections describe what customers report on average. Here, we ask whether the average conceals groups who gain a great deal more or a great deal less. Two divisions can be examined with these data: whether the customer was using a product in that category for the first time, and whether they had a grid connection before adopting.

We focus only on two dimensions, because the dimensions of interest are recorded in different survey modules and rarely for the same person. Requiring rurality, sex, education and grid connection together leaves 1,740 respondents out of 78,729, so a single model carrying all of them is not estimable and we do not attempt one. Each dimension is estimated separately, on its own maximal sample, using the specification behind Figure 1. Supplementary Section D sets out the estimation, the two control sets and the three floors that decide whether a cell can be reported at all, and reports every estimate discussed below as a figure.

First-time users report larger gains than repeat buyers. Prior access is the best covered of the two, recorded for 46,815 customers, and it gives the clearest heterogeneity result in the study. In Column (5) of Table D1 of the Supplementary Section, pooling across technologies, customers using a product in that category for the first time report a quality-of-life change 0.161 points higher than repeat buyers on the five-point scale (95 per cent interval 0.110 to 0.211, on 22,284 customers across 86 companies). The association is positive for four of the five technologies that can be estimated, and clearly so for two: 0.300 for clean cooking and 0.161 for SHS. Appliances are at 0.181, with an interval that just includes zero, and mini-grids at 0.021 are the one null. Solar lanterns are negative at -0.158 but not distinguishable from zero. Supplementary Section D.1 plots the full set of estimates in Figures D1 and D2.

The same pattern appears in satisfaction with the supplier, at 0.184 points on the ten-point scale for the pooled estimate and 0.457 for mini-grids. This is the one dimension on which mini-grids show the largest effect rather than the smallest, which fits their position observed in Section 1.1: a first-time mini-grid customer is acquiring a service they have never had, and evaluates the supplier accordingly.

We acknowledge two cautions with this result. First-time use is not randomly assigned: a household buying its first solar product differs from a repeat buyer in wealth, location and expectation, and nothing here observes those differences beyond the controls. There is also a mechanical reason to expect a positive gap, since a customer with no prior product is comparing against nothing while a repeat buyer is comparing against what they already owned. The two groups answer the question relative to different baselines, so the estimate describes what customers report rather than what the product delivers.

Customers without a prior grid connection gain more, where it can be measured.

Prior grid connection is recorded for 15,507 customers, and requiring it alongside an outcome and the control set leaves far fewer. Only SHS and mini-grids clear the floors for quality of life, only SHS for satisfaction, and no technology at all for income: just 538 customers

answered both the income and the grid questions with the controls present, so only a pooled income estimate is possible.

Where it can be measured, Column (5) of Table D2 of the Supplementary Section shows that the association is positive. For SHS, customers with no prior connection report a quality-of-life change 0.192 points higher (95 per cent interval 0.068 to 0.316, on 4,048 customers across 18 companies). Mini-grids point the same way at 0.177 (0.027 to 0.327, on 1,545 customers across seven companies), and pooling the technologies gives 0.130 (0.040 to 0.221, on 6,234 customers across 29 companies). Supplementary Section D.2 plots the three outcomes in Figures D4 to D6.

The direction is what the composition of the sample implies. A customer who had no connection is buying first access, and the change from nothing to something is larger than the change from unreliable supply to supplemented unreliable supply. That is the same logic Section 1.1 applies to technologies, here applied to customers.

Satisfaction with the supplier shows no such difference, and the contrast is worth noting. Prior connection is associated with how much the product changes a household's life. It is not associated with how the household rates the company that sold it. Whatever drives the supplier relationship, it is not whether the customer had electricity beforehand.

Because Indian customers are overwhelmingly connected and East African customers are not, a grid comparison risks being a comparison of countries in disguise. We therefore estimate every specification twice: with and without India. For SHS the question hardly arises: India contributes no SHS respondents to this sample, and dropping India moves the SHS estimate only from 0.192 to 0.191, through the controls and fixed effects that are estimated jointly with the other technologies. The pooled estimate rises slightly without India, to 0.144. For mini-grids it cannot be settled: removing India leaves 845 respondents across four companies, below the floor at which a company random intercept is identifiable. The honest statement is that these data cannot answer it for mini-grids, not that India makes no difference. Two further cautions apply to the grid results as a whole. The least-squares estimates point the same way but are about a third as large and not distinguishable from zero at the 5 per

cent level, and with the full control set, which removes India and a third of the sample, the Tobit estimates are smaller and not significant either. Supplementary Section D.2 reports the comparison in full.

This gives the fifth stylised fact. The customers who gain most are those who had least before. First-time buyers report larger improvements than repeat buyers, most clearly for SHS and clean cooking, and customers without a prior grid connection report larger improvements than those with one. The gains are concentrated where the baseline was lowest, which is where the policy case for these products is strongest.

1.6 The risks of adoption fall on customers

The benefits documented in the preceding sections reach only the customers whose purchase works out. Buying an off-grid product is a commitment made under uncertainty, and most of that uncertainty is carried by the customer rather than the company. This section examines two sides of that risk. The first is *product risk*: once in use, the product may not deliver what the customer expected. The second is *contract risk*: most customers buy on credit and commit to months of payments on terms they may not fully understand when they sign. Knowing where each risk falls, and what is associated with reducing it, shows where suppliers and policy can protect the gains reported so far.

We measure product risk with three outcomes. A customer *reported a challenge* if they named at least one problem with the product, is a *detractor* if they gave a score of six or below when asked how likely they are to recommend their supplier on a ten-point scale, and has *discontinued* if they no longer use the product.^{vii} For each product we estimate the probability of each outcome at a common demographic profile, so that differences between products do not reflect who was surveyed, and then ask which customer characteristics and

^{vii}All definitions are borrowed from the report by 60 Decibels¹¹ based on this data. Every rate in this section is a share of the customers who were asked the relevant question, because companies chose which survey modules their projects carried. Dividing by all 78,729 interviews instead would count each customer who was never asked as a non-event. Table F1 reports both denominators.

which company practices are associated with more or less risk.^{viii}

Problems are common, abandonment is rare. Among the 70,426 customers asked, 32.1 per cent report at least one challenge. Among the 34,360 asked to rate their supplier, 17.3 per cent are detractors, and among the 33,746 asked whether they still use the product, 3.9 per cent have stopped. Figure 5 shows the same ordering within every core technology: the modelled share reporting a challenge runs from 23.2 per cent for clean cooking to 39.3 per cent for mini-grids, and in each case it is well above the share that has stopped. The appliance subcategories in Figure 6 follow the same pattern. Problems, in other words, are a normal part of owning these products, but for the large majority of customers a problem is a reason to complain rather than a reason to give the product up. That is consistent with the high welfare ratings in Section 1.1: a product that delivers real value is worth keeping even when it does not work up to expectation.

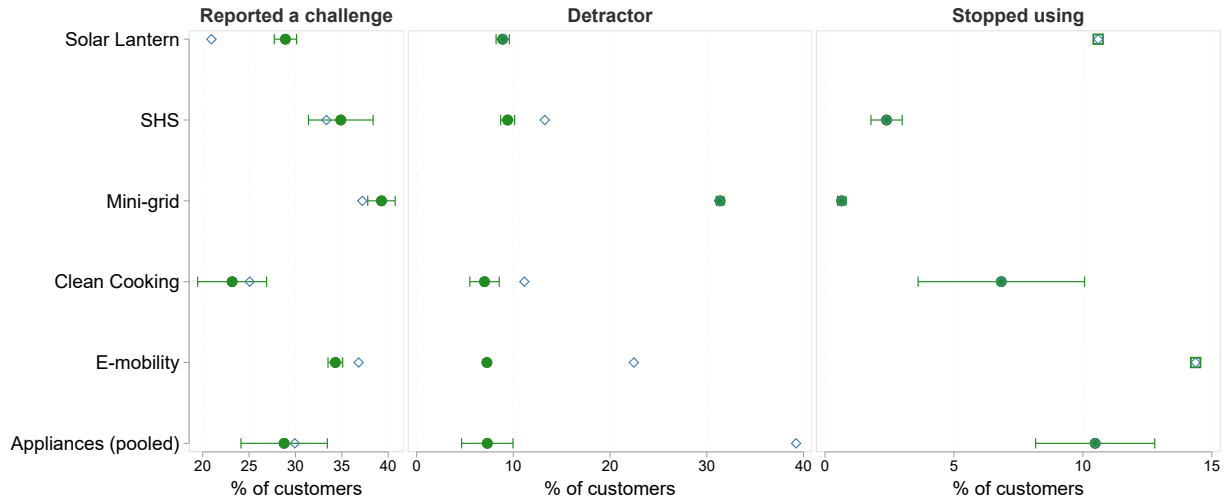
Customers stay with a service and walk away from an object. Which customers stop is shaped by how easily they can. Mini-grids sit at both extremes of Figure 5: they have the highest share of detractors, at 31.4 per cent, and the lowest discontinuation rate, at 0.7 per cent. SHS follow, with 2.4 per cent having stopped. At the other end are products a household owns outright and can put aside: e-mobility at 14.4 per cent and solar lanterns at 10.6 per cent in Figure 5, and refrigerators at 13.1 per cent and solar water pumps at 12.1 per cent in Figure 6.

The intuition is straightforward. A mini-grid connection is an ongoing, metered service, and leaving it means going back to having no electricity at all, especially for those without prior electricity access. So a dissatisfied customer complains and remains connected. This is the same position mini-grids hold in Section 1.1, where they are the only category rated materially lower on satisfaction. A SHS is an asset, but most are bought on credit (Section

^{viii}Challenges and detraction are estimated by logit with the full demographic control set. Discontinuation is estimated by a linear probability model with country and survey-year fixed effects only, because the questionnaire stops asking demographic questions once a customer reports having stopped: of 1,332 discontinuers, only 18 have a complete control set. The estimates behind Figures 5 and 6 are in Table F2.

1.3), and a customer paying towards ownership has every reason to keep the system running. A lantern, a motorbike or a pump carries no such tie: when it fails or stops being needed, it is simply set aside.^{ix}

Figure 5: **How often adoption goes wrong: core technologies**

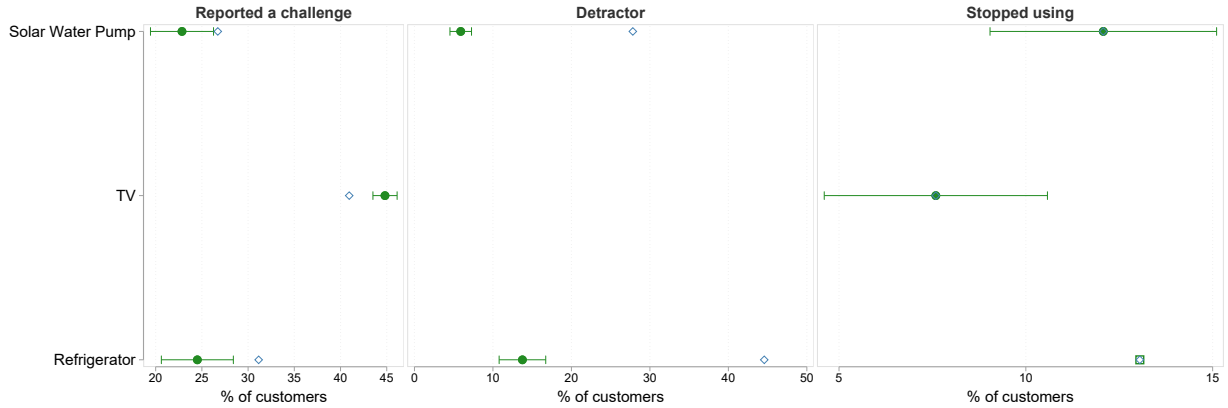


Notes. Each marker is the modelled probability that a customer of that product reports the outcome, predicted at a common demographic profile so that differences between products are not differences in who was surveyed. Green circles = adjusted probabilities, with 95% CI; blue diamonds = unadjusted shares. Challenges and detraction are estimated by logit with the full demographic control set; discontinuation is estimated by linear probability with country and survey-year fixed effects only, because the questionnaire stops asking demographic questions once a customer reports having stopped using the product, which leaves 18 of 1,332 discontinuers with a complete control set. A hollow square with no interval marks a cell where no interval is identified, because that product's companies are fully separated by country and survey year, so the fixed effects absorb all variation between companies. Standard errors are clustered on company where a product has more than one, and robust otherwise. All estimates are conditional associations.

What goes wrong is mostly whether the energy keeps flowing. In their own words, customers describe problems with performance rather than price. Figure E2 in Supplementary Section E reports the three most common themes for each product. Among customers describing a challenge, system reliability leads for mini-grids (55.1 per cent) and SHS (37.0 per cent), and battery and power performance leads for solar lanterns (53.5 per cent) and e-mobility (28.6 per cent). Reliability and durability are also the most common reason detractors give for SHS (52.7 per cent), solar lanterns (43.5 per cent) and mini-grids (40.3 per

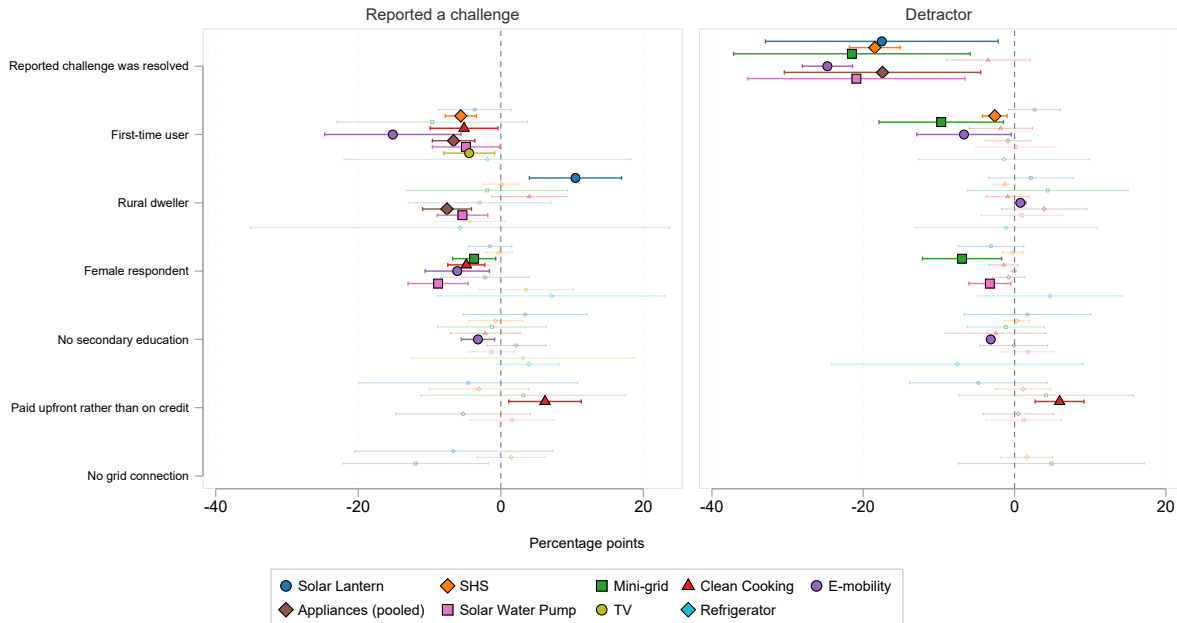
^{ix}Solar water pumps are also used seasonally, so a pump that fails during the growing season may stand idle until the next one.

Figure 6: How often adoption goes wrong: appliance subcategories



Notes. Constructed exactly as Figure 5, for the appliance subcategories with enough respondents to estimate. TVs rest on a single company for discontinuation and have no detractor estimate, while solar water pumps rest on six or seven companies throughout, so the two should not be read as equally reliable.

Figure 7: Which customers carry the risk



Notes. Average marginal effects in percentage points, by product and risk outcome. A positive value means the characteristic is associated with *more* risk. The six customer characteristics come from different survey modules and are rarely recorded for the same person, so they are estimated in separate blocks rather than in one regression; requiring all six at once leaves no respondents. Each block reports its own sample size. Whiskers are 95 per cent confidence intervals, and an estimate is drawn at full strength only where it is significant at the 5 per cent level and rests on more than one company. Whether a reported challenge was resolved is included for detraction only: it is undefined for customers who never reported a challenge. Discontinuation has no risk-factor model, because the demographic questions are not put to customers who have stopped using the product.

cent), and product failure is the most common reason for stopping among SHS (53.5 per cent) and solar lantern (58.3 per cent) users.^x Product risk, then, is largely a matter of whether the product keeps working, which is something the supplier can act on.

Resolving a problem is the strongest lever a company has. The top row of Figure 7 shows what happens when the supplier acts. Among customers who reported a challenge, having it resolved is associated with a lower probability of being a detractor in six of the seven products we can estimate: by 24.7 percentage points for e-mobility, 21.5 for mini-grids, 20.9 for solar water pumps, 18.5 for SHS, 17.5 for solar lanterns and 17.5 for appliances as a group. These are the largest associations in the figure. A problem on its own does not turn a customer against the supplier; an unanswered one does. This result is also in line with the findings in Section 1.1, where satisfaction with the supplier separated companies more than it separated products: what customers judge is how the company responds when something goes wrong.

First-time users report fewer problems. The second row of Figure 7 shows that customers using a product of that kind for the first time are less likely to report a challenge, by 5.6 percentage points for SHS (95 per cent interval -7.8 to -3.4 , on 11,394 customers), 15.2 for e-mobility, 6.6 for appliances as a group and 5.2 for clean cooking. They are also less likely to be detractors, by 2.6 points for SHS and 9.7 for mini-grids. This is the mirror image of the result in Section 1.5, where first-time users report larger gains. A customer with no earlier product has nothing to compare against, so fewer shortcomings register as problems, while a repeat buyer judges the new product against one they already know. The remaining customer characteristics in the figure, such as sex, rurality and education, are mostly small and do not point consistently in one direction.

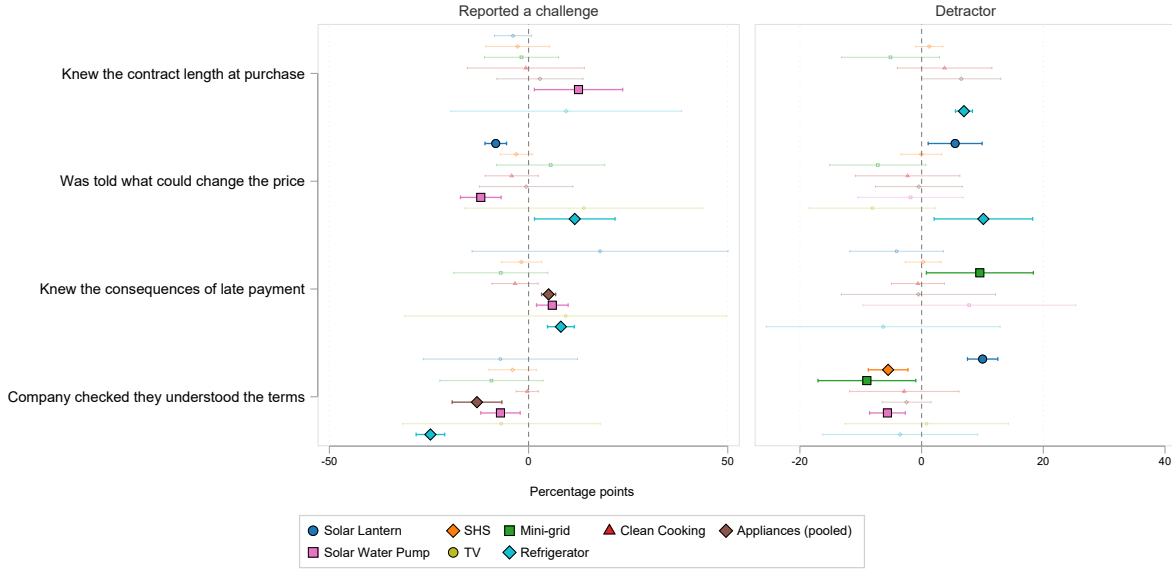
^xClean cooking is the exception for stopping, where the leading reason is that the stove does not suit the fuel or the way the household cooks (28.9 per cent). Shares are a composition within the customers who gave a reason, not a share of all customers.

Contract risk: what the customer understood at the point of sale. The second side of risk arises before the product is used. Three in four customers asked, 75.1 per cent, bought on credit (Section 1.3). A credit purchase commits the household to a stream of payments over months or years, and in many pay-as-you-go arrangements a missed payment can mean penalties or a product switched off until the account is brought up to date. A customer who signs without understanding how long the contract runs, what happens if they pay late or what could change the price can end up paying more than expected or losing the use of a product they have partly paid for. What the seller explains, and whether the buyer understood it, therefore determines how much of this risk the customer carries without knowing it.

The surveys asked credit customers four questions about what the company told them at the point of sale, and Figure 8 relates each to later problems and to detraction. The clearest result is for whether the company *checked that the customer understood* the key terms. Where it did, customers were less likely to report a problem later: by 12.9 percentage points for appliances as a group (95 per cent interval -19.2 to -6.7), 24.6 for refrigerators and 7.1 for solar water pumps. They were also less likely to be detractors: by 5.5 points for SHS (95 per cent interval -8.8 to -2.2 , on 6,847 customers), 9.0 for mini-grids and 5.6 for solar water pumps. A customer who understood the contract knows what to expect, so fewer events come as a surprise and fewer turn into disputes with the supplier. Unlike schooling or location, checking comprehension is something a company controls, and something a lender or regulator can require.

Limitations. Four points qualify these results. First, they are associations. Companies that resolve problems may also sell better products or serve easier markets, and problems that get resolved may be the milder ones, so the resolution estimates should not be read as the effect of after-sales service alone. Second, the other three disclosure items in Figure 8 are mixed. Knowing the consequences of late payment is associated with *more* reported problems for appliances (5.0 points) and refrigerators (8.1 points), most plausibly because a customer who has already fallen behind is the one who has learned what happens next, and

Figure 8: What the seller disclosed, and whether the customer later reported a problem



Notes. Average marginal effects from a logit, in percentage points. A positive value means the disclosure is associated with *more* reported risk. Each product has its own colour and marker, matching Figure 7. Whiskers are 95 per cent confidence intervals, and an estimate is drawn at full strength only where it is significant at the 5 per cent level and identified by more than one company. These four variables record what the company disclosed at the point of sale. They are not characteristics of the customer, and they are put mainly to customers who bought on credit, roughly 12,000 of the 15,614 asked about credit at all. The sample is therefore narrower than in Figure 7 and the two should not be read as one panel. Each model also controls for sex, education, household size and age, with country and survey-year fixed effects and standard errors clustered on company. These are conditional associations, not effects.

for solar lanterns the comprehension check goes with more detraction rather than less. Third, several products rest on few companies: TVs contribute one company to the discontinuation estimate, e-mobility three and refrigerators two or three, so their intervals are wide or cannot be computed (see Table F2). Fourth, discontinuation is modelled without demographic controls, so we can say which products customers leave but not which customers leave them.

This gives the sixth stylised fact. Adoption risk is shaped less by who the customer is than by how the product is sold and serviced. Customers stay with services and walk away from objects; when something goes wrong, a company that resolves it keeps the customer's goodwill; and where the seller checks that the buyer understood the contract, fewer problems follow. Each of these is within the reach of the companies themselves.

1.7 Discussion

Our results yield six stylised facts about off-grid technology expansion, one from each of the preceding sections.

First, reported benefits are high everywhere and differ little between technologies (Section 1.1). Nine in ten customers report an improvement in quality of life, and the simplest products rank at least as highly as the most capable ones. The practical implication is that the choice of technology matters less for welfare than the question of whether a household gets a working product at all.

Second, each technology delivers that benefit through one dominant channel, and for most products it is not money (Section 1.2). Safety and security carry SHS and mini-grids, health carries clean cooking, travel convenience carries e-mobility, farm productivity carries solar water pumps and family bonding carries TVs. Lower spending is the benefit customers name most readily in their own words, yet among the weakest predictors of how much their lives changed. Both are true: a cost saving is felt by nearly every customer in nearly the same way, so it raises the average while explaining little of the difference between one customer and another.

Third, off-grid energy reaches households the grid has not, but the better-off among them, and payment terms are set by business model rather than by means (Section 1.3). Most customers are first-time users without a prior grid connection, yet adopters are more urban, more often male and considerably better educated than the unelectrified population of the countries surveyed. Credit is the norm: three quarters of the customers asked bought on credit, and whether a product is sold for cash or on credit follows its delivery model rather than the customer's income. Payment terms therefore shape which products a household can reach more than whether it can take part at all.

Fourth, education predicts how much a customer gains, not whether the purchase goes wrong (Section 1.4). Completing primary schooling is associated with a quality-of-life change 0.16 points higher than no formal education, with similar estimates at higher levels.

Yet schooling is essentially unrelated to whether a customer reports a problem with the product (Figure 7). It is better read as a marker of the capabilities and circumstances a household brings to the product, including income we cannot observe, than as a skill that protects it.

Fifth, the customers who gain most are those who had least before (Section 1.5).

First-time buyers report larger improvements than repeat buyers, by 0.161 points pooled and most clearly for SHS and clean cooking, and customers without a prior grid connection report larger improvements than those with one, by 0.130 points pooled. The same first-time users also report fewer problems (Section 1.6). The gains concentrate where the baseline was lowest, which is where the policy case for these products is strongest.

Sixth, adoption risk is shaped less by who the customer is than by how the product is sold and serviced (Section 1.6).

About a third of customers report a challenge, but only 3.9 per cent stop using the product. Customers stay with services and walk away from objects: mini-grids have the largest share of detractors and the smallest share who stop. Whether a reported problem was resolved is associated with 17 to 25 percentage points less detraction, more than any customer characteristic we observe, and where the seller checked that a credit customer understood the terms, fewer problems followed.

Conclusion. Taken together, these facts point to a consistent conclusion. Off-grid technologies deliver real and broad welfare gains, through channels specific to what each product does. The constraints on those gains lie less in the hardware than in the market around it: in who the products reach, and in the commercial relationship once they are bought, that is, whether the customer understood what they signed and whether someone fixes the product when it fails. For the climate finance that motivates this paper, the message is encouraging. The gains reach households at the electrification frontier, are largest for those who had least before, and run through channels that matter for living with a changing climate, such as farm productivity for solar water pumps and food preservation for refrigerators. The levers that protect those gains, resolving problems and making sure buyers understand their con-

tracts, are within reach of the companies themselves. With universal energy access under Sustainable Development Goal 7 due by 2030, and climate finance high on the agenda of COP31, off-grid energy offers a direct route from pledges to measurable improvements in people’s daily lives.

Implications for policy and practice. Four implications follow, each tied to one of the facts above. First, programmes that evaluate or subsidise these products on energy expenditure alone will miss most of what they do; safety, health, time and productivity are where the welfare differences between customers lie. Second, the households that gain most are the ones the market reaches least. Standalone commercial deployment is unlikely to reach the most marginalised, so subsidies or results-based finance that reward reaching first-time and unconnected customers, alongside integration with social protection, financial inclusion and digital literacy programmes, would direct support where the returns are largest. Third, consumer protection in credit sales should require that sellers confirm a customer has understood the key terms, rather than only that the terms were disclosed. Fourth, because reliability is the most common complaint and resolving it is the strongest lever on customer satisfaction, product quality standards and enforceable after-sales obligations, such as warranties, repair networks and complaint resolution, would address the risk that currently falls on the customer.

Limitations. We close with the limits of this evidence. The data are cross-sectional, observational and self-reported, and customers select into both products and surveys; because companies commissioned the surveys, firms that invest in customer feedback may also be over-represented. Every estimate here is a conditional association, not a causal effect. Outcomes are reported retrospectively, so customers with different starting points answer relative to different baselines, and mechanisms and outcomes come from the same respondent in the same interview, so the mechanism contributions rank channels within a product rather than identifying them. Because surveys come from a small number of projects within each product, it is the number of companies rather than the number of respondents that

bounds what can be inferred, and several products in this study rest on fewer than five. The data also contain no measure of climate exposure, so the adaptation value of the channels above is suggested rather than tested here. Finally, survey modules varied across projects, so characteristics such as grid connection, sex and education are rarely observed together, and demographic questions were not put to customers who had stopped using the product. A common core module asked of every respondent, including those who stopped, would let future survey rounds answer the questions these data cannot.

2 Methods

2.1 Data

The analysis draws on a proprietary dataset assembled by 60 Decibels, a global social impact measurement firm specialising in end-user surveys across vulnerable communities. The dataset comprises 474 unique survey projects conducted from 2020 to 2023 across 31 countries, yielding 78,729 individual customer observations. Geographic representation is concentrated in sub-Saharan Africa (88% of respondents), with the largest country shares from Kenya (22.6%), Tanzania (10.9%), Uganda (9.1%), Nigeria (8.2%), and Zambia (7.5%). Additional coverage spans South and Southeast Asia (11.0%, predominantly India at 7.0%) and Latin America and the Caribbean (1.0%). This distribution reflects 60 Decibels’ own network, as well as the current geography of off-grid energy market activity, rather than the full universe of energy-poor populations.

Each project is defined as a distinct combination of company, country, and survey year. For each project, respondents were selected through telephone interviews conducted by a network of over 1,200 local researchers. For each project, participants were drawn from random samples of the registered customer contact databases provided by 164 participating energy companies. To ensure internal validity, 60 Decibels performed demographic checks to verify that sampled respondents matched the broader profile of each company’s registered

user base.

It is worth noting that, because the data are drawn from registered customers of participating companies rather than from the broader population of energy-poor households, the results describe the distribution of benefits among technology adopters rather than among all those who could potentially benefit. This distinction is vital for interpreting the external validity of our findings, as the sample represents a self-selected group that has already overcome initial market entry barriers.

Variable definitions and summary statistics

The full dataset covers 13 product types which can be collapsed into six core technologies: solar home systems (SHS, 49% of observations), mini-grids (19%), clean cooking technologies (14%), appliances (12%), solar lanterns (4%), and e-mobility (1%). The appliance category encompasses specialised end-use devices powered via off-grid systems, including solar water pumps (SWPs), refrigerators, smartphones and TVs, which together account for approximately 95% of the appliances. The remaining 5% are solar mills (2.3%), solar water heaters (1.8%) and fans (1.1%).^{xi} Full product definitions are provided in Supplementary Table A1, and Supplementary Section A shows the distribution of customers across countries and off-grid products.

The surveys include multiple questions on product use and users' sociodemographic characteristics, several of which inform the analysis throughout the paper. All variables and definitions are reported in Supplementary Table A2.

One feature of the instrument shapes how several results in this paper must be read. Satisfaction is elicited in two different ways across the survey programme. Some projects ask how likely the customer is to recommend the company that supplied the product; others ask the same about the product itself. No respondent was asked both questions, so the two measures

^{xi}The raw dataset also included 32 individuals who owned "other appliances" comprising cold transportation and energy-agriculture services. We excluded these observations from all analyses due to small sample size.

are recorded for disjoint sets of customers and cannot be pooled, averaged, or compared as a paired difference. The supplier question covers 34,360 customers and the product question 38,678. We use the supplier measure throughout. The reasons, which turn on where in the survey programme each question was asked, are set out in Supplementary Section [B](#).

Coverage varies substantially across the other variables too, for the same reason: companies commissioned surveys with different modules. Sex is recorded for 73,552 customers, education for 48,515, rurality for 41,980, payment method for 15,614 and prior grid connection for 15,507, out of 78,729 interviews. Every statistic in this paper is computed over the customers for whom the relevant variable is recorded, and the denominator is reported alongside it. Missingness of this kind reflects survey design rather than refusal, so it does not bias a statistic within the group that was asked, but it does mean that different statistics describe different subsets of companies.

Individual- and household-level covariates include the highest education level attained by any household member (ranging from no formal education to tertiary; $N = 48,515$), household size (mean: 6.3 members; $N = 50,575$), respondent age (mean: 41 years; range: 18–100; $N = 51,467$), gender (33% female; $N = 73,552$), and a binary rural residence indicator (55% rural; $N = 41,980$). Summary statistics for all variables are presented in Table [A3](#).

Section [1.1](#) focuses on three primary outcomes capturing perceived benefits. The first outcome is improvements in quality of life. It is measured on a five-point scale from “got much worse” (1) to “very much improved” (5). The mean is 4.4, and 91.9% of the 69,547 respondents with non-missing data report an improvement. The second outcome is perceived change in income. It is measured on a five-point scale from “very much decreased” (1) to “very much increased” (5). The sample is restricted to customers with productive uses, excluding personal use. Among the 8,435 respondents with available data, 74.6% report an increase (mean = 4.0). The last outcome is satisfaction with the supplier, measured as the likelihood of recommending the company that supplied the product, elicited on a scale from 1 (“not at all likely”) to 10 (“extremely likely”) ($N = 34,360$; mean = 8.0). Customers scoring 1 to 6 are classified as detractors, a definition used in Section [1.6](#). The full response

distributions are shown in Supplementary Figure [A2](#).

Qualitative Thematic Coding: Approach and Validation

A distinctive feature of the 60 Decibels methodology is the integration of standardized quantitative instruments with open-ended qualitative questions. This approach allows stakeholders/customers to define impact in their own words, ensuring that the metrics of success are relevant to the end-users’ lived experiences. Sections [1.2](#) and [1.6](#) use qualitative responses grouped into thematic categories, reported in Supplementary Section [E](#).

The qualitative analysis follows a systematic thematic coding process: (i) inductive discovery: respondents are asked open-ended questions regarding changes in their quality of life, income changes, challenges faced, or reasons for recommending a product; (ii) categorisation: raw verbal responses are reviewed and “coded” into common themes by researchers; and (iii) frequency determination: metrics of impact are then prioritized based on the frequency with which specific themes emerge across the sample. All this was done by 60 Decibels. For the analysis we also construct an exclusive remapping of those themes, which assigns each answer to a single dominant theme so that shares within a product sum to 100 per cent; Supplementary Section [E](#) describes it and states which of the two codings each figure uses.

The reliability of this qualitative data gathering process is supported by the use of local researchers who possess the cultural and linguistic nuance necessary for accurate interviewing. Furthermore, the standardization of coding across thousands of surveys allows for the creation of genuine social benchmarks, enabling comparative performance analysis across sub-sectors.

However, three primary methodological limitations warrant acknowledgement. First, as the data are self-reported, they are susceptible to recall bias and acquiescence bias, where respondents may over-report positive changes due to social desirability or recent acquisition excitement. Second, while 60 Decibels applies consistent thematic categories, the specific inter-rater reliability (such as Cohen’s κ or Krippendorff’s α)^{[43](#)[44](#)} achieved during the coding

of the approximately 79,000 responses is not explicitly disclosed in the reports. Finally, the lack of a longitudinal panel structure prevents the direct observation of outcomes for the same individual before and after acquisition. Consequently, we utilize retrospective questions, where users report the change since adoption, as proxies.

Data access

The research team signed a data agreement to use the 60 Decibels data for research purposes. The data are proprietary and can be purchased from 60 Decibels (<https://60decibels.com/contact/>). Snapshots of the data could be found in the report¹¹.

2.2 Analysis

All estimates are conditional associations. The data are a cross-section of adopters, so no specification identifies the effect of a technology on its users; what the models do is compare customers within the same country and survey year, net of observed characteristics, while respecting the fact that respondents are clustered in projects and companies. Unless stated otherwise, every model includes country and survey-year fixed effects, and standard errors are clustered on company, the level at which surveys were commissioned. Where a product rests on a single company, clustering is impossible and we use heteroskedasticity-robust errors instead.

2.2.1 Perceived benefits by technology (Figure 1)

The baseline is a two-limit Tobit with random intercepts for companies and for projects within companies:

$$Y_{ijc}^* = \mathbf{Tech}_j \beta + \mathbf{X}_{ijc} \theta + \gamma_k + \delta_t + u_c + v_{jc} + \varepsilon_{ijc}, \quad Y_{ijc} = \min\{\max\{Y_{ijc}^*, L_1\}, L_2\}, \quad (1)$$

where i indexes respondents, j projects and c companies; $\mathbf{Tech}_j$ are technology indicators with mini-grids as the reference; $\mathbf{X}_{ijc}$ holds education, rurality, sex, and standardised household size and age; γ_k and δ_t are country and survey-year fixed effects; and $u_c \sim \mathcal{N}(0, \sigma_u^2)$, $v_{jc} \sim \mathcal{N}(0, \sigma_v^2)$ and $\varepsilon_{ijc} \sim \mathcal{N}(0, \sigma_\varepsilon^2)$. The limits are $(L_1, L_2) = (1, 5)$ for quality of life and change in income, and $(1, 10)$ for satisfaction with the supplier. The model is fitted by maximum likelihood with Stata’s `metobit`.^{xii}

Three features of the data motivate this choice. First, responses pile up at the top of each scale (more than half of quality-of-life answers are 5), and a linear model of a censored outcome understates differences between groups^{45;46}. Second, each project covers one technology and many companies sell only one, so project or company fixed effects would absorb the technology contrast; random intercepts keep it identified while allowing for dependence within projects and companies. Third, Tobit models of bounded self-reports are standard in the welfare and off-grid literatures^{12;27;47;48}.

Figure 1 reports average marginal effects on the expected value of the observed, censored outcome⁴⁹, so each estimate is a difference from mini-grids in points of the original scale. All specifications for an outcome are fitted on one sample, the respondents with every control recorded, so differences between them reflect the controls and not the sample. The figure shows two reduced specifications (education only, and no controls) and the OLS equivalent of each, estimated with `reghdfe`.

The identifying assumption is that, within a country and survey year and given the controls, the remaining differences between technologies are not driven by unobserved project or company characteristics such as product quality, targeting or after-sales service. The random intercepts absorb level differences between companies only on the assumption that they are unrelated to the technology a company sells, and the Tobit additionally assumes normal, homoskedastic errors. Appendix G tests the sensitivity of the technology ranking

^{xii}Every fit converges, but for each outcome one of the two random-intercept variances is estimated at zero: the company variance for quality of life and change in income, and the project variance for satisfaction with the supplier. Each model therefore carries one effective random intercept, at the project level for the first two outcomes and at the company level for the third.

to these assumptions in four ways. A three-level ordered logit (`meologit`) with the same fixed effects, controls and random intercepts treats each outcome as ordered categories, so it relies on neither the normal error nor the censoring limits; a two-limit Tobit without random intercepts, with the same country and survey-year fixed effects and company-clustered errors, removes the distributional assumption on u_c and v_{jc} (both in Section G.1, Figures G1 and G2); the same Tobit is re-estimated on the countries with customers of at least three technologies, where technology contrasts are drawn within the same national markets (Section G.2, Figures G3 and G4); and each specification in Figure 1 is re-estimated on its own maximal sample (Section G.3, Figure G5).

2.2.2 Mechanisms (Figures 2 and 3)

For each product p , we report two or three quantities per mechanism item M_m , each scored on the same 1–5 scale as quality of life. The first is the item’s mean, predicted from a regression on the controls and fixed effects with rurality, sex, household size and age set to their means across all products, so that products are compared at a common customer profile. The second is the item’s contribution to welfare outcome Y , the coefficient α_m in

$$Y_{ip} = \sum_m \alpha_m M_{m,ip} + \mathbf{X}_{ip} \theta + \gamma_k + \delta_t + \varepsilon_{ip}, \quad (2)$$

estimated by OLS separately for each product and outcome. All of a product’s items enter jointly, so each α_m is a partial association holding the other channels fixed, and the coefficients are left unstandardised because the items share one scale. Cells with fewer than 50 observations are not estimated, and income contributions are marked where fewer than a quarter of a product’s customers use it to earn. Mechanisms and outcomes come from the same interview, so α_m ranks channels within a product and is not a mediation effect. Appendix C repeats Equation (2) as a Tobit and finds the same ranking in every product. The open-ended themes (Appendix E) are modelled as one linear probability model per theme, with the same controls, fixed effects and common profile.

2.2.3 Adopter profiles and customer characteristics (Table 1, Figure 4)

Table 1 is descriptive. Each share is computed over the customers asked the relevant question, with the denominator shown in each cell. Section G.4 re-estimates the same profiles net of country and survey-year fixed effects, with one linear probability model per characteristic (Table G1). Figure 4 plots the coefficients on the controls from the OLS version of the baseline in Figure 1. Education enters as indicators relative to no formal schooling, and household size and age are in standard deviations.

2.2.4 Risks of adoption (Figures 5 to 8)

The three product-risk outcomes, reporting a challenge, being a detractor (supplier score 1–6) and having stopped using the product, are binary and are estimated product by product. Challenges and detraction are fitted by logit on sex, education, and standardised household size and age, and reported as rates predicted at the common profile; logit keeps predictions inside the unit interval for products with low incidence. Rurality is left out of this headline set because it is recorded for far fewer customers. Discontinuation is fitted as a linear probability model with fixed effects only, because the questionnaire skips the demographic block for customers who have stopped: of 1,332 who stopped, 18 have complete demographics. Its adjusted rate therefore equals the raw rate, and the model supplies only the clustered interval.

The risk factors in Figure 7 are estimated by logit in blocks, because the characteristics come from different survey modules: paid upfront and grid access are never recorded together once controls are required. A core block enters first-time use, rurality, sex and no secondary education with household size, age and the fixed effects; each further block adds one characteristic (an alternative education coding, paid upfront, no grid access, or, for detraction only, whether a reported challenge was resolved) and reports its own sample. Resolution is excluded from the challenge model because it is defined only for customers who reported one, and discontinuation has no risk-factor model at all for the reason above. Contract risk (Figure 8) is a separate logit for each product and outcome on the four point-of-sale infor-

mation items entered jointly, with the headline controls, estimated on the customers who were asked them, mostly credit buyers.

Every cell needs at least 50 observations, and an incidence estimate at least 20 events. Estimates are drawn at full strength of colour only if significant at 5 per cent and based on more than one company. Appendix F reports all rates on both denominators (Table F1) and repeats the detractor rates under the 60 Decibels classification (Table F2), which gives the same ordering of products.

2.2.5 Heterogeneity (Section 1.5)

Each dimension G (first-time use, no prior grid connection) is added to Equation (1) together with its interaction with the technology indicators,

$$Y_{ijc}^* = \mathbf{Tech}_j \beta + \lambda G_i + (\mathbf{Tech}_j \times G_i) \boldsymbol{\mu} + \mathbf{X}_{ijc} \boldsymbol{\theta} + \gamma_k + \delta_t + u_c + v_{jc} + \varepsilon_{ijc}, \quad (3)$$

so the gap for technology p is $\lambda + \mu_p$, tested directly rather than read off two separate models. A pooled gap comes from the same model without the interaction. Both are reported as coefficients under the Tobit and under OLS with clustered errors. The two dimensions come from different modules, so each is estimated in its own model on its own maximal sample, under the full controls and again without rurality. A product is reported only with at least 200 respondents, five companies and 100 respondents in the smaller group. Appendix D explains these choices, and Sections D.1 and D.2 report the estimates.

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Supplementary Information

A Data description and summary statistics

Table A1: Definitions of Off-grid Products

Product	Definition (60 Decibels)
Solar Home Systems (SHS)	A stand-alone solar system typically consisting of multiple lights and the capacity to power additional services, with larger photovoltaic panels than solar lanterns.
Mini-grid	A generation and distribution system that supplies electricity to multiple customers through a local network of connections.
Solar Lantern	A portable lamp powered by a photovoltaic (PV) panel, often referred to as pico-PV lighting.
Clean Cooking	Fuel-efficient and/or low-emission cookstoves and cooking appliances that use cleaner fuels or improved combustion technologies.
Appliances	Any electrical device that can be powered by a stand-alone solar home system or mini-grid connection.
E-mobility	The use of vehicles that are partially or fully powered by electricity, including motorcycles, bicycles, cars, and other electric transport options.
Refrigerator	An electric cooling appliance used for food preservation and storage.
Television (TV)	An electronic device used for viewing broadcast or digital video content.
Fan	An electric appliance used to circulate air for cooling and ventilation purposes.
Smartphone	A portable handheld device with advanced computing capability, internet connectivity, and communication functions.
Solar Water Pump (SWP)	A water pumping system powered by solar photovoltaic energy, typically used for irrigation or water supply.
Solar Heater	A device that uses solar energy to generate heat, commonly for water heating.
Solar Mill	A solar-powered milling machine used for agricultural processing such as grain grinding.

Notes: All definitions are provided by 60 Decibels¹¹ as used in the data collection process.

Table A2: Definitions of variables used in the analysis

Variable	Definition
Quality of Life (QOL)	Measures the perceived impact of the product on overall well-being using a five-point ordinal scale ranging from “got much worse” (1) to “very much improved” (5). Respondents report whether their quality of life has changed since adopting the product.
Change in Income	Measures perceived changes in household income attributable to the use of the product, particularly among productive users. Responses are recorded on a five-point scale ranging from “very much decreased” (1) to “very much increased” (5).
Satisfaction with the supplier	The likelihood that a customer would recommend <i>the company that supplied the product</i> to a friend or family member, on a scale from 1 (“not at all likely”) to 10 (“extremely likely”). This is the satisfaction measure used throughout the paper, and it is reported as satisfaction with the supplier so that its subject is unambiguous.
Satisfaction with the product	The same question asked about <i>the product</i> rather than the company. ^{xiii}
Net Promoter Score segment	Classifies customers from the supplier recommendation score into detractors (1–6), passives (7–8) and promoters (9–10), following the standard Net Promoter Score construction used by 60 Decibels.
<i>Socio-demographic characteristics</i>	
Education	The highest level of schooling attained by any member of the household: no education, primary, lower secondary, upper secondary, and tertiary education. Thus, “no secondary education” denotes households whose highest attainment is primary schooling or none.
Household Size	The total number of individuals living in the household, including the respondent, children, and other adults residing in the dwelling.
Age	Age of the survey respondent in years at the time of the interview.
Female	= 1 if the main user is female, and 0 otherwise.
Rural	= 1 if the respondent lives in a rural area (village or countryside), and 0 otherwise (peri-urban or urban locations).

^{xiii}No respondent was asked both questions, so the two measures are recorded for disjoint groups of customers and are never pooled or compared as a paired difference. It is reported in the summary statistics and examined on its own in Section B, but is not used in the main analysis; the reasons are set out there.

Variable	Definition
<i>Access and adopter characteristics</i>	
First-time user	= 1 if the customer had no previous access to a product in that category before the purchase, and 0 if they had owned or used one before.
Paid upfront	= 1 if the customer paid for the product in full at the point of sale, and 0 if they purchased on credit and pay in instalments under a signed contract with the company.
No grid access	= 1 if the household or business had no connection to the electricity grid before adopting the product, and 0 if it had one.
<i>Purchase information, asked of customers buying on credit</i>	
Knew the contract length	= 1 if the customer knew how long the contract or sales agreement was for at the time of purchase.
Was told what could change the price	= 1 if the company representative disclosed any circumstances that could change the price or the length of the payment plan.
Knew the consequence of late payment	= 1 if the customer knew what would happen if they made late payments or none at all.
Terms and conditions checked	= 1 if the company checked that the customer understood the key terms and conditions of the agreement.
<i>Adoption risk</i>	
Reported a challenge	= 1 if the customer reports having experienced any challenge with the product since acquiring it, and 0 if they report none.
Challenge resolved	= 1 if a customer who reported a challenge states that it was subsequently resolved, and 0 otherwise. Defined only for customers who reported a challenge.
Detractor	= 1 if the customer gives a recommendation score of 6 or below, and 0 otherwise, following the Net Promoter Score convention.
Discontinued use	= 1 if the customer reports no longer using the product at the time of the survey, and 0 if they are still using it.

Notes: This table defines every other variable used in the empirical analysis. All ordinal scales are coded so that higher values indicate more positive outcomes, and all binary indicators take the value 1 when the stated condition holds. Variable names and polarity match those used in Table 1 and in the summary statistics table.

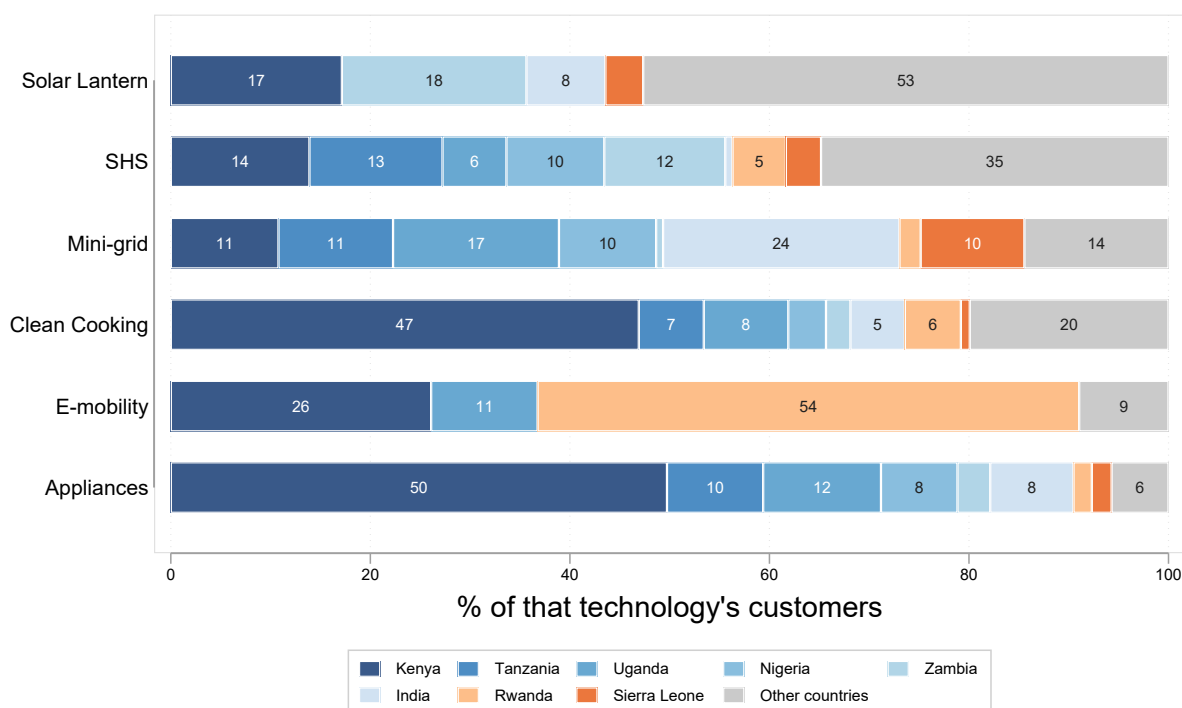
Table A3: Summary statistics

	N	Mean	Std. Dev.		N	Mean	Std. Dev.
Products				Socio-demographics			
SHS	78729	0.491	0.500	Female	73552	0.326	0.469
Mini-grid	78729	0.194	0.395	No education	48515	0.026	0.160
Clean Cooking	78729	0.143	0.350	Primary	48515	0.141	0.348
Solar lantern	78729	0.039	0.192	Lower secondary	48515	0.198	0.399
E-mobility	78729	0.013	0.115	Upper secondary	48515	0.287	0.452
Appliances	78729	0.121	0.326	Tertiary	48515	0.348	0.476
Solar Water Pump	9535	0.480	0.500	Household size	50575	6.335	3.450
Refrigerator	9535	0.193	0.395	Age (in years)	51467	40.983	11.476
Smartphone	9535	0.158	0.365	Rural dweller	41980	0.549	0.498
TV	9535	0.115	0.319				
Solar Mill	9535	0.023	0.151	Access and payment			
Solar Heater	9535	0.018	0.134	First-time users	46815	0.762	0.426
Fan	9535	0.011	0.106	No grid access	15507	0.665	0.472
				Paid upfront	15614	0.249	0.432
Welfare outcomes				Purchase information (credit customers)			
Quality of life [1 to 5]	69547	4.442	0.708	Knew the contract length	12648	0.937	0.242
Change in income [1 to 5]	8435	4.016	0.862	Was told what could change the price	11835	0.737	0.440
				Knew the consequence of late payment	12368	0.872	0.334
Satisfaction with the supplier				Company checked they understood the terms	12470	0.854	0.353
Recommendation score [1 to 10]	34360	8.043	2.255				
Promoters (9–10)	34360	0.545	0.498	Region			
Passive (7–8)	34360	0.282	0.450	Africa	78729	0.881	0.324
Detractors (1–6)	34360	0.173	0.378	Asia	78729	0.110	0.312
				Latin America & Caribbean	78729	0.010	0.098
Satisfaction with the product (separate sample)							
Recommendation score [1 to 10]	38678	8.428	1.723				
Promoters (9–10)	38678	0.583	0.493				
Passive (7–8)	38678	0.299	0.458				
Detractors (1–6)	38678	0.118	0.323				

Notes: This table reports summary statistics for every variable used in the paper. Product and appliance categories are defined in Table A1; all other variables are defined in Table A2. Figures in square brackets give the range of the ordinal scale, with higher values indicating better outcomes. Every N is a count of non-missing responses, so each row carries its own denominator. These differ sharply because companies chose which questions their surveys would carry. A mean based on a smaller N therefore describes the customers who were asked, not the full sample.

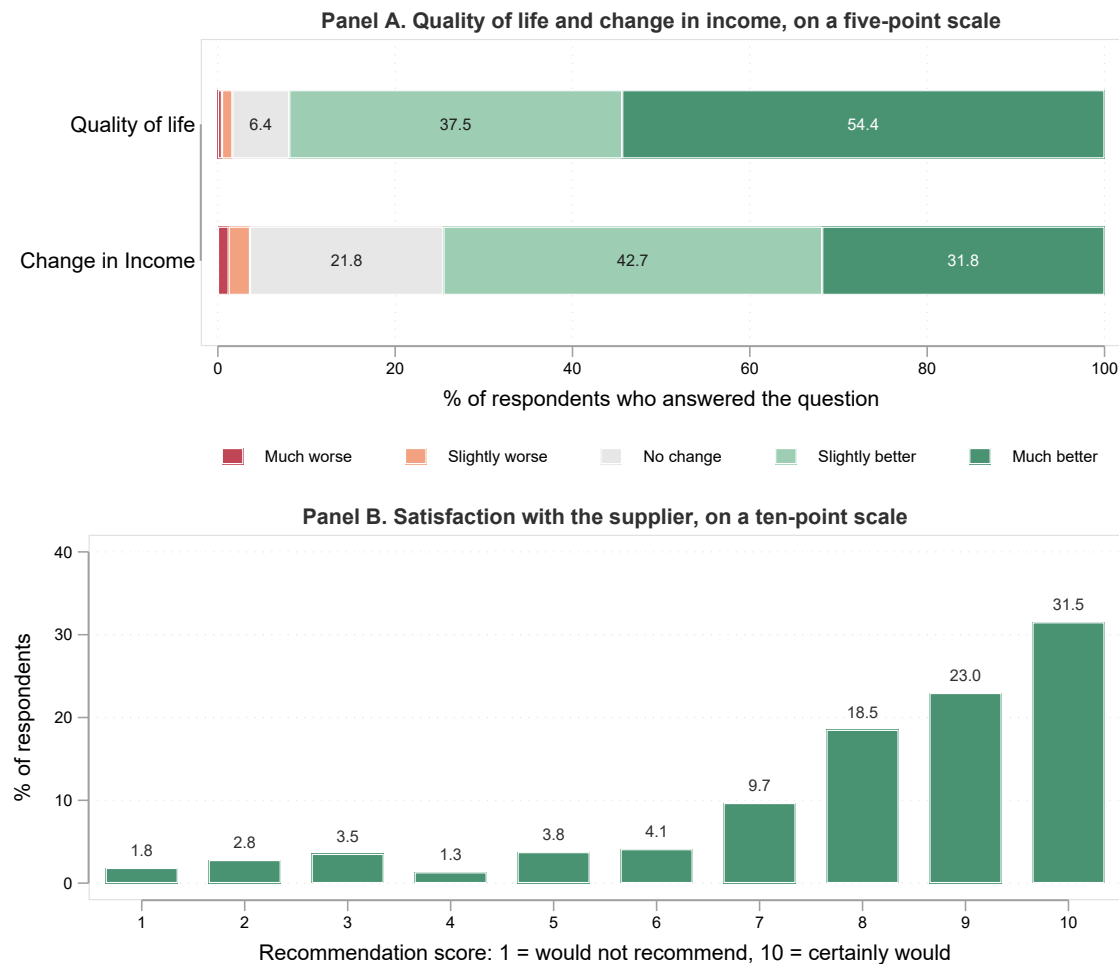
Country composition and welfare distribution. Customers are concentrated in Africa (88%), with more than 50% coming from Kenya, Tanzania, Uganda, and Nigeria. In Figure A1, we disaggregate the sample by technology and across countries. SHS has the widest spatial distribution (across 26 countries), followed by clean cooking (across 16 countries), mini-grids (across 12 countries), and appliances (across 11 countries). Kenya is the only country that has customers across all technologies. Figure A2 shows the distribution of customers' responses across the welfare indicators.

Figure A1: **Percentages of customers by technology and country**



Notes. Each bar is one technology and shows how its customers are distributed across the countries where they were surveyed, so every bar sums to 100 per cent. The eight countries contributing the most customers overall are shown separately and the remainder are pooled as *Other countries*, in grey. Segments are labelled where they reach 5 per cent; smaller ones are drawn but not labelled. The figure is about *concentration*: a bar dominated by one or two colours means that technology's evidence comes from very few countries, which matters for how far its results generalise.

Figure A2: Distribution of customers' responses by welfare indicators



Notes. Each indicator appears once, on the scale it was measured on. **Panel A** covers quality of life and change in income, both recorded on a five-point scale running from *got much worse* to *very much improved*, drawn as stacked bars summing to 100 per cent. Shares below 5 per cent are not labelled. **Panel B** covers satisfaction with the supplier, which is a ten-point recommendation score and so cannot be placed on the same axis without forcing a correspondence between the two scales that does not exist. Every share is of respondents who answered that question, and the denominators differ sharply between indicators: 69,547 for quality of life, 8,435 for change in income and 34,360 for supplier satisfaction.

B Measuring satisfaction: the supplier & the product

The surveys contain two recommendation questions. One asks how likely the customer is to recommend the *company* that supplied the product. The other asks the same about the *product*. They are not variants of one measure: enumerators asked one or the other, and no respondent answered both. The supplier question covers 34,360 customers and the product question 38,678, with an overlap of zero. The main text uses the supplier question throughout and calls it satisfaction with the supplier. This section sets out why, and reports what the product question shows when estimated on its own.

The two measures rank technologies the same way. Table B1 estimates the specification behind Figure 1 three times: once on the product question, once on the supplier question, and once on whichever of the two a respondent was asked. As in Figure 1, mini-grids are the reference category. The conclusion that matters survives the choice: mini-grid customers are the least satisfied. Under the supplier question and the combined measure, every other technology scores 1.1 to 1.6 points higher on the ten-point scale ($p < 0.001$). Under the product question, clean cooking (2.34), SHS (1.75) and appliances (1.74) score significantly higher, solar lanterns higher but not significantly, and e-mobility is the only estimate below mini-grids (-0.37 , not significant). The ordering among the other technologies is less stable: clean cooking ranks first under the product and combined measures, and solar lanterns under the supplier question, where the differences between technologies other than mini-grids are small.

Why the product question cannot carry the analysis. Two obstacles rule it out, and neither is a matter of preference. First, it does not coexist with the mechanism batteries. The survey projects that asked customers to rate individual dimensions of their experience, which Section 1.2 relies on, are largely not the projects that asked the product recommendation question. The two overlap in only two of the eight product groups. Estimating the contribution of a mechanism to product satisfaction returns no observations at all for clean

Table B1: Customer satisfaction under three candidate measures

	(1) Product	(2) Company	(3) Whichever asked
Appliances	1.740*	1.104***	1.254***
Clean Cooking	2.341**	1.276***	1.548***
Solar Lantern	1.339	1.616***	1.431***
SHS	1.750*	1.209***	1.312***
E-mobility	-0.365	1.475***	1.312***
Respondents	6,045	17,006	23,051
Companies	29	64	84

Notes. Average marginal effects from a mixed-effects two-limit Tobit, in points of the recommendation scale, relative to mini-grids, the reference category of Figure 1. The specification is the one behind Figure 1: country and survey-year fixed effects, education, rurality, sex, household size and age, with random intercepts for company and project. Column (1) asks whether the respondent would recommend the *product*, column (2) the *company*. No respondent was asked both, so the two columns rest on disjoint samples rather than on the same people. Column (3) takes whichever question was asked and is therefore the union of the two. The product question has the widest raw coverage (38,678 respondents) but the narrowest estimation sample, because the surveys that asked it largely did not record rurality. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

cooking, e-mobility, solar lanterns, solar water pumps, refrigerators and TVs. There is no model to report.

Second, it collapses under the control set. The surveys that asked the product question largely did not record whether the customer lives in a rural area, which is one of the demographic controls in the baseline specification. Requiring the full control set reduces the product-question sample to 6,045 customers across 29 companies, against 17,006 across 64 for the supplier question. The estimates in column (1) of Table B1 rest on that smaller sample, which is why their confidence intervals are so much wider.

C Mechanism contributions under the Tobit specification

Section 1.2 reports mechanism contributions estimated by least squares. This section reports the same quantities estimated by two-limit Tobit with a company random intercept, so that the choice of estimator can be inspected rather than taken on trust.

The two estimators agree on ranking and differ on scale. Within every product and outcome, the two specifications place the mechanism channels in the same order, with one exception between two items that neither estimator distinguishes from zero (travel time and transport spending, for e-mobility income). For SHS the safety and security item carries a least-squares contribution to quality of life of 0.528 and a Tobit contribution of 1.081; energy spending carries 0.048 and 0.139 respectively. The Tobit coefficients are larger throughout, by a factor of between about one and a half and three, and this is what censoring implies: a Tobit coefficient is expressed on the latent index, which is unbounded, while a least-squares coefficient is expressed on the observed five-point scale, which is not. Since more than half of quality-of-life responses sit at the maximum, the latent index has to move considerably further than the observed score to produce the same visible change.

Why the main text uses least squares. Three reasons, in order of weight.

The quantities in Section 1.2 are meant to be read against each other and against the improvement column, which is a mean on the five-point scale. A least-squares contribution is on that same scale, so a reader can see directly that a one-point increase in reported safety is associated with roughly half a point of reported quality of life. The Tobit coefficient answers a different question, about a latent index that is not observed and has no natural unit, and it cannot be compared with the improvement column at all.

Second, the section's claim is about *ranking* channels within a product, not about the size of any one channel. Both estimators support that claim identically, so the additional structure

the Tobit imposes buys nothing for the argument while making the numbers harder to interpret.

Third, the Tobit requires a company random intercept to be identified, and several products here rest on very few companies. Where that structure is weak, the estimates become sensitive to it in ways the least-squares specification, which only needs a clustered standard error, does not.

The Tobit results are reported here in full so that a reader who prefers the censoring correction can apply it. Nothing in Section 1.2 depends on the choice.

Table C1: Mechanism improvement and contribution to welfare, core technologies

Product	Mechanism	Improvement	Contribution to		
		(mean, 1–5)	Quality of life	Income	Satisfaction
SHS	Safety and security	4.658***	1.081***	0.444***	1.032***
	Energy spending	3.688***	0.139***	0.089**	0.141***
Mini-grid	Safety and security	4.415***	0.913***	0.434***	1.268***
	Energy spending	3.403***	0.156***	0.146***	0.278***
Solar Lantern	Safety and security	4.671***	0.801***	0.480	0.607***
	Energy spending	4.249***	0.399***	0.270	0.585***
Clean Cooking	Health	4.421***	0.678***	—	0.292***
	Cooking time	4.304***	0.103***	—	0.131***
	Cooking spending	4.360***	0.215***	—	0.100**
E-mobility	Travel convenience	4.594***	0.662***	0.776***	1.080***
	Travel time	4.052***	0.014	0.058	0.133
	Transport spending	3.755***	0.115*	0.101	0.096

Notes. **Estimator.** Two-limit tobit with a company random intercept; plain two-limit tobit with robust errors where the product has one company. **Adjustment.** Home safety and asset security are combined into a single item for SHS, mini-grid and solar lantern, because respondents give the same answer to both in 90 to 96 per cent of cases and entered separately they carry variance inflation factors near 500. All models control for education, rurality, gender, household size and age, with country and survey-year fixed effects. Improvement is the adjusted mean of the item on its 1–5 scale, predicted at a common demographic profile, with 3 = no change. Contribution is the coefficient on that item in a regression of the outcome on all of the product’s mechanism items together, so each is a partial contribution holding the others fixed. Satisfaction is the 1–10 company recommendation scale. Mechanism items differ by product and are comparable within a product, not across products. Mechanisms and outcomes are reported by the same respondent in the same interview, so these are conditional associations, not causal effects. Tobit coefficients are on the latent index and are therefore larger than the corresponding least-squares estimates; they are not directly comparable in magnitude.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table C2: Mechanism improvement and contribution to welfare, appliance subcategories

Product	Mechanism	Improvement (mean, 1–5)	Contribution to		
			Quality of life	Income	Satisfaction
Solar Water Pump	Farm productivity	4.300***	0.944***	0.895***	0.891***
	Land cultivated	3.947***	-0.009	0.145**	-0.066
	Irrigation spending	4.018***	0.069*	-0.022	0.073
Refrigerator	Family diet	3.907***	0.481***	0.444***	-0.106
	Market/cooking time	3.378***	-0.288***	-0.132	-0.234
	Cooling spending	3.110	0.212**	0.070	0.093
TV	Knowledge & awareness	4.743***	0.312	–	-0.466
	Family bonding	4.776***	0.688**	–	1.239*
	TV spending	2.193***	-0.057	–	0.124

Notes. **Estimator.** Two-limit tobit with a company random intercept; plain two-limit tobit with robust errors where the product has one company. **Adjustment.** Home safety and asset security are combined into a single item for SHS, mini-grid and solar lantern, because respondents give the same answer to both in 90 to 96 per cent of cases and entered separately they carry variance inflation factors near 500. All models control for education, rurality, gender, household size and age, with country and survey-year fixed effects. Improvement is the adjusted mean of the item on its 1–5 scale, predicted at a common demographic profile, with 3 = no change. Contribution is the coefficient on that item in a regression of the outcome on all of the product’s mechanism items together, so each is a partial contribution holding the others fixed. Satisfaction is the 1–10 company recommendation scale. Mechanism items differ by product and are comparable within a product, not across products. Mechanisms and outcomes are reported by the same respondent in the same interview, so these are conditional associations, not causal effects. Tobit coefficients are on the latent index and are therefore larger than the corresponding least-squares estimates; they are not directly comparable in magnitude. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

D Heterogeneity: who benefits most

We ask whether the association between a technology and a reported outcome differs across groups of customers. The specification is the one behind Figure 1: country and survey-year fixed effects, controls for education, rurality, sex, household size and age, and random intercepts for company and project. Each dimension is estimated for all three outcomes, quality of life, change in income, and satisfaction with the supplier, and each outcome is reported in its own figure because a coefficient of 0.2 means one thing on a five-point scale and another on a ten-point one.

One dimension per model, never several. The dimensions of interest do not co-occur in these data. They come from different survey modules, and companies chose which modules their surveys carried. Requiring rurality, sex, education and prior grid connection together leaves 1,740 respondents out of 78,729. A single model carrying all four interactions is therefore not estimable, and we do not attempt one. Each dimension is estimated separately on its own maximal sample. The cost is that the dimensions cannot be held constant against one another; the alternative was no estimate at all.

Two control sets, and what separates them. Each dimension is estimated under the full control set and under the same set without rurality. This is not a routine robustness exercise. For prior grid connection the two differ in a specific and consequential way: not one of the 2,221 Indian respondents in the grid sample has a rurality answer, so requiring rurality removes India from the analysis altogether. The full control set is therefore the without-India analysis, whether or not that was intended. Reporting both makes the choice visible. The reduced set also recovers sample: for quality of life it raises the grid sample from 4,047 customers across 19 companies to 6,234 across 29, and it is the difference between one estimable technology and two.

Three floors, and why the binding one is the smaller group. A technology enters a figure only if its cell holds at least 200 respondents, comes from at least five companies, and has at least 100 respondents on the smaller side of the split. The third condition is the one that binds. A clean cooking cell of 283 respondents passed a total-sample threshold while only 20 of those respondents lacked a grid connection. We consider this sample too small to make reliable inferences. A comparison is only as precise as its smaller group.

The five-company floor follows from the structure of the data rather than from convention. Within a product, surveys come from a few projects, each run by one company, so cluster counts are small even where the number of respondents is large. A company random intercept is not identifiable below roughly five companies, and with one company a clustered standard error cannot be computed at all. A four-company cell in the without-India grid sample illustrates the consequence: its least-squares standard error *halved* on a sample 45 per cent smaller, which is the wrong direction, and the corresponding Tobit model did not converge.

What each dimension can support. This is a property of the survey design rather than of the model, and it is worth stating before any result is quoted. For prior grid connection, quality of life is estimable for SHS and mini-grids only, satisfaction for SHS only, and income only pooled: just 538 customers answered both the income and the grid questions with the controls present. For first-time use, five of six technologies clear the floors for quality of life, four for satisfaction and two for income. Prior access is recorded for 46,815 customers against 15,507 for grid connection, which is why it supports more of the technology ladder.

Interactions rather than split samples. Within a dimension, we estimate one model with a technology-by-group interaction rather than separate models per group. Two stratified models yield two confidence intervals and leave the reader to judge whether they overlap, which is not the same question as whether the difference is distinguishable from zero. The interaction gives that test directly, and estimates the controls and fixed effects on one sample. The base technology is pinned explicitly, to mini-grids wherever they clear the floors, rather

than left to the software; the gap within each technology does not depend on this choice.^{xiv}

These are conditional associations. No dimension here is randomly assigned. Customers without a prior grid connection differ from those with one in ways no control observes, and the same is true of first-time users. For first-time use there is also a mechanical reason to expect a positive gap: a customer with no prior product is comparing against nothing, while a repeat buyer is comparing against what they already owned, so the question is answered relative to a different baseline for the two groups.

D.1 Prior access: first-time users

Prior access is recorded for 46,815 customers, which is why more of the technology ladder can be estimated on this dimension than on any other. Section 1.5 reports the results. Figures D1 to D3 plot every estimate that clears the floors, and Table D1 gives the same estimates as numbers, under both control sets and both estimators.

Quality of life is the best covered outcome, with five technologies estimable on 22,284 customers across 86 companies. Satisfaction with the supplier covers four technologies and income only two, because the income question is put to customers who report earning from the product. One cell is worth flagging rather than quoting. Mini-grids reverse between the two control sets for quality of life, 0.308 with rurality and 0.021 without on a larger sample, so the mini-grid figure should not be read on its own until the difference is understood.

^{xiv}This is because Stata orders the levels of an encoded variable alphabetically and the data carry a stored base preference.

Table D1: Outcomes and first-time use, by technology

		Figure 1 controls		Without rurality	
	N / firms (1)	OLS (2)	Metobit (3)	OLS (4)	Metobit (5)
<i>Quality of life</i>					
pooled	22,284 / 86	0.085***	0.186***	0.076***	0.161***
Solar Lantern	1,102 / 5	—	—	-0.117	-0.158
SHS	13,995 / 45	0.067**	0.156***	0.073***	0.161***
Mini-grid	2,158 / 11	0.197***	0.308*	0.014	0.021
Clean Cooking	2,612 / 15	0.150***	0.314***	0.142***	0.300***
Appliances	1,931 / 11	0.050	0.175	0.120	0.181
<i>Change in income</i>					
pooled	3,324 / 74	0.044	0.087	0.040	0.088
SHS	857 / 39	-0.103	-0.181	-0.096	-0.168
Appliances	1,031 / 9	0.119	0.246*	0.130*	0.257*
<i>Satisfaction with the supplier</i>					
pooled	17,363 / 65	0.163***	0.198***	0.151***	0.184***
SHS	10,514 / 32	0.165***	0.192***	0.157***	0.177***
Mini-grid	1,341 / 6	0.403**	0.488**	0.377**	0.457*
Clean Cooking	2,406 / 12	0.151	0.344**	0.149	0.348**
Appliances	1,768 / 9	0.049	-0.027	0.047	-0.028

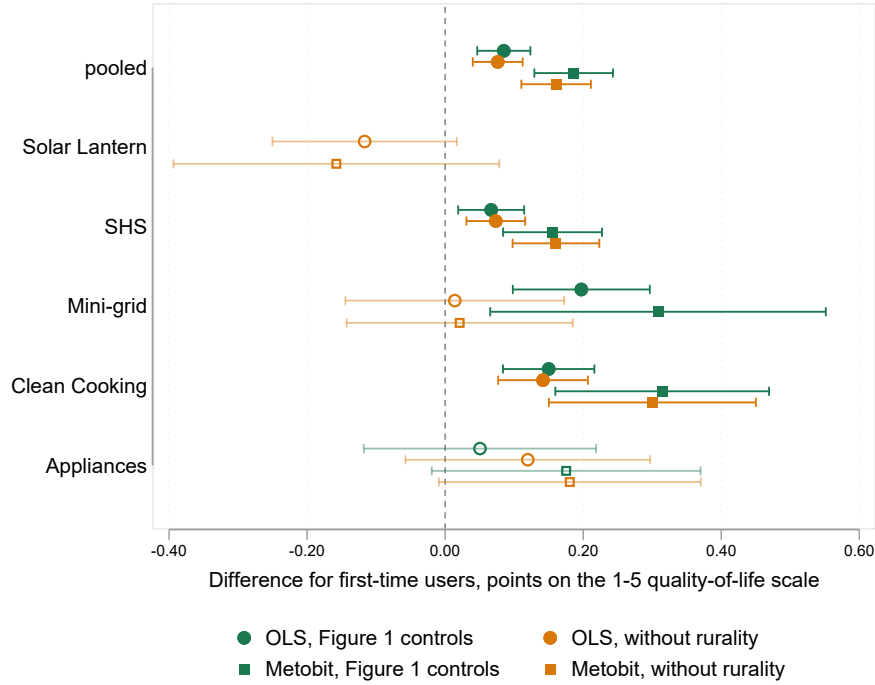
Notes. Each entry is the difference between customers who were using a product in that category for the first time and customers who had owned one before, in points of that outcome's own scale: five points for quality of life and income, ten for satisfaction. A positive value means first-time users report the better outcome. A dash means the model was not estimated or did not converge. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

D.2 Prior grid access

Section 1.3 in the main text shows that a grid connection in these data records connection rather than reliable supply, and that the two kinds of customer are mixed together in the sample. This section asks whether they report different outcomes. The method is described above.

Coverage is the binding constraint. Grid connection is recorded for 15,507 customers, and requiring it alongside an outcome and the control set leaves far fewer. Only SHS and mini-grids clear the floors for quality of life, only SHS for satisfaction with the supplier, and no technology at all for income: just 538 customers answered both the income and grid questions with the controls present, so only a pooled income estimate is possible. E-mobility is absent rather than thin, because no e-mobility customer was asked the grid question.

Figure D1: **First-time users compared with repeat buyers: quality of life**



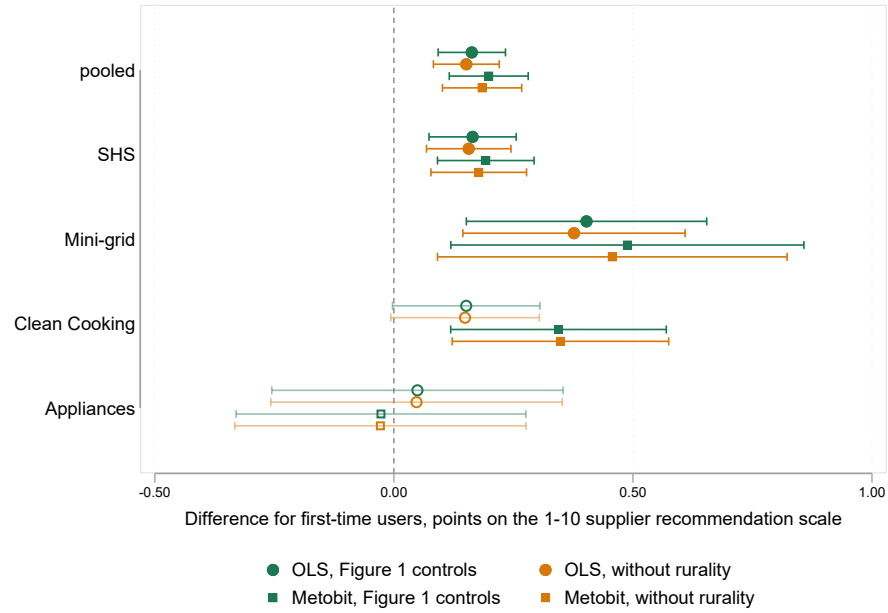
Notes. Each marker is the difference between customers using a product in that category for the first time and customers who had owned one before, with its 95 per cent confidence interval. A positive value means first-time users report the better outcome. Filled markers are significant at the 5 per cent level, hollow markers are not. Estimation, the two control sets and the three floors are described in Section D.

India, and what the comparison can and cannot settle. Because Indian customers are overwhelmingly connected and East African customers are not, a grid comparison could be a comparison of countries in disguise. We estimate every specification twice, once on all countries and once with India excluded.

For SHS the question hardly arises: India contributes no SHS respondents to this sample at all, and dropping India moves the SHS estimate only from 0.192 to 0.191, through the controls and fixed effects that are estimated jointly with the other technologies. The headline result is therefore not an artefact of Indian composition, and that is established rather than assumed.

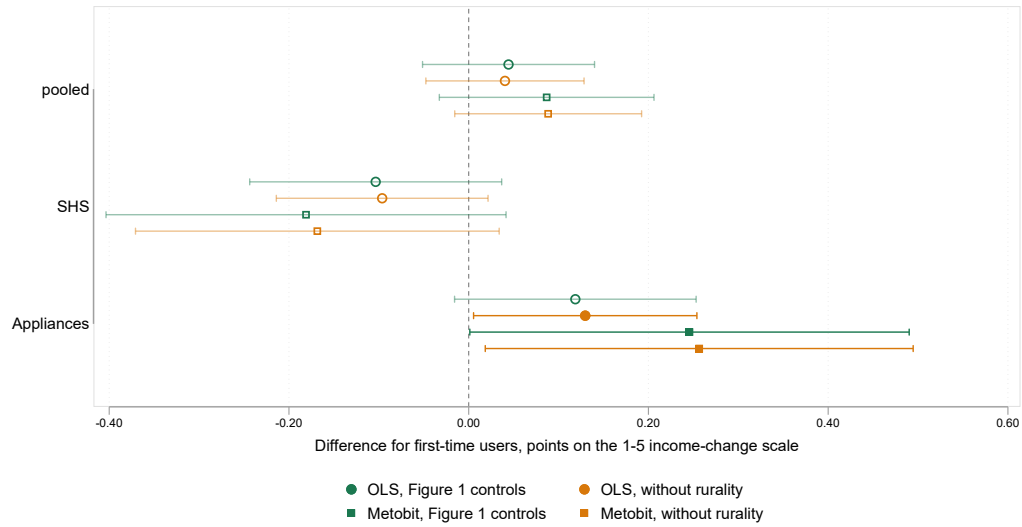
For mini-grids the comparison cannot be settled. Removing India leaves 845 respondents across four companies, below the five-company floor. The estimate that can be computed

Figure D2: **First-time users compared with repeat buyers: satisfaction with the supplier**



Notes. Just as Figure D1.

Figure D3: **First-time users compared with repeat buyers: change in income**



Notes. Just as Figure D1. Income is asked only of customers who report using the product to earn, so the sample is much smaller than for the other two outcomes and only two technologies clear the floors.

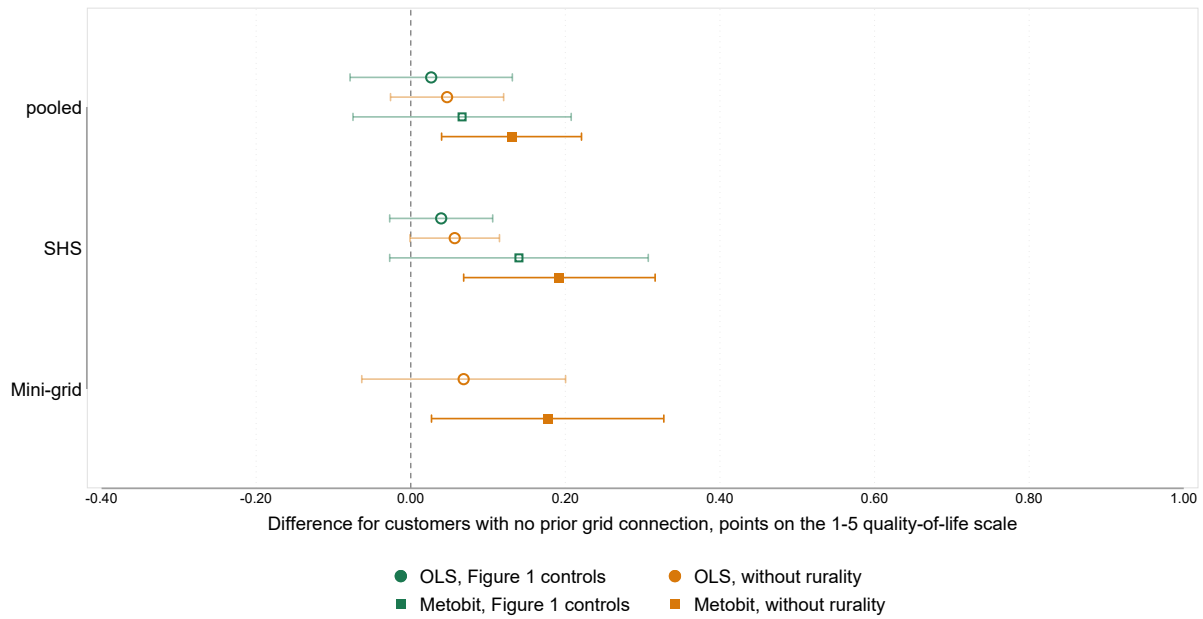
Table D2: Outcomes and prior grid access, by technology

		Figure 1 controls		Without rurality	
	N / firms	OLS	Metobit	OLS	Metobit
	(1)	(2)	(3)	(4)	(5)
<i>Quality of life</i>					
All countries					
pooled	6,234 / 29	0.026	0.066	0.047	0.130**
SHS	4,048 / 18	0.039	0.140	0.057	0.192**
Mini-grid	1,545 / 7	—	—	0.068	0.177*
Excluding India					
pooled	5,329 / 25	0.026	0.066	0.052	0.144*
SHS	4,048 / 18	0.039	0.140	0.050	0.191**
<i>Change in income</i>					
All countries					
pooled	538 / 14	—	—	0.162	0.200*
<i>Satisfaction with the supplier</i>					
All countries					
pooled	2,833 / 13	0.035	0.110	0.071	0.180
SHS	2,156 / 9	0.011	0.137	0.005	0.135
Excluding India					
pooled	2,643 / 12	0.035	0.110	-0.012	0.040
SHS	2,156 / 9	0.011	0.137	0.005	0.135

Notes. Each entry is the difference between customers who had no grid connection before adopting and customers who did, in points of that outcome's own scale: five points for quality of life and income, ten for satisfaction. A positive value means the customers without a prior connection report the better outcome. A dash means the model was not estimated or did not converge. The table additionally shows the full comparison with and without India. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

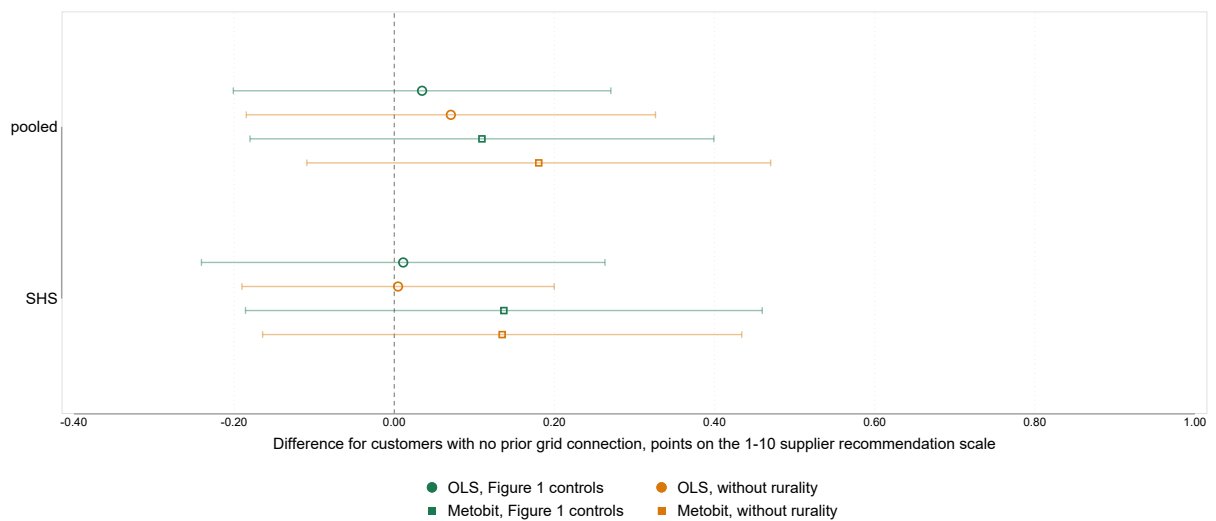
behaves in a way that warns against relying on it: its least-squares standard error halves on a sample 45 per cent smaller, which is the wrong direction, and the corresponding Tobit model does not converge, which is what a random intercept should do when asked to identify a variance from four groups. The honest conclusion is that these data cannot answer the question for mini-grids, not that India makes no difference.

Figure D4: Outcomes and prior grid access: quality of life



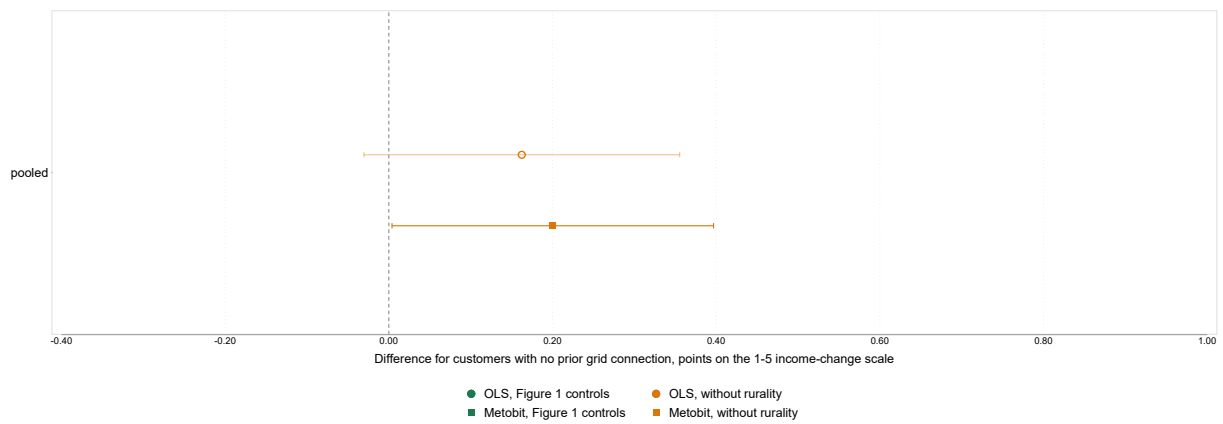
Notes. Each marker is the difference between customers who had no grid connection before adopting and customers who had one, with its 95 per cent confidence interval. A positive value means the customers without a prior connection report the better outcome. Filled markers are significant at the 5 per cent level, hollow markers are not. Two control sets are shown, and for this dimension the difference between them is also whether India is in the sample: see Section D. All markers are estimated on the full sample including India; the estimates excluding India are not plotted and are reported in the “Excluding India” rows of Table D2.

Figure D5: Outcomes and prior grid access: satisfaction with the supplier



Notes. Just as Figure D4.

Figure D6: Outcomes and prior grid access: change in income



Notes. Just as Figure D4.

E What customers say in their own words

Alongside the structured rating scales, each survey puts a small number of open-ended questions to the customer: how their quality of life changed, why they would or would not recommend the supplier, and how they earn from the product. Answers are recorded verbatim in the respondent's own words and then coded into themes. This section explains how those themes were built and reports them by product.

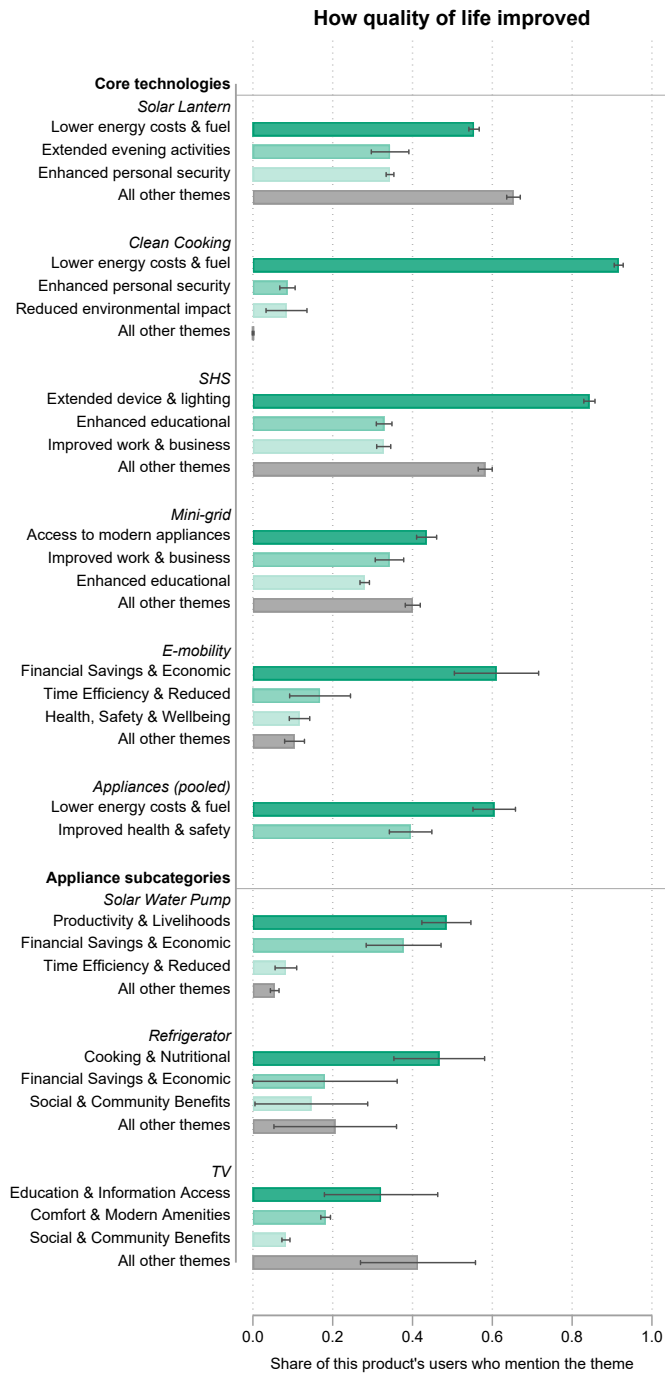
How the themes were constructed. The answers are coded in two ways. The first is 60 Decibels' own coding. Verbatim answers were reviewed to discover the categories that recur across a question, without imposing a list in advance; each answer was then assigned to one or more of those categories, so that each theme becomes an indicator for whether a given customer mentioned it. The second is our remapped coding, which reads the same verbatim answers and assigns each one to a single dominant theme.

The two codings differ in ways that matter for interpretation. Under 60 Decibels' coding a single answer may carry several themes, so shares within a product need not sum to 100 per cent, and a customer who gives a longer answer contributes to more themes than one who gives a short one. Its theme lists were also developed across the whole survey programme rather than per product, so some themes are rarely used for some products, and appliance answers are seldom coded at all: on the quality-of-life question it codes 3.1 per cent of solar water pump users and 0.2 per cent of TV users. The remapped coding is exclusive, so its shares stack to 100 per cent, and it codes far more answers: 19,343 answers to the challenges question against 12,716 under the original coding.

We therefore use each coding where it is strongest. Figure [E1](#) uses 60 Decibels' coding for the core technologies and the remapped coding for the appliance subcategories. Figure [E2](#), on what goes wrong, uses the remapped coding throughout. The open question also reaches more companies than the structured rating battery does, 53 against 25 for SHS, because more survey projects carried it.

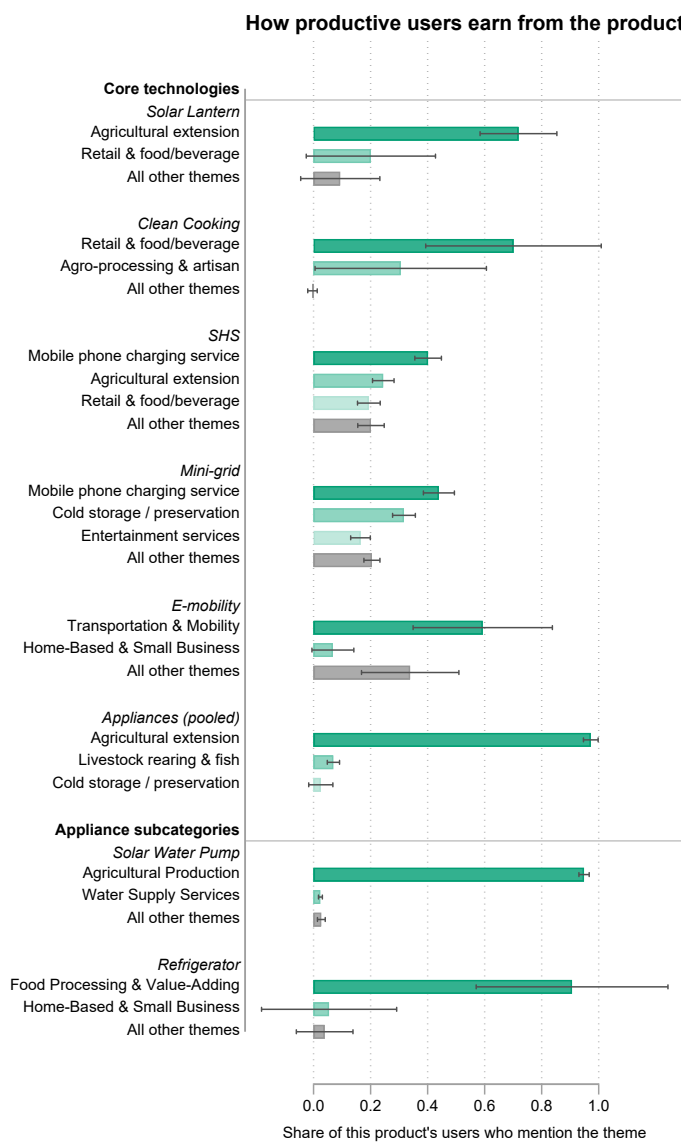
How the shares are estimated. For each product we take the three most frequently mentioned themes and pool the remainder into a residual. Each theme is then estimated as a separate linear probability model with country and survey-year fixed effects, standard errors clustered on company, and prediction at the same demographic profile used in Section 1.2, so that differences between products are not differences in who was surveyed. A residual category labelled *other* is never counted among the three, because a large *other* bar carries no interpretation.

Figure E1: What customers say in their own words



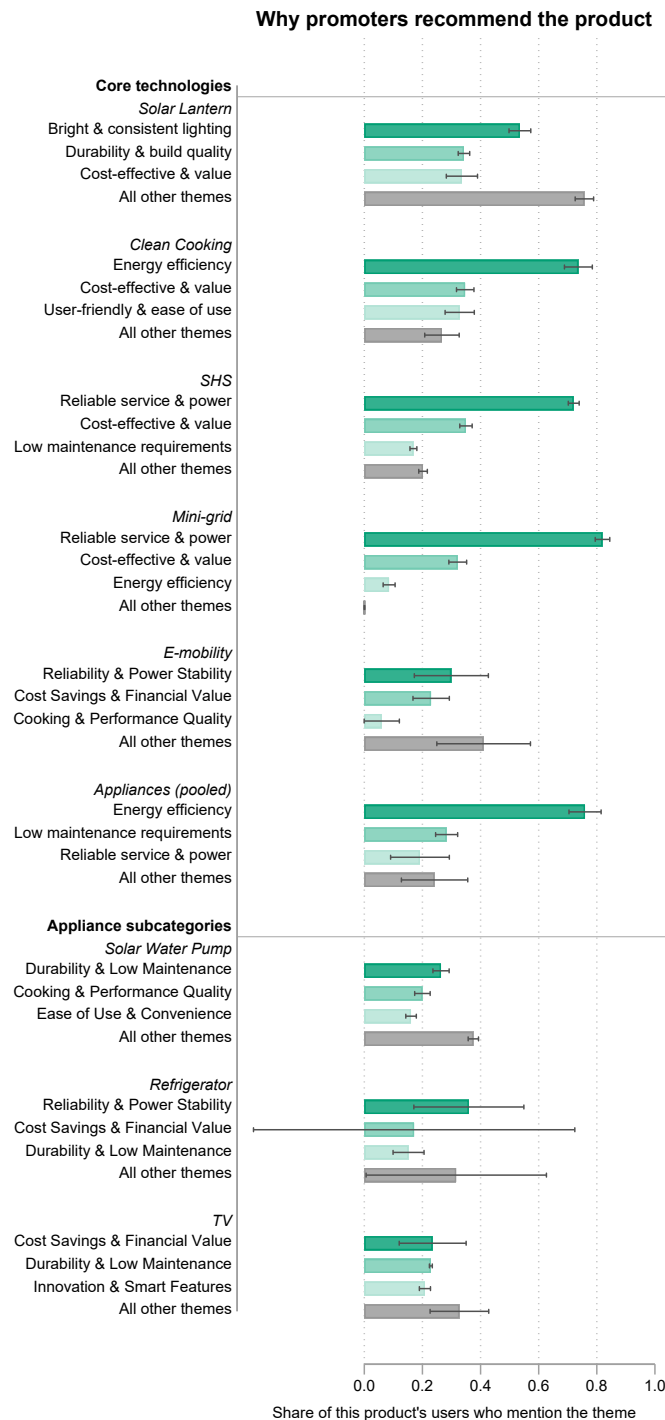
(a) How quality of life improved

Figure E1: What customers say in their own words (continued)



(b) How productive users earn

Figure E1: What customers say in their own words (continued)



(c) Why customers recommend the supplier

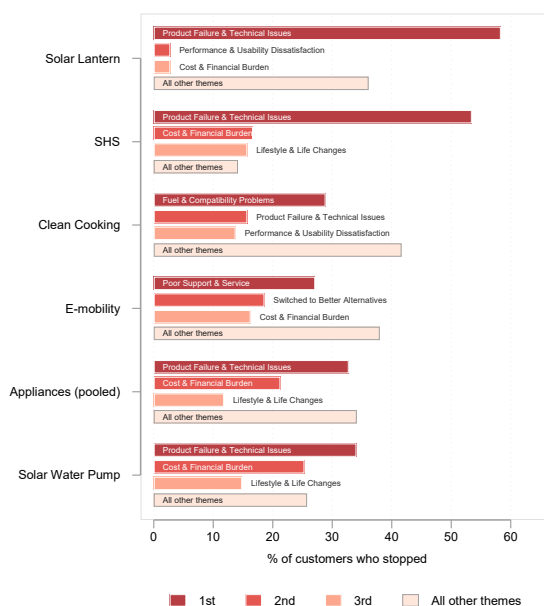
Notes. Each bar is the adjusted share of customers whose open-ended answer was coded into that theme, showing the three most frequently mentioned themes per product plus a residual. One linear probability model per theme, with country and survey-year fixed effects, clustered on company and predicted at the same demographic profile used in Section 1.2. The core technologies use 60 Decibels' coding, under which an answer can carry several themes, so their bars need not sum to 100 per cent; the appliance subcategories use the remapped coding, which assigns one theme per answer. A residual labelled *other* is never counted among the three. Supplementary Section E describes how the themes were constructed.

Figure E2: What goes wrong, in the words of customers



(a) Challenges reported

(b) Reasons given by detractors



(c) Reasons for stopping

Notes. Adjusted share of customers whose open-ended answer was coded into each theme, showing the three most common themes per product plus a residual. Themes are taken from the exclusive remapped coding rather than the original keyword lists, because it covers 19,343 challenge responses against 12,716 and its shares therefore sum honestly. A residual labelled *other* is never counted among the top three. Estimated as one linear probability model per theme, with country and survey-year fixed effects and standard errors clustered on company.

F Adoption risk: supporting tables

This section reports the estimates behind Figures 5 and 6, together with the denominator check that motivates the rates quoted in Section 1.6.

The headline rates depend on the denominator. Table F1 reports each rate twice: once over the customers who were actually asked the question, and once over all 78,729 interviews. Because companies chose which modules their surveys carried, the second denominator counts every customer who was never asked as though the outcome had not occurred, so it measures the reach of the survey programme rather than the experience of customers. The two differ by more than a factor of two for detractor, 17.3 per cent against 7.6, and by a factor of two for discontinuation, 3.9 per cent against 1.7. Every rate quoted in Section 1.6 uses the first denominator.

Table F1: Adoption risk: how each rate depends on its denominator

Outcome	Positive (1)	Asked (2)	% of asked (3)	% of all (4)
Reported a challenge	22,586	70,426	32.1	28.7
Detractor (i.e. satisfaction score ≤ 6)	5,954	34,360	17.3	7.6
Stopped using the product	1,332	33,746	3.9	1.7

Notes. Each of these questions is put to a subset of respondents rather than to all 78,729 interviews, because companies chose which modules their surveys carried. Column (1) counts the customers who report the outcome and column (2) those who were asked about it. Column (3) is the rate among customers actually asked and is the rate quoted in Section 1.6. Column (4) divides by every interview instead, which counts each customer who was never asked as though the outcome did not occur. The gap between the two columns is widest for detractor, 17.3 against 7.6 per cent, because the supplier recommendation question reaches fewer than half the sample. Column (4) therefore describes the coverage of the survey programme, not the experience of customers, and is shown only so that the two can be told apart.

Incidence by technology. Table F2 gives the modelled probabilities plotted in Figures 5 and 6, with the sample size and the number of companies behind each estimate. The company count is the figure to read before relying on any row.

Table F2: Adoption risk by product, adjusted and unadjusted

Product	Risk	Adjusted	95% CI	Raw	Asked	Firms
Mini-grid	Challenge	39.3	[37.8, 40.7]	37.2	13,913	21
SHS	Challenge	34.9	[31.4, 38.4]	33.3	34,801	56
E-mobility	Challenge	34.3	[33.5, 35.1]	36.8	921	3
Solar Lantern	Challenge	28.9	[27.7, 30.1]	20.9	2,769	5
Appliances (pooled)	Challenge	28.8	[24.1, 33.4]	29.9	7,681	13
Clean Cooking	Challenge	23.2	[19.5, 26.9]	25.1	10,341	16
Mini-grid	Detractor (scale 1-6)	31.4	[31.0, 31.8]	31.3	2,318	6
SHS	Detractor (scale 1-6)	9.4	[8.7, 10.1]	13.3	17,749	35
Solar Lantern	Detractor (scale 1-6)	8.9	[8.2, 9.6]	9.0	1,086	4
Appliances (pooled)	Detractor (scale 1-6)	7.3	[4.7, 10.0]	39.2	4,353	9
E-mobility	Detractor (scale 1-6)	7.3	[7.2, 7.4]	22.5	739	2
Clean Cooking	Detractor (scale 1-6)	7.0	[5.5, 8.5]	11.1	8,115	13
Mini-grid	Detractor (60dB NPS)	22.0	[20.3, 23.6]	19.7	15,010	21
SHS	Detractor (60dB NPS)	9.5	[8.6, 10.4]	11.1	37,073	56
Appliances (pooled)	Detractor (60dB NPS)	8.4	[6.3, 10.5]	29.1	7,062	13
Solar Lantern	Detractor (60dB NPS)	8.0	[7.4, 8.6]	6.6	2,173	5
E-mobility	Detractor (60dB NPS)	7.7	[7.1, 8.2]	19.8	921	3
Clean Cooking	Detractor (60dB NPS)	6.9	[4.9, 8.9]	9.8	10,344	16
E-mobility	Stopped use	14.4	—	14.4	494	3
Solar Lantern	Stopped use	10.6	—	10.6	1,633	6
Appliances (pooled)	Stopped use	10.5	[8.2, 12.8]	10.5	3,369	13
Clean Cooking	Stopped use	6.8	[3.6, 10.1]	6.8	3,802	19
SHS	Stopped use	2.4	[1.8, 3.0]	2.4	18,159	51
Mini-grid	Stopped use	0.7	[0.5, 0.8]	0.7	6,289	17
TV	Challenge	44.8	[43.5, 46.1]	40.9	1,016	5
Refrigerator	Challenge	24.5	[20.6, 28.4]	31.1	1,493	3
Solar Water Pump	Challenge	22.9	[19.4, 26.3]	26.7	3,630	6
Refrigerator	Detractor (scale 1-6)	13.8	[10.8, 16.7]	44.6	866	2
Solar Water Pump	Detractor (scale 1-6)	5.9	[4.5, 7.3]	27.8	2,221	6
Refrigerator	Detractor (60dB NPS)	13.8	[11.7, 15.9]	39.4	1,127	3
TV	Detractor (60dB NPS)	9.7	[8.0, 11.5]	10.9	1,018	5
Solar Water Pump	Detractor (60dB NPS)	5.9	[4.5, 7.3]	24.2	2,973	6
Refrigerator	Stopped use	13.1	—	13.1	521	3
Solar Water Pump	Stopped use	12.1	[9.0, 15.1]	12.1	2,170	7
TV	Stopped use	7.6	[4.6, 10.6]	7.6	303	1

Notes. The risks are: *Challenge*, the customer reports a problem with the product; *Detractor (scale 1-6)*, the customer scores 1 to 6 on the supplier recommendation scale; *Detractor (60dB NPS)*, the classification supplied by 60 Decibels; *Stopped use*, the customer has stopped using the product. **Adjusted** is the predicted probability at a common demographic profile, so a product's risk is not an artefact of who was surveyed; **Raw** is the unadjusted share among respondents asked. Challenge and detraction come from a logit; discontinuation from a linear probability model, because logit discards whole countries where nobody stopped and returns an upward-biased rate. Discontinuation carries no demographic controls, since they are not collected from customers who have stopped, so for that risk the adjusted and raw values coincide and the model contributes only the interval. A dash means no interval is identified: the product's companies are fully separated by country and survey year, so the fixed effects absorb all variation between companies. Standard errors are clustered on company where a product has more than one, robust otherwise.

G Robustness

This appendix asks whether the comparison of technologies in Figure 1 depends on the estimator, on the countries in the sample, or on holding the sample fixed across specifications. Each check changes one of these choices and keeps the others. In every check with full controls, solar lanterns record the largest quality-of-life premium over mini-grids and e-mobility the smallest, every technology records a positive income premium, and mini-grid customers are the least satisfied with their supplier. Section G.4 then asks whether the adopter profiles in Table 1 depend on where and when each product was surveyed.

G.1 Alternative estimators

The baseline in Figure 1 is a Tobit with random intercepts for companies and for projects within companies. It treats each answer as a censored score with normal errors, and it assumes that the company and project intercepts are unrelated to the technology sold. The OLS version of every specification, shown as squares in Figure 1, drops all three assumptions at the cost of ignoring that the scales are bounded. Here we keep the bounded scales and change one assumption at a time.

Ordered categories instead of a continuous score. Figure G1 replaces the Tobit with a three-level ordered logit (`meologit`) with the same fixed effects, controls, random intercepts and samples. It treats each outcome as ordered categories, so it relies on neither the normal error nor the censoring limits, and it reports how each technology shifts the probability of every answer relative to mini-grids.^{xv} The ranking in Figure 1 survives intact. Solar lantern customers are 31 percentage points more likely than mini-grid customers to report that their quality of life improved very much (95 per cent interval 16 to 47), followed by clean cooking (25 points), SHS (24) and appliances (17), while the shift for e-mobility (10 points) is not distinguishable from zero. Every technology is also associated with a higher probability of

^{xv}For satisfaction with the supplier, the ten-point score is grouped before estimation into detractors (1 to 6), passives (7 and 8) and promoters (9 and 10), the grouping behind the Net Promoter Score.

the top income answer, from 15 points for SHS to 29 for appliances, and with a probability of being a promoter of the supplier between 29 and 40 points higher than for mini-grids. The probabilities of the lower answers fall correspondingly.

No random intercepts. Figure G2 drops the random intercepts and estimates a two-limit Tobit with country and survey-year fixed effects and standard errors clustered on company, under three sets of controls: none, education only, and the full set.^{xvi} The ordering is again unchanged. With full controls, the quality-of-life coefficients run from 1.05 for solar lanterns through 0.81 for clean cooking, 0.71 for SHS and 0.41 for appliances to 0.17 for e-mobility, which again is not distinguishable from zero. Every income coefficient is positive and significant, with SHS the smallest at 0.51, and satisfaction is higher for every technology than for mini-grids, most of all for solar lanterns at 2.20. Changing the controls never moves a coefficient by more than 0.12. These coefficients are on the latent index rather than on the observed scale, so they are larger than the marginal effects in Figure 1; the ordering, not the size, is what should be compared.

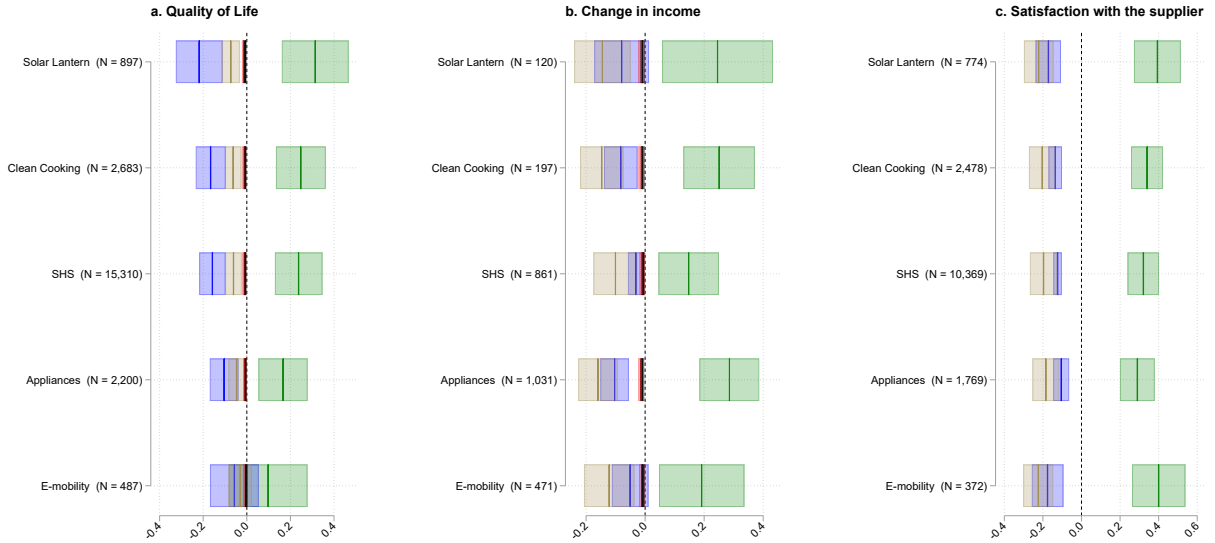
G.2 Using countries that have customers across at least three technologies

As shown in Figure A1, technologies are unevenly distributed across countries. Some countries have customers for only one or just a few of the technologies. Here, we restrict our sample to only countries that have customers of at least 3 technologies in order to sufficiently capture within-country-technology differences. This reduces the number of countries to 13, shown in Figure G3. We then re-estimate the Tobit of Figure G2 on this subsample, which keeps 16,548 of the 23,013 customers in the quality-of-life sample and 66 of its 84 companies. The results, in Figure G4, are similar to the estimates on all countries.

Solar lanterns again record the largest quality-of-life coefficient (1.22) and e-mobility the

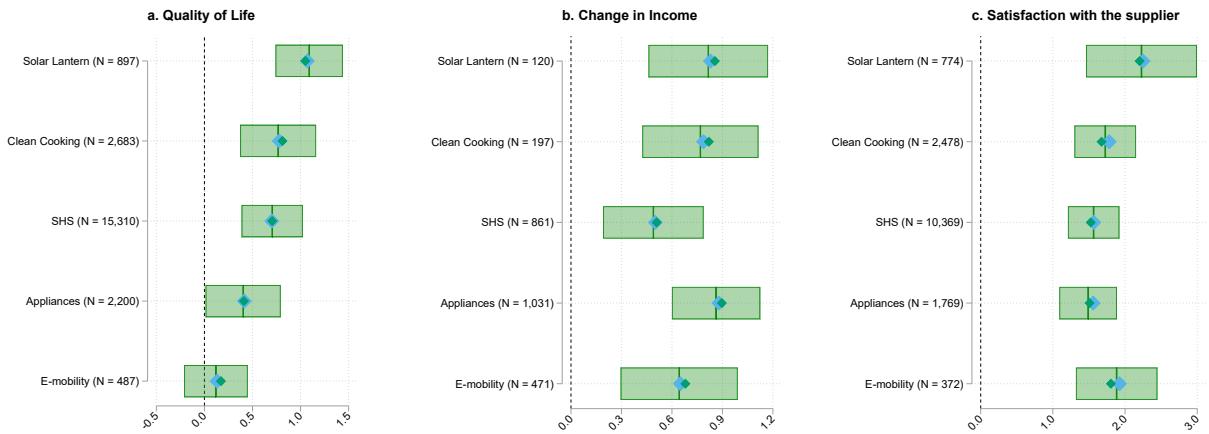
^{xvi}The fixed effects are the additive country and survey-year effects of Figure 1. The full control set adds the square of household size, and the censoring limits are the observed minimum and maximum of each scale.

Figure G1: Technology differences under a three-level ordered logit



Notes. Average marginal effects of each technology on the probability of each answer, relative to mini-grids, from a three-level ordered logit with country and survey-year fixed effects, the controls of Figure 1, and random intercepts for company and project, on the samples of Figure 1. Each bar is a 95 per cent confidence interval, with the point estimate as a vertical line. Panels (a) and (b): green is the top answer, blue the second, brown no change, and red and black the two lowest. Panel (c): green is promoters (9 and 10), blue passives (7 and 8) and brown detractors (1 to 6). The number of customers is shown beside each technology.

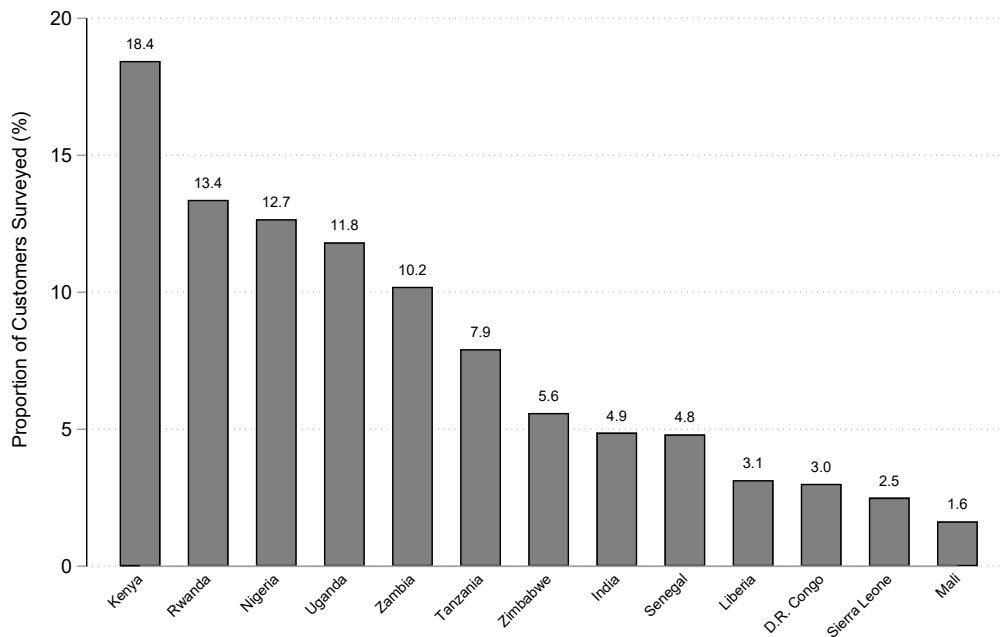
Figure G2: Technology differences under a Tobit without random intercepts



Notes. Coefficients on each technology, relative to mini-grids, from two-limit Tobit models with country and survey-year fixed effects and standard errors clustered on company, on the customers with every control recorded. Coefficients are on the latent index. The bar is the specification without controls, with its 95 per cent confidence interval; the larger diamond adds education, and the smaller diamond the full control set (education, rurality, sex, household size and its square, and age). The number of customers is shown beside each technology.

smallest (0.16, not distinguishable from zero), with appliances fourth. SHS (0.82) and clean cooking (0.71) change places, but their intervals overlap almost entirely. Every income coefficient remains positive and significant, with SHS again the smallest, and satisfaction with the supplier remains highest for solar lanterns. The comparison of technologies therefore does not rest on the countries where only one or two technologies were surveyed.

Figure G3: **Countries with customers across at least three technologies**

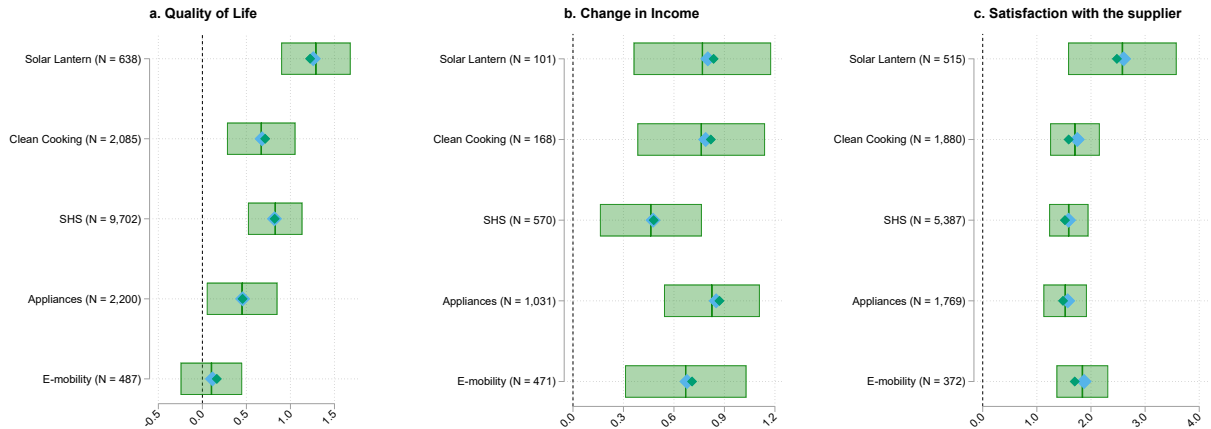


Notes. Share of each country in the quality-of-life sample of the 13 countries where customers of at least three technologies were surveyed (16,548 customers).

G.3 Holding the sample fixed across specifications

Figure 1 holds the sample fixed within each outcome: every specification is estimated on the customers with all controls recorded, so the differences between specifications reflect the controls and not the sample. Figure G5 relaxes this and estimates each specification on every customer it can use. The specification with full controls is unchanged by construction, since its sample is the same. The reduced specifications draw on many more customers, up to almost seven times as many, from surveys that did not record the controls.

Figure G4: **Technology differences in the countries with at least three technologies**

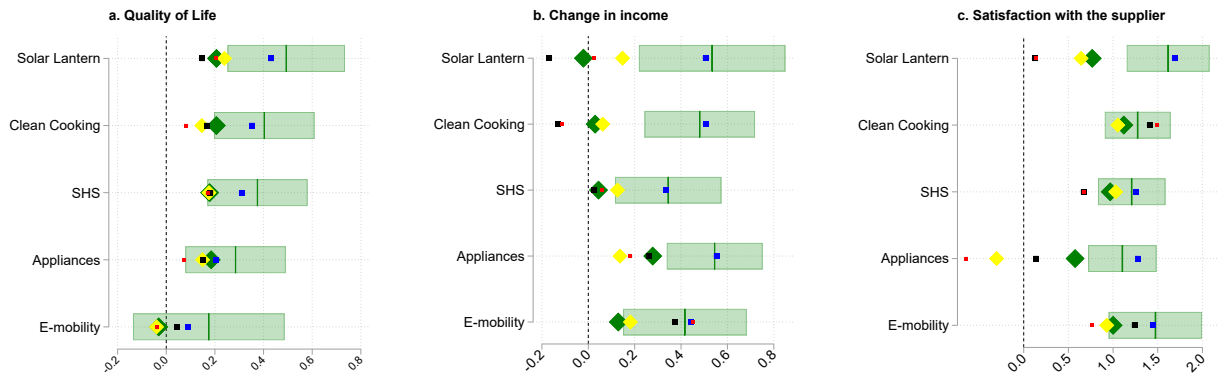


Notes. As Figure G2, estimated on the 13 countries in Figure G3 only.

The reduced estimates move a long way for all three outcomes. For quality of life they remain positive for every technology except e-mobility but are roughly half the size of those in Figure 1: 0.21 and 0.24 for solar lanterns against 0.49, and 0.18 for SHS against 0.37. For income, the Tobit estimates without the full controls are indistinguishable from zero for every technology except appliances with the education control, and among their OLS versions only appliances and e-mobility remain significant. For satisfaction, the reduced Tobit estimates remain positive and significant for SHS and clean cooking but are smaller for every technology, and for appliances without controls the estimate turns negative (-0.30 , not significant). Within the fixed sample of Figure 1, by contrast, removing the controls barely moves any estimate. The change therefore comes from adding customers rather than from removing controls: the reduced specifications on the larger samples compare a different set of surveys and companies. This is why Figure 1 uses one sample per outcome, and why the number of companies behind each technology matters more than the number of customers.

These checks vary the estimator, the countries and the sample. None of them addresses the selection of customers into products and into surveys, so they show that the comparison of technologies is not an artefact of a modelling choice, not that it identifies the effect of a technology.

Figure G5: Technology differences with each specification on its own maximal sample



Notes. As Figure 1, except that each specification is estimated on every customer with the variables it uses, so the sample grows as controls are removed. The baseline with full controls is identical to Figure 1.

G.4 Adopter composition controlling for country and survey year

Table 1 reports unconditional shares. Because projects are specific to a company, country, and year, part of the variation in adopter composition across technologies may reflect where and when each technology was surveyed rather than the technology itself. Table G1 re-estimates the same profiles with country and survey-year fixed effects. For each characteristic, a linear probability model on the product indicators and the fixed effects predicts the share each product would show if its customers had the country and survey-year mix of all customers asked.

The adjustment leaves the contrasts drawn in Section 1.3 in place. The overlap of first-time use and no grid connection keeps its order, from 87.7 per cent for mini-grids and 75.9 per cent for SHS down to 21.6 per cent for clean cooking. Mini-grid and e-mobility customers still mostly pay upfront (78.8 and 88.7 per cent), while SHS customers mostly buy on credit (10.4 per cent pay upfront). The share without secondary education stays below 20 per cent for every technology, solar lantern and mini-grid customers remain the most rural, and clean cooking still has the largest share of women (55.6 per cent) and mini-grids the smallest (24.3 per cent).

The one column that changes is grid access, and it changes in the direction Section [1.3](#) anticipates. Compared within countries, 78.9 per cent of mini-grid customers had no grid connection, the highest share of any technology, against 55.0 per cent in Table [1](#). The mini-grid customers who report a connection are concentrated in India, and once the comparison is made within countries, a larger share of mini-grid customers than of SHS customers (68.3 per cent) had no connection.

Most appliance subcategories cannot be adjusted. Solar fans, heaters and mills were each surveyed among the customers of a single company, so the adjustment cannot separate the product from the company that sells it, and the other subcategories rest on two to ten companies.

Table G1: **Profile of off-grid product adopters, adjusted for country and survey year**

Off-grid products	Access to energy (%)			Commercial and demographic (%)				
	First-time users	No grid access	First-time & no grid	Paid upfront	No sec. education	Rural	Female	Interviews
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Core technologies								
Solar lantern	69.1 [2,461]	53.8 [1,214]	61.1 [741]	26.4 [586]	11.3 [1,838]	78.3 [2,073]	40.5 [2,962]	3,033
Clean cooking	83.4 [8,948]	13.0 [668]	21.6 [575]	52.7 [1,689]	5.7 [4,411]	31.9 [8,644]	55.6 [9,991]	11,238
Solar home systems (SHS)	75.6 [20,238]	68.3 [5,626]	75.9 [3,837]	10.4 [3,260]	19.1 [23,260]	61.2 [19,873]	29.8 [30,651]	38,636
Mini-grid	76.7 [4,453]	78.9 [4,024]	87.7 [1,336]	78.8 [1,159]	19.3 [10,795]	78.6 [1,949]	24.3 [14,797]	15,237
E-mobility	52.2 [913]	—	—	88.7 [329]	7.1 [611]	57.5 [728]	30.7 [978]	1,050
Appliances (pooled)	71.4 [4,734]	25.5 [277]	40.4 [187]	19.8 [1,459]	9.6 [3,703]	49.5 [4,637]	26.1 [8,604]	9,535
Appliance subcategories								
Solar water pump (SWP)	87.9 [2,552]	—	—	18.7 [877]	7.1 [1,645]	64.3 [1,667]	17.9 [4,164]	4,577
Refrigerator	25.3 [692]	—	—	13.4 [302]	15.5 [328]	59.3 [731]	44.1 [1,568]	1,841
TV	80.2 [349]	37.7 [69]	46.0 [63]	—	12.3 [539]	60.3 [578]	27.0 [1,065]	1,100
Smartphone	56.9 [643]	—	—	—	—	30.6 [1,169]	24.8 [1,307]	1,510
Solar fan	—	—	—	—	—	—	—	108
Solar heater	—	—	—	—	—	—	—	175
Solar mill	—	—	—	—	—	—	—	224
All core technologies	76.2	66.5	72.0	24.9	16.7	54.9	32.6	78,729
Non-missing obs.	46,815	15,507	9,492	15,614	48,515	41,980	73,552	78,729

Notes: Each cell is the share of that product's customers with the characteristic, predicted from a linear probability model with country and survey-year fixed effects as if every product's customers had the country and survey-year mix of all customers asked. The core technologies come from one model per characteristic on the six technology indicators, the appliance subcategories from one on the thirteen product indicators. The bracketed figure is the number of that product's customers surveyed in a country where at least one other product was asked the same question: only these customers identify the share, because the fixed effect absorbs a country where a single product was surveyed. A dash means the question was never put to customers of that product, or that the customers who identify the share come from fewer than two companies, so the adjustment cannot separate the product from the company that sells it. The last two rows and the final column are those of Table 1: the adjustment changes how a total divides among products, not the total.