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Market Formation under Fixed Supply Costs:

The Case of Energy-Efficient Biomass Stoves in Rwanda

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Abstract: Many technologies with substantial private and social benefits diffuse only slowly in low-income countries. Existing explanations typically focus on household demand and give little attention to the conditions under which markets for these technologies emerge. We study market formation for energy-efficient biomass cookstoves in rural Rwanda by combining experimental evidence on households' willingness to pay with detailed administrative data on the costs of supplying cookstoves. Randomized variation in stove prices identifies the willingness-to-pay schedule, while production and distribution cost data allow us to estimate the average cost of supplying cookstoves at different levels of market penetration. Comparing these two schedules shows that average supply costs remain above households' willingness to pay throughout the observed range of adoption. Decentralized markets are therefore unlikely to become commercially self-sustaining under prevailing conditions. Back-of-the-envelope welfare calculations suggest that the subsidy required to bridge this gap is justified by the climate benefits alone and may also be warranted by household time savings that are not fully reflected in the willingness to pay.

Keywords: Improved cookstoves; market formation; fixed supply costs; technology adoption; subsidies

JEL Codes: O12, O33, Q41, H23

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1. Introduction

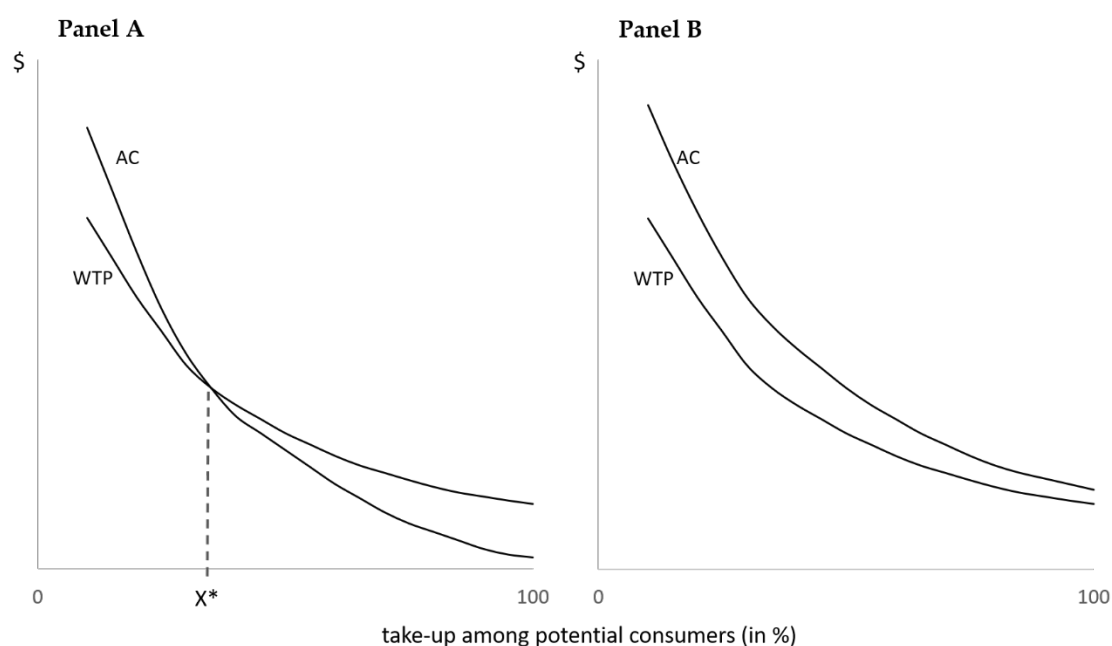
Markets are central to the process of economic development. They enable households to access new technologies, adopt more productive production methods, and improve their standard of living. Yet markets themselves do not emerge automatically. In many low-income settings, suppliers must incur substantial fixed costs before reaching geographically dispersed consumers. Investments in transport, marketing, distribution networks, training, certification, or local service provision are often required before the first unit can be sold. These fixed costs imply that average supply costs decline with market size, so that profitable supply itself depends on achieving sufficient scale. This means that technologies capable of generating substantial private and social benefits may fail to diffuse because decentralized markets never develop in the first place.

This paper studies market formation for energy-efficient biomass cookstoves (EEBC) in rural Rwanda. EEBCs provide an interesting application because they occupy an intermediate position on the energy ladder. Unlike electricity, they do not require expensive physical infrastructure, yet unlike traditional cooking methods they promise meaningful gains in fuel efficiency and environmental performance. Over the past two decades governments, NGOs, and development agencies have invested heavily in promoting EEBCs throughout rural Sub-Saharan Africa, motivated by their potential to reduce firewood consumption, slow forest degradation, lower carbon emissions, and improve household welfare. Despite these efforts, however, self-sustaining commercial markets have rarely emerged in rural Africa.

Recent research has increasingly emphasized the role of fixed costs and increasing returns in shaping market development. Lee et al. (2020), for example, show that high connection costs prevent grid operators from delivering rural electrification in Kenya on a cost-recovering basis, even under universal coverage. Foster and Rosenzweig (2022) demonstrate how fixed transaction costs in factor markets shape equilibrium farm size and agricultural mechanization. Bassi et al. (2022) show that producers may need to coordinate collectively to overcome fixed costs before profitable markets emerge. Anissa et al. (2021) show that fixed costs associated with quality certification can prevent the emergence of certified agricultural markets despite strong buyer demand, and Do Nascimento Miguel et al. (2026) demonstrate that fixed costs associated with separating certified and conventional output may give rise to

multiple market equilibria depending on market expectations. Atkin and Donaldson (2015) and Grant and Startz (2022) study how fixed exchange costs may fragment markets and shape intermediary chains. Although these studies examine different sectors, they point to the same underlying mechanism: market development depends not only on household demand, but also on whether suppliers can recover the fixed costs associated with entering and serving new markets. Whether decentralized markets emerge is therefore ultimately an empirical question.

Figure 1: Supply and demand in the presence of fixed supply costs



Note: AC represents average supply costs and WTP captures the willingness to pay, or marginal utility from consumption. In Panel A, a viable market can exist if a sufficiently large share of the potential consumers adopts the good ($>X^*$). In Panel B, suppliers can never recoup their fixed costs regardless of the adoption rate.

Figure 1 illustrates two generic outcomes that may arise when suppliers face fixed entry costs. The downward-sloping curve represents households' willingness to pay for a technology, while the second curve represents the average cost of supplying that technology. In Panel A, average supply costs eventually fall below willingness to pay as market size increases. Although suppliers may initially hesitate to enter because fixed costs are high relative to expected income from sales, sufficient adoption creates a self-sustaining market. Temporary interventions that coordinate expectations or reduce entry costs may therefore permanently establish a viable market. In Panel B, by contrast, average supply costs remain above willingness to pay throughout the relevant range of adoption. In this case decentralized markets cannot sustain diffusion, irrespective of suppliers' expectations or coordination

among potential buyers. Distinguishing between these two cases is fundamental for understanding whether market-based development is feasible and for determining the appropriate role of public policy.

The existing literature on EEBC adoption has predominantly approached the question from the demand side. Researchers have examined why households appear reluctant to adopt EEBCs, emphasizing explanations such as liquidity constraints, imperfect information, learning-by-using, uncertainty about product quality, and intra-household decision-making. While these mechanisms undoubtedly influence adoption decisions, they implicitly assume that EEBCs are available whenever households decide to purchase them. Much less attention has been devoted to the economics of market formation itself. Yet supplying EEBC to remote rural communities requires manufacturers, distributors, and installers to incur substantial fixed costs related to transport, community promotion, installer training, and local distribution. Whether these costs can be recovered through stove sales remains largely unknown.

Our objective is to determine whether decentralized markets can sustain the diffusion of EEBC once these supply-side costs are considered. We ask whether households' willingness to pay intersects the average cost of supplying energy-efficient biomass stoves or not. To answer this question, we combine experimental evidence on household demand with detailed information on the costs of supplying energy-efficient biomass stoves. We exploit a randomized field experiment in rural Rwanda in which communities were randomly assigned different subsidy levels for an energy-efficient biomass cookstove. Random assignment generates exogenous variation in adoption rates, allowing us to estimate households' willingness to pay. We combine these data with detailed administrative information on the costs of promoting, transporting, and installing cookstoves in each community. Because many of these costs are fixed at the community level, average supply costs decline as adoption increases. Jointly estimating the demand curve and the average cost curve enables us to determine empirically which panel of Figure 1 best characterizes the market for energy-efficient biomass stoves.

Our findings closely correspond to Panel B. Although households value EEBC and demand is price-responsive, estimated willingness to pay remains below average supply costs

across the observed adoption range. Community-level fixed costs for promotion, transport, and installer training prevent average costs from falling below willingness to pay, precluding a self-sustaining market equilibrium. Thus, widespread EEBC adoption in our study area is unlikely to emerge through market forces alone. Whether governments should intervene depends on additional market failures, such as environmental externalities, liquidity constraints, and other factors causing private willingness to pay to diverge from social value. We probe these issues in the discussion, below.

This paper contributes to three strands of literature. First, it contributes to a growing literature on market formation under fixed costs. Recent work discussed above has demonstrated the importance of fixed costs for various sectors and we extend this literature to household energy technologies. Second, we contribute to the literature on EEBCs (Alem, 2026). We shift attention from household demand to market formation. To our knowledge, this is the first study to combine experimentally identified cookstove demand with empirically estimated average supply costs to test directly whether a viable market equilibrium exists. Finally, the paper contributes to the broader literature on technology adoption in developing countries by demonstrating that, absent governmental distribution programs, understanding diffusion requires understanding market formation. Technologies cannot diffuse unless markets first emerge.

2. Market formation along the energy ladder

Access to modern cooking energy is an important component of economic development. Cleaner and more efficient technologies can improve living standards, reduce time spent collecting fuel and preparing meals, and generate environmental benefits. The transition from traditional biomass to modern energy sources is commonly described as the energy ladder: as incomes rise and technologies become available, households gradually shift towards cleaner alternatives such as LPG and electricity, although many continue to use multiple fuels simultaneously, commonly referred to as *fuel stacking*.

An often overlooked feature of the energy ladder is that transitions require markets to form. Adoption depends not only on household demand but also on suppliers' ability to profitably distribute, install, and maintain new technologies. These challenges differ across technologies. Electricity requires substantial infrastructure investments and thus involves

large fixed costs. Lee et al. (2020), for example, show that average grid connection costs in rural Kenya exceed households' willingness to pay even under universal coverage, highlighting the limits of decentralized markets and the potential role of public intervention. EEBCs, by contrast, improve the efficiency of existing biomass fuels without requiring major infrastructure. Their relatively low hardware costs make them seemingly well suited to market-mediated diffusion. If markets fail even for such inexpensive technologies, this raises broader questions about the ability of decentralized markets to support transitions along the energy ladder.

EEBCs can reduce fuel consumption, lowering household expenditures or time spent collecting fuel, while potentially mitigating forest degradation and carbon emissions (Jeuland and Pattanayak, 2012; Bailis et al., 2015; Bensch et al., 2021). Empirical studies document substantial fuel savings (Bensch and Peters, 2015; Brooks et al., 2016; Gebreegziabher et al., 2018; Mekonnen et al., 2022).¹ Yet adoption often remains limited. Most explanations focus on household demand, emphasizing liquidity constraints (Bensch et al., 2015; Levine et al., 2018; Berkouwer and Dean, 2022), imperfect information and learning (Bensch and Peters, 2020; Bluffstone et al., 2022), and intra-household decision making, particularly when women benefit from reduced cooking burdens but men control expenditures (Miller and Mobarak, 2013; Krishnapriya et al., 2024).

Much less attention has been paid to the supply-side conditions under which EEBC markets emerge. Serving remote rural communities requires customer outreach, transport, installer training, installation, and after-sales support. Many of these activities incur fixed costs at the community level, causing average supply costs to decline with adoption. Profitable market formation may therefore depend on reaching sufficient scale.

Emerging evidence points to the importance of these constraints. Bensch and Peters (2020) find that Senegalese households were willing to purchase replacement stoves years after initial adoption, yet commercial markets failed to emerge because suppliers rarely served remote

¹ Evidence on health impacts is mixed. While most energy-efficient biomass stoves are not designed to reduce emissions, advanced stoves can substantially reduce emissions in laboratory settings. Realized health gains however depend on sustained use, maintenance, ambient pollution, and the displacement of traditional stoves (Jeuland and Pattanayak, 2012; Hanna et al., 2016; Mortimer et al., 2017; Berkouwer and Dean, 2026).

communities. Sievert et al. (2024) document low margins, uncertain demand, and high distribution costs among stove vendors, while Pattanayak et al. (2019) show that combining promotion with consumer finance and last-mile distribution support substantially increases adoption. Together, these findings suggest that household willingness to pay alone may be insufficient to sustain rural EEBC markets.

3. Study context, experimental design and data

Roughly 900 million people in Sub-Saharan Africa rely primarily on biomass fuels such as firewood and charcoal for cooking. In rural Rwanda, firewood remains the dominant cooking fuel. Around four out of every five households collect firewood themselves, while most of the remaining households purchase firewood in local markets. Because transport costs are high, these markets are highly localized. Alternative fuels such as charcoal, liquefied petroleum gas (LPG), and electricity play only a very small role in rural cooking. Agricultural residues are occasionally used as supplementary fuels when firewood is scarce. Dependence on traditional biomass imposes substantial costs on rural households. Collecting firewood requires considerable time and effort, particularly for women and children who perform most fuel collection activities. In our study area, households spend more than five hours per week collecting biomass fuels on average (Munyehirwe et al., 2026). Heavy reliance on firewood also contributes to forest degradation and carbon emissions, motivating the Government of Rwanda to promote more energy-efficient cooking technologies.

3.1 Study context

The technology considered in this paper is the *Canarumwe*, a locally produced energy-efficient biomass cookstove. Unlike cleaner-burning technologies such as LPG or electric stoves, the *Canarumwe* continues to use traditional biomass fuels but improves combustion efficiency, thereby reducing firewood consumption. The stove was designed as an affordable intermediate technology that could improve household energy efficiency while remaining compatible with existing cooking practices. Beginning in 2010, the Government of Rwanda initiated a national program to promote production and dissemination of the *Canarumwe* stove. Local production units were established, producers and installers were trained, and households were expected to purchase the stove at cost-covering prices. Despite these efforts,

adoption remained limited, particularly in remote communities. The data analyzed in this paper originate from a pilot intervention conducted during the second phase of this national promotion program.

3.2 *Experimental design*

To evaluate household demand for EEBC, a cluster-randomized field experiment was implemented during 2015. The experiment covered 84 rural communities distributed across six districts participating in the second phase of the national cookstove promotion program. Communities were selected from non-adjacent administrative cells to minimize spillovers between treatment communities. Within each selected cell, one community (*umudugudu*) was randomly selected for inclusion in the experiment. Communities were randomly assigned to one of four experimental arms consisting of a control group and three price treatments (21 communities per arm). The intervention followed the Government's standard implementation strategy. Local stove producers and installers received the same technical training provided elsewhere in Rwanda, after which community promotion meetings were organized to introduce households to the *Canarumwe* stove and demonstrate its use.

The experimental treatments differed only in the price households were asked to pay for the stove and its installation (i.e., in the subsidy provided). Households in the three treatment arms could purchase the stove at prices of RWF 0, RWF 1,250 (=EUR 1.61), or RWF 2,500 (=EUR 3.21)². Households were also required to provide locally available construction materials such as sand, bricks, and water for installation. In the two positive-price treatments, installment payments were permitted to reduce liquidity constraints. Following the community meetings, households could purchase the stove immediately or at any point during the subsequent implementation period. Random variation in prices generates exogenous variation in community-level adoption rates. This experimental variation provides the basis for identifying households' willingness to pay for EEBC.

3.3 *Data*

Our empirical analysis combines household survey data with detailed administrative information collected during implementation of the intervention. The household survey was

² Throughout the paper, we use the May 2015 exchange rate of 1 EUR = 778 RWF.

conducted between February and March 2018 and covers 1,672 randomly selected households across the 84 study communities, corresponding to approximately twenty households per community. The questionnaire collected information on household demographic characteristics, cooking practices, fuel use, ownership of EEBC, and other socioeconomic variables.

Table 1. Components of stove supply costs (EUR per stove)

Cost level	Activity	Description	Mean	SD	Median
District	Installer training	Central district-level training events, including facilitator salary and materials, multiplied by number of events per district	0.67	0.82	0.41
District	Stove transport	Transport of stoves from production site to district capital	0.24	0.44	0.00
Community	Installer training	Installer travel from community to district capital	0.53	0.53	0.38
Community	Promotion event	Promotion event in community (all-in)	5.35	5.34	3.59
Community	Stove transport	Transport of stoves from district capital to community	1.68	1.18	1.35
Stove	Installation	Installation in household	0.50	0.00	0.50
Stove	Hardware	Linear cost per stove	1.70	0.00	1.70
TOTAL		Average total cost per stove	10.67	7.70	7.80

Note: All costs are expressed in EUR per stove. Cost components are grouped by the administrative level at which expenditures originate (district, community, or individual stove). District-level training and transportation costs are allocated equally across communities within each district. For each community, the allocated district costs and direct community expenditures are divided by the number of stoves installed. Installation and hardware costs are calculated directly on a per-stove basis. Transportation costs are step-fixed, increasing when additional trucks are required. The descriptive statistics are restricted to communities with at least one stove installation; communities with zero installations are excluded because their average cost per stove is undefined.

Because no baseline survey was conducted prior to randomization, balance is assessed using household and community characteristics that cannot plausibly have been affected by the intervention. Appendix Table A1 reports the corresponding balance tests. Although randomization produced some differences across treatment groups—as expected given the relatively small number of communities—no systematic pattern emerges. Throughout the

empirical analysis, we include pre-treatment community characteristics as controls to improve precision.

A unique feature of the study is the availability of detailed administrative records documenting the costs incurred in supplying EEBC. These records were carefully collected during implementation of the intervention and distinguish between expenditures incurred at different stages of the delivery process. Specifically, the administrative data identify costs incurred once at the district level, costs incurred for serving individual communities, and costs that vary proportionally with the number of stoves installed. District-level expenditures primarily consist of organizing and conducting installer training. Community-level expenditures include community promotion meetings, transport of stoves to individual communities, and travel costs incurred by installers. Finally, variable costs include stove hardware and installation labor. Table 1 summarizes the main categories of supply costs observed during implementation, and this detailed cost information forms the basis for estimating the average cost of supplying EEBC under alternative levels of market penetration.

Our estimates are based on the costs observed during the pilot implementation. Some higher-level fixed costs, such as producer training or supply-chain development, may decline as markets expand regionally or nationally. By contrast, many of the community-level costs documented in Table 1—including community promotion, last-mile transport, and local installation—must be incurred whenever a new community is served and therefore remain relevant even at larger scales. The main analysis is based on pooling district and community level costs that were actually incurred in the experiment, but we report a robustness exercise that excludes all district-level expenditures, providing an optimistic lower bound on average supply costs under large-scale implementation.

3.4 Empirical strategy

Our empirical strategy proceeds in three steps. First, we estimate households' willingness to pay for EEBC using the random variation in stove prices generated by the experiment. Differences in adoption across treatment arms identify the demand schedule for EEBC. Second, we estimate the average cost of supplying EEBC using the administrative cost records summarized in Table 1. Combining community-level adoption rates with detailed information on implementation costs allows us to estimate how average supply costs vary with market

size. In particular, the presence of district- and community-level fixed costs implies that average costs may decline substantially as more households adopt the technology. Finally, we combine the estimated demand schedule and the estimated average cost schedule to evaluate whether decentralized markets generate a viable equilibrium.

4. Household demand for energy-efficient biomass stoves

We estimate the following reduced-form relationship between stove prices and community-level adoption:

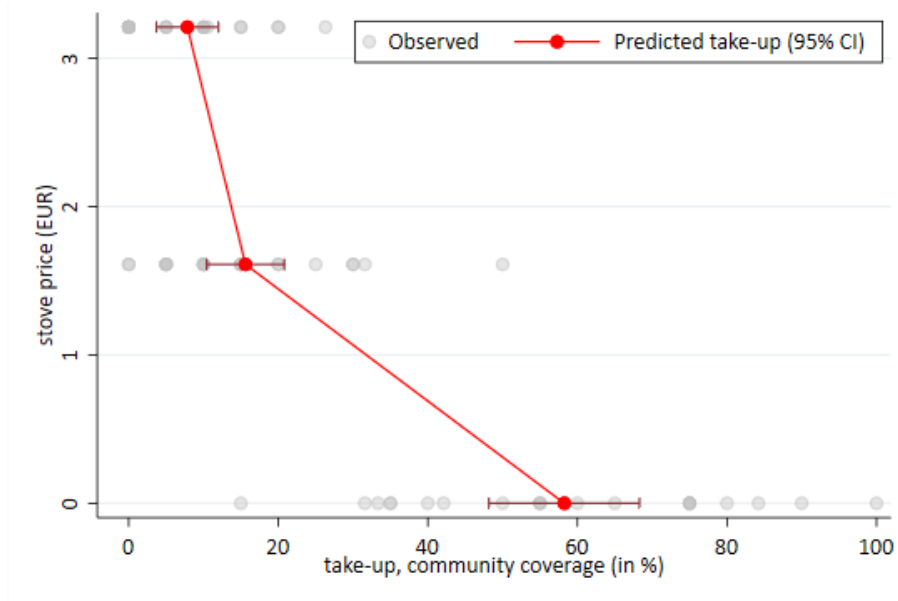
$$Y_c = \alpha + \beta_1 T_c^H + \beta_2 T_c^M + \beta_3 T_c^N + X_c \gamma + \varepsilon_c, \quad (1)$$

where Y_c denotes the share of households adopting an improved cookstove in community c , T_c^H , T_c^M , and T_c^N indicate assignment to the high-, medium-, and no-subsidy treatment arms, respectively, and X_c contains a small set of pre-treatment community characteristics included to improve precision. Standard errors are robust to heteroskedasticity. Regression estimates are reported in Appendix Table A2. Throughout the paper we focus on community-level adoption rates rather than the absolute number of stoves sold because market penetration is the relevant measure for evaluating market formation. But we obtain similar results when using the number of stoves per community as the proxy of community-level adoption (see Appendix D).

Figure 2 summarizes the experimental evidence. Each point represents the average adoption rate observed at one of the experimentally assigned prices, and the fitted line provides the corresponding willingness-to-pay schedule. As expected, adoption declines monotonically with price.³ When households receive the stove free of charge, adoption is highest. Introducing even a modest purchase price substantially reduces uptake, and adoption falls further when households are asked to pay the full program price. The finding that demand is downward sloping indicates that households value the improved stove and respond to incentives. The pricing experiment confirms that affordability is a determinant of adoption.

³ We define adoption as ordering a stove after the marketing events. We observe actual usage to be only slightly lower up to 2.5 years after ordering the stove (see also Munyehirwe et al., 2026).

Figure 2: Estimated demand for energy-efficient biomass stoves



However, adoption remains incomplete even when households receive the stove free of charge, reflecting that monetary costs are not the only barriers to adoption. Installing an improved cookstove requires households to modify their kitchen, provide local construction materials, and learn how to use a new technology. More generally, households may differ in their cooking practices, preferences, or perceptions of the stove's benefits. Consequently, a sizable minority of some 40% chooses not to adopt even when the purchase price is zero.

5. The cost of supplying energy-efficient biomass stoves

The second ingredient required to evaluate market formation is the cost of supplying EEBC to rural households. These costs cannot be inferred from observed market transactions because self-sustaining commercial markets for the *Canarumwe* stove had not yet developed. Instead, we exploit the detailed administrative records to estimate the average cost of supplying EEBC at different levels of market penetration.

5.1 Estimating average supply costs

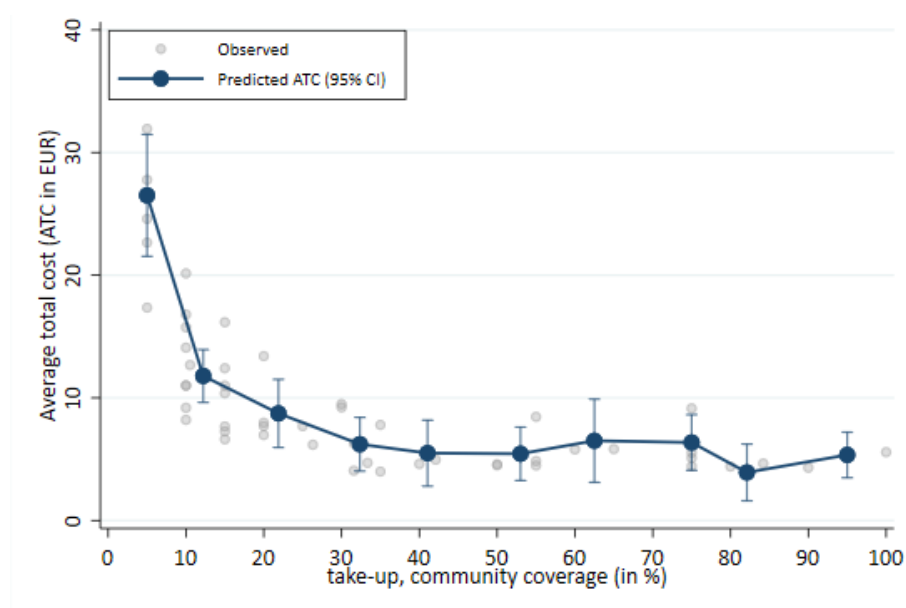
Table 1 summarized the main cost categories observed during implementation of the intervention; costs incurred at the district and community level, and costs varying proportionally with the number of stoves installed. District- and community-level expenditures are fixed once a community is included in the distribution network, so average

supply costs decline rapidly at low adoption rates before gradually approaching the underlying variable cost of supplying an additional stove. To estimate this relationship, we first calculate the total cost of supplying EEBC to each community by combining the district-level, community-level, and household-level expenditures recorded during implementation. Average cost is obtained by dividing total implementation costs by the number of stoves installed in each community. We relate this average cost measure to community-level adoption using flexible functional forms and compare alternative specifications in Appendix Table A4. Because the non-parametric specification provides the best fit to the observed data, we use this specification throughout the remainder of the paper. Results using alternative functional forms are qualitatively similar (see Appendix E).

5.2 Average supply costs

Figure 3 presents the estimated average cost schedule. As expected, average supply costs decline sharply as adoption increases. At low adoption levels, fixed expenditures associated with entering a community are spread over only a small number of households, resulting in high average costs per stove. As market penetration increases, these fixed costs are distributed across more installations, causing average costs to fall rapidly. At higher adoption levels, the curve gradually flattens as average costs become increasingly dominated by hardware and installation costs that vary with the number of stoves supplied.

Figure 3: The economics of supplying cookstoves

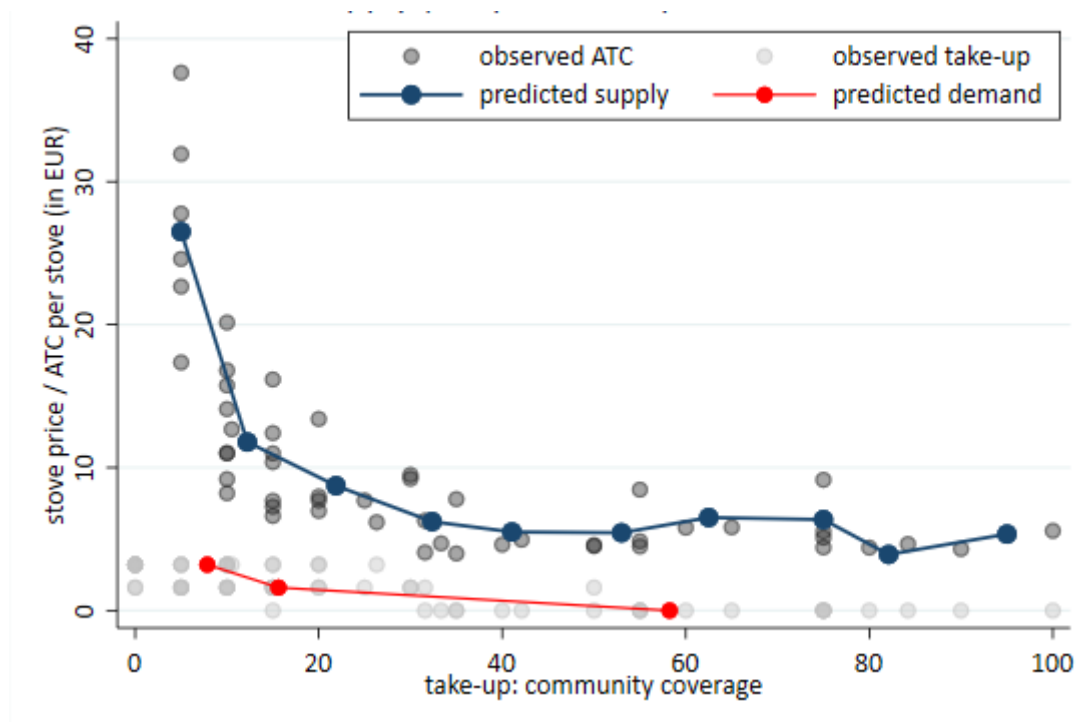


The estimated schedule captures the economies of scale associated with rural distribution. Importantly, these economies arise even though the physical stove itself is inexpensive. Relative to technologies such as rural electrification, improved biomass cookstoves require only modest hardware investments. Nevertheless, the logistical costs of reaching dispersed rural households generate substantial scale economies that may influence whether decentralized markets emerge.

6. Market formation

Figure 4 overlays the estimated willingness-to-pay and average-cost schedules, providing the empirical counterpart to Figure 1. If willingness to pay exceeds average costs at sufficiently high adoption rates, market formation requires only overcoming an initial coordination problem. Our data suggest otherwise. Although average costs decline substantially with adoption, they remain above willingness to pay throughout the observed range. This result is robust to alternative functional forms and to measuring adoption by the number of stoves sold rather than the share of households adopting (Appendices C–E). Under prevailing conditions, decentralized markets are therefore unlikely to sustain widespread EEBC diffusion in rural Rwanda, as suppliers cannot recover their fixed costs. Sustained subsidies would be needed to bridge the gap between willingness to pay and average costs.

Figure 4: Supply of and demand for stoves



The gap between average supply costs and willingness to pay varies from approximately 20-25 EUR for adoption shares of 5-10%, to EUR 5-7 for adoption shares of 50-60% (the maximum that can be achieved in this context). If the government or an NGO seeks to promote adoption of the *Canarumwe* stove, per unit costs are minimized if the stove is offered at zero cost to households. An adoption share of 60% can be achieved at a per-unit subsidy of EUR 7 to suppliers (who then offer the stove at zero cost to all interested households), but if stoves are traded at a cost of 2-3 EUR the per-unit subsidy would have to be approximately EUR 20 to achieve an adoption share of 5-10%.

Our main conclusion about fixed costs causing market formation failure is unchanged when we exclude all district-level expenditures, allowing these costs to be fully absorbed through regional economies of scale; community-level promotion and last-mile distribution costs alone remain sufficient to keep average costs above willingness to pay (see Appendix F).

7. Subsidizing improved cooking stoves

The absence of a commercially viable market does not imply that promoting EEBC is socially undesirable. Commercial viability and social desirability are distinct concepts. Households' willingness to pay reflects (a subset of) private benefits under existing market conditions, whereas the social value of EEBC may also include reduced carbon emissions, slower forest degradation, and other benefits that are not fully internalized by individual households. Observed willingness to pay may underestimate true private benefits if households face liquidity constraints or undervalue the opportunity cost of collecting firewood. Liquidity constraints are relatively unimportant in the context of the roll-out of the *Canarumwe* stove, because payments could be made in installments. But we explore whether external benefits or non-internalized private benefits warrant the introduction of a subsidy scheme to make *Canarumwe* stoves available at zero cost. To obtain a conservative estimate of the benefits, we assume that the stove's effective performance declines linearly over four years—from 100% of its initial effectiveness in the first year to 75%, 50% and 25% in subsequent years—reflecting gradual deterioration, imperfect maintenance and partial reversion to traditional cooking practices (see also Hanna et al., 2016). We also assume a 3% discount rate to weigh future gains from adoption.

First consider the carbon benefits associated with reduced biomass consumption. Munyehirwe et al. (2026) estimate that adoption of the Canarumwe stove reduces fuelwood consumption by approximately 3 kg per household per day. Following the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006), we assume that freshly collected fuelwood contains 15% moisture and that dry woody biomass consists of 47% carbon by weight. Since oxidation of one ton of carbon produces 44/12 tonnes of carbon dioxide, the observed reduction in fuelwood consumption corresponds to approximately 1.6 tons of CO₂ emissions during the first year of use if all harvested biomass were non-renewable. This benchmark overstates the climate benefits because part of the harvested fuelwood originates from sustainably managed biomass that is replenished through natural regrowth. Following the accounting methodology adopted by the UNFCCC for improved cookstove projects, we multiply gross emission reductions by the fraction of non-renewable biomass (fNRB). The current UNFCCC default value for Rwanda equals 0.33, implying that approximately one-third of the avoided fuelwood consumption contributes to a permanent reduction in atmospheric carbon dioxide (UNFCCC, 2025). Applying a real social discount rate of 3% yields a discounted lifetime reduction of approximately 1.25 tons of CO₂ per stove.

Dividing the EUR 7 subsidy required per adopted stove by its estimated discounted lifetime emission reduction of 1.25 tons of CO₂ gives a break-even social shadow price of carbon of EUR 5.6 per ton of CO₂. Therefore, if avoided CO₂ is valued above EUR 5.6 per ton, the climate benefits alone exceed the subsidy cost. Recent estimates of the social cost of carbon are generally far above this threshold. A meta-analysis reports recent estimates of approximately US\$40-525 per tCO₂, depending on the discount rate used (Tol, 2023). Although these estimates are highly sensitive to ethical and modelling assumptions, even the lower figure considerably exceeds the break-even value of EUR 5.6 per tCO₂ calculated here.⁴

It is important to keep in mind that this back-of-the-envelope calculation is based on various conservative assumptions. It is likely that the stove lasts longer than 4 years. Munyehirwe et al. (2026) indicate that 60% of the households who purchased a stove were still

⁴ Also recent transaction prices for high-quality cookstove carbon credits in voluntary carbon markets exceed the break-even value as they typically exceed USD 15 per tCO₂e (Abatable, 2025). But of course, selling reduced carbon emissions on the voluntary carbon market requires that the seller has to incur monitoring and verification costs—pushing down net earnings.

using it after 2.5 years. We also ignore methane and nitrous oxide emissions, which are also major greenhouse gases. Furthermore, values for fNRB are highly uncertain since they rely on complex modelling assumptions. Older estimates using different methodologies suggested a fNRB of 0.5 rather than 0.33 for Rwanda (Bailis, 2015)⁵. Under assumptions of a five-year declining benefit stream, a 50% fraction of non-renewable biomass, inclusion of avoided methane and nitrous-oxide emissions,⁶ and a 3% social discount rate, the carbon shadow price required to justify a EUR 7 subsidy is approximately EUR 2.6 per tCO₂e. That is far below both most estimates of the social cost of carbon and recent prices associated with high-quality cookstove credits. Conclusions with respect to welfare are therefore reinforced.

Second, households may not fully internalize the private benefits of adoption. Munyehirwe et al. (2026) estimate that women and girls account for approximately 75% of biomass-collection time in the study area. If household purchasing decisions underweight their time savings, willingness to pay understates the welfare gains from adoption. Only benefits not already reflected in willingness to pay, however, provide an additional rationale for subsidization.

Munyehirwe et al. (2026) estimate that adoption reduces biomass collection by seven hours per month. Using an average rural agricultural wage of RWF 752 per day (NISR et al., 2018)⁷, an eight-hour workday, and valuing time at 60% of the market wage to account for

⁵ The UNFCCC default fNRB does not explicitly account for deadwood as a separate source of household fuelwood supply. This may matter in our setting because a substantial share of collected fuelwood consists of deadwood. To the extent that such deadwood is not related to prior harvesting of live biomass, it substantially reduces pressure on standing biomass. The applicable fNRB for our study households could therefore be lower than the UNFCCC default. The magnitude of this adjustment cannot be inferred mechanically from the observed share of deadwood, however, because it depends on the origin and renewability of the deadwood itself. As a conservative sensitivity exercise, we therefore consider an effective fNRB 50% below the UNFCCC default. Since credited emission reductions are proportional to fNRB, the break-even carbon price would correspondingly double, from EUR 5.6 to approximately EUR 11.2 per tCO₂. This remains well below commonly used estimates of the social cost of carbon, so the qualitative conclusion is unchanged even under this substantially more conservative assumption.

⁶ For methane and nitrous oxide, we use the IPCC residential-combustion defaults for wood: 300 kg CH₄/TJ and 4 kg N₂O/TJ, together with the IPCC net calorific value of 15.6 TJ/Gg for wood. Converted using 100-year global-warming potentials of 28 for CH₄ and 265 for N₂O, the avoided non-CO₂ emissions are approximately: 0.143 tCO₂e from CH₄ and 0.018 tCO₂e from N₂O.

⁷ The 2018 Comprehensive Food Security and Vulnerability Analysis reports an average daily wage of RWF 752 for unskilled rural agricultural labour (range: RWF 500–2,000; NISR et al., 2018). As this is an

limited earning opportunities (Agness et al., 2025), we obtain an hourly value of approximately RWF 56.

This implies annual time savings of RWF 4,725. Assuming benefits decline to 75%, 50%, and 25% of their initial level over the following three years and applying a 3% discount rate yields a lifetime value of RWF 11,139 (EUR 14.32) per stove. A EUR 7 subsidy is therefore justified by time savings alone if at least 49% of their value is excluded from willingness to pay. Given that women and girls account for 75% of collection time, this threshold is met if household purchasing decisions omit at least 65% of their time benefits, even when men's and boys' benefits are fully internalized. This is a threshold calculation, not evidence that such an intra-household wedge exists. If all time savings are already reflected in willingness to pay, they provide no additional rationale for subsidization.

Under conservative assumptions, the environmental benefits associated with reduced carbon emissions are sufficient to justify a subsidy that bridges the approximately EUR 7 gap between households' willingness to pay and average supply costs at the highest observed adoption rate. Time savings provide an additional potential justification, but would warrant this subsidy on their own only if approximately 49% of their estimated value is not reflected in households' willingness to pay.

8. Discussion and Conclusion

This paper examined whether decentralized markets can sustain the diffusion of improved biomass cookstoves in rural Rwanda. Combining experimentally estimated willingness to pay with administrative supply-cost data, we assessed whether commercial suppliers can profitably serve dispersed rural communities.

Our findings suggest they cannot. Although households value EEBC and demand responds strongly to price, average supply costs exceed willingness to pay throughout the observed adoption range. High fixed costs for promotion, transport, installer training, and

average rather than a peak-season wage, we use RWF 750 as a benchmark for year-round earning opportunities.

distribution prevent markets from becoming self-sustaining. The main barrier to diffusion is therefore not a temporary coordination problem, but the persistent costs of serving rural communities. Our analysis abstracts from dynamic reductions in supply costs that may arise as markets mature. Experience, learning-by-doing, or larger production volumes could reduce some upstream costs associated with manufacturing, training, or logistics. Such effects would shift the average-cost schedule downward and increase the scope for market formation. A simple robustness analysis suggests that dropping district-level costs from the analysis does not materially alter the conclusions. Moreover, many costs arise at the community level and must be incurred whenever suppliers enter new markets. These costs are unlikely to disappear as national production expands.

These findings have important implications for public policy. Whether markets emerge and whether governments should intervene are distinct questions. Commercial viability depends on whether suppliers can recover their costs, whereas the desirability of public intervention depends on the broader social benefits generated by adoption, including environmental externalities, intra-household welfare gains, and the extent to which liquidity constraints or other frictions depress households' willingness to pay. The absence of a commercially viable market should not be interpreted as evidence that promoting EEBC is socially inefficient. In fact, some simple back-of-the-envelope calculations suggest that for the case of improved cooking stoves in Rwanda, subsidizing the full gap between willingness to pay and average supply costs is justified by reduced carbon emissions alone. Non-internalized time-savings for women responsible for fuelwood collection provide an additional potential justification, but would warrant this subsidy independently only if approximately 65% of their estimated value is not reflected in households' willingness to pay.

More broadly, the paper contributes to a growing literature emphasizing the role of fixed costs in shaping market formation in developing countries. While previous work has documented similar mechanisms for rural electrification, agricultural markets, collective action, and quality certification, our results suggest that they are equally relevant for relatively inexpensive household technologies such as EEBC. Understanding why markets do—or do not—emerge is an essential complement to understanding why households adopt new technologies. Market formation and policy evaluation should therefore be viewed as separate, though closely related, questions when designing interventions to promote welfare-enhancing

technologies in low-income economies. Understanding technology adoption requires understanding household demand; understanding technology diffusion requires understanding market formation. The approach developed here could be applied to a wide range of technologies characterized by substantial fixed supply costs.

Appendix

Appendix A: Balance test

Table A1: Randomization balance on household and community level

Variable	mean	subsidy			t-test, p-value					
	control	no	med	full	(1)-(2)	(1)-(3)	(1)-(4)	(2)-(3)	(2)-(4)	(3)-(4)
Households characteristics										
household has separate kitchen	0.79	0.79	0.83	0.81	0.924	0.453	0.662	0.321	0.531	0.707
hoh education >= alphabetization	0.58	0.62	0.55	0.56	0.306	0.588	0.718	0.128	0.145	0.821
=1 head of household is female	0.26	0.29	0.27	0.25	0.470	0.876	0.656	0.561	0.280	0.556
age of head of household	48.35	47.73	48.81	49.43	0.639	0.686	0.408	0.314	0.174	0.556
#hh members	4.97	4.91	4.80	5.14	0.722	0.287	0.283	0.522	0.181	0.038**
=1 high quality walls	0.43	0.45	0.43	0.42	0.825	0.995	0.951	0.828	0.772	0.958
=1 high quality soil	0.11	0.11	0.16	0.16	0.977	0.341	0.223	0.329	0.187	0.903
household owns cows	0.46	0.43	0.34	0.45	0.745	0.127	0.922	0.183	0.832	0.166
household owns goats and/or sheep	0.35	0.37	0.37	0.44	0.619	0.564	0.063*	0.956	0.170	0.175
household owns pigs	0.15	0.16	0.16	0.20	0.942	0.904	0.401	0.963	0.436	0.448
USD-monthly overall non-energy HH expenditures	46.68	47.45	48.45	44.39	0.858	0.784	0.589	0.872	0.423	0.510
household saves money	0.58	0.63	0.67	0.59	0.310	0.078*	0.937	0.351	0.347	0.089*
N	422	418	418	414						
Community characteristics										
distance to the main road in km	16.79	20.76	19.43	20.86	0.502	0.582	0.410	0.824	0.988	0.777
access road to community is dirt road	0.48	0.48	0.52	0.86	1.000	0.765	0.008***	0.765	0.008***	0.019**
installer participated in earlier stove campaigns	n/a	0.10	0.19	0.14				0.390	0.644	0.688
access to public transport easy or very easy	0.29	0.38	0.48	0.38	0.524	0.213	0.524	0.544	1.000	0.544
mobile phone network is good	0.57	0.52	0.52	0.71	0.764	0.764	0.346	1.000	0.213	0.213
cell bureau in community	0.24	0.05	0.19	0.10	0.081*	0.715	0.224	0.160	0.560	0.390
any type of school in community	0.14	0.10	0.24	0.14	0.644	0.444	1.000	0.224	0.644	0.444
any type of health infrastructure in community	0.10	0.00	0.00	0.05	0.154	0.154	0.560	N/A	0.323	0.323
access to national electricity grid in community	0.43	0.29	0.33	0.43	0.346	0.537	1.000	0.746	0.346	0.537
number of inhabitants in community	1319	668	739	754	0.233	0.297	0.305	0.564	0.382	0.924
number of households in community	178	148	178	163	0.331	0.994	0.669	0.149	0.484	0.581
N	21	21	21	21						

Note: The value displayed for t-tests are p-values. Standard errors are clustered at the community level. ***, **, and * indicate significance at the 1, 5, and 10 percent critical level. High quality walls= wall material is better than wood or clay/mud; high quality soil= soil material is better than earth; HH saves money= household saves money formally or informally; Hoh edu >= alphabetization=Hoh visited at least alphabetization courses; #Hh members= number of household members including children

Appendix B: Regression results for the willingness to pay schedule

Table A2: Adoption by subsidy level

VARIABLES	(1) percentage of HH in community with EEBC
treat = 1, no subsidy	7.901*** (0.002)
treat = 2, medium subsidy	15.669*** (0.000)
treat = 3, high subsidy	58.286*** (0.000)
distance to the main road in km	0.003 (0.982)
installer participated in earlier stove campaigns	5.575 (0.340)
access to public transport easy or very easy	-2.905 (0.496)
mobile phone network is good	-0.266 (0.934)
cell bureau in community	0.090 (0.982)
any type of school in community	-0.706 (0.874)
any type of health infrastructure in community	7.839* (0.089)
access to national electricity grid in community	-1.815 (0.664)
Constant	1.050 (0.739)
Observations	84
R-squared	0.760

Note: Robust p-values in parentheses; *** p<0.01, ** p<0.05, * p<0.1.

Appendix C: Regression results for the supply curve

We assess robustness to potential endogeneity by instrumenting community coverage with the randomized stove price. The OLS and IV estimates are similar (−0.17 and −0.20, respectively; both $p < 0.001$; Table A3, columns 1 and 2), supporting the robustness of the estimated negative relationship between adoption and average supply costs. We therefore report OLS as the main specification, consistent with Lee, Miguel and Wolfram (2020). The same patterns hold if we use the number of stoves sold per community as our measure of stove adoption (Column 3 and 4).

Table A3: OLS vs. IV estimates

VARIABLES	(1) ATC adoption OLS	on (2) ATC adoption IV	on (3) ATC adoption OLS	on (4) ATC adoption IV
share	-0.173*** (0.000)	-0.202*** (0.000)		
stoves			-0.127*** (0.000)	-0.149*** (0.000)
Community controls	Yes	Yes	Yes	Yes
Constant	18.441*** (0.000)	19.192*** (0.000)	17.365*** (0.000)	17.972*** (0.000)
Observations	53	53	53	53
R-squared	0.454	0.445	0.489	0.479

Note: Robust p-values in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Share = Share of households in a community that adopted a stove; stoves=number of households in a community adopting a stove. The IV estimation instruments community coverage with the randomized price level. Communities with zero stove uptake are eliminated from the estimation (no subsidy communities: N=8, medium subsidy: N=2).

Second, we test which functional form of the supply curve best fits the empirical patterns in our data. We use a linear function (Table A4 - Column 1 and 5), a non-linear function introducing a squared adoption term (Column 2 and 6), a quadratic function only using the squared adoption term (Column 3 and 7), and a non-parametric specification where we convert the continuous adoption indicators into several bins and regress the ATC on these bins (Columns 4 and 8). As indicated by the R2, the non-parametric form gives the best fit.

Table A4: Comparing different functional forms of supply curve

VARIABLES	(1) OLS: ATC on coverage	(2) OLS: ATC on coverage	(3) OLS: ATC on coverage	(4) OLS: ATC on coverage	(5) OLS: ATC on coverage	(6) OLS: ATC on coverage	(7) OLS: ATC on coverage	(8) OLS: ATC on coverage
Share	-0.173*** (0.000)	-0.664*** (0.000)						
Share sq.		0.005*** (0.000)	-0.001*** (0.000)					
Stoves					-0.127*** (0.000)	-0.404*** (0.000)		
Stoves sq.						0.002*** (0.000)	-0.001*** (0.000)	
Share bin1				-14.718*** (0.000)				-13.462*** (0.000)
Share bin2				-17.772*** (0.000)				-18.877*** (0.000)
Share bin3				-20.284*** (0.000)				-21.204*** (0.000)
Share bin4				-21.010*** (0.000)				-21.194*** (0.000)
Share bin5				-21.065*** (0.000)				-22.849*** (0.000)
Share bin6				-20.000*** (0.000)				-23.047*** (0.000)
Share bin7				-20.143*** (0.000)				-24.044*** (0.000)
Share bin8				-22.587*** (0.000)				-24.362*** (0.000)
Share bin9				-21.159*** (0.000)				-23.570*** (0.000)
Share bin10								-24.200*** (0.000)
Share bin11								-23.026*** (0.000)
Share bin15								-24.449*** (0.000)
Community controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	18.441*** (0.000)	23.713*** (0.000)	15.851*** (0.000)	28.006*** (0.000)	17.365*** (0.000)	22.272*** (0.000)	14.720*** (0.000)	29.183*** (0.000)
Observations	53	53	53	53	53	53	53	53
R-squared	0.454	0.644	0.320	0.845	0.489	0.674	0.321	0.933

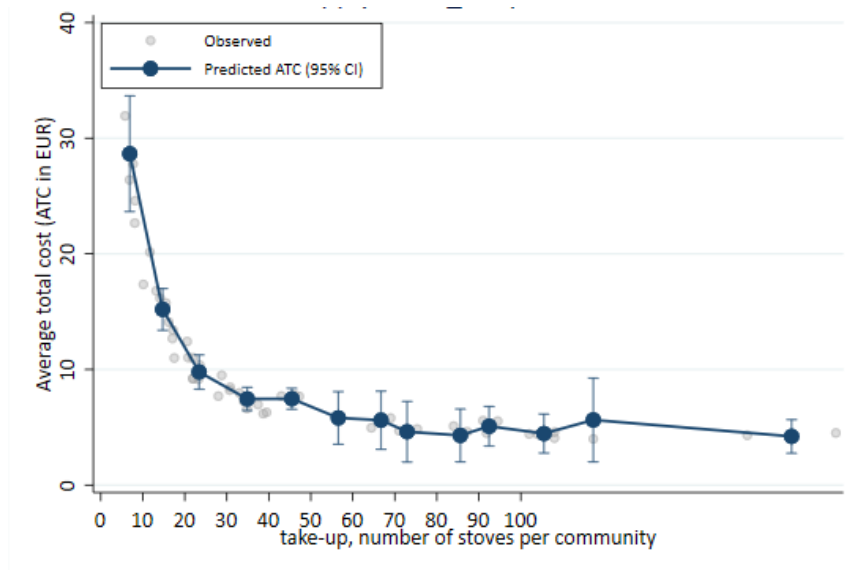
Note: *Share* = Share of households in a community that adopted a stove; *stoves*=number of households in a community adopting a stove. *Share bin** = Community coverage is grouped into ten percentage-point/stove bins (0–10, 10–20, ..., 90–100). The lowest bin (0–10) serves as the reference category. The regression includes community-level controls and is estimated using OLS with heteroskedasticity-robust standard errors. Communities with zero stove uptake are eliminated from the estimation (no subsidy communities: N=8, medium subsidy: N=2).

Appendix D: Sensitivity to take-up definition

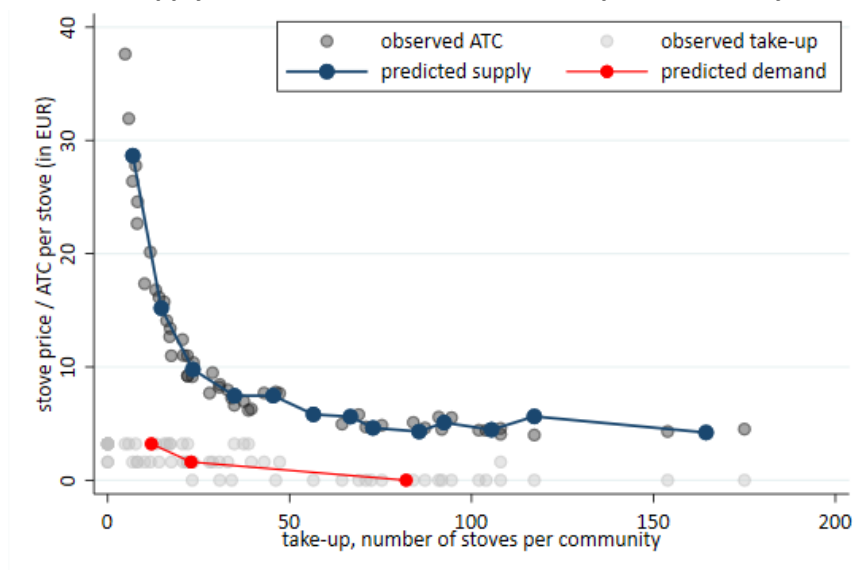
We test if defining community-level adoption differently changes our conclusions. Figure A1 illustrates that using the number of stoves per community as the proxy of community-level adoption, instead of the share of HHs adopting per community, does not alter our conclusions. Supply and demand do not meet at any adoption level.

Figure A1: Take-up defined as number of stoves per community

Panel A – number of stoves per community - nonparametric



Panel B – supply and demand, number of stoves per community

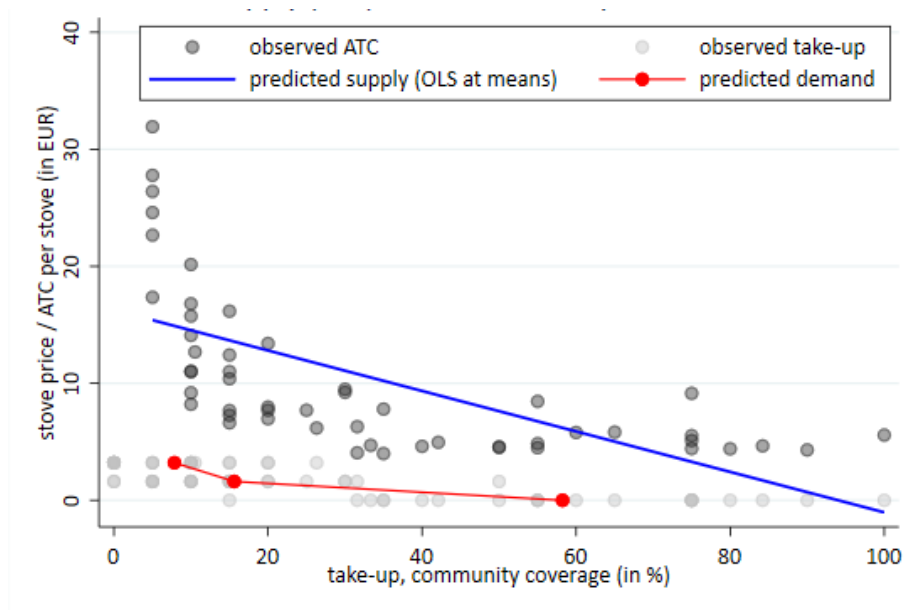


Appendix E: Sensitivity to functional form of supply-curve

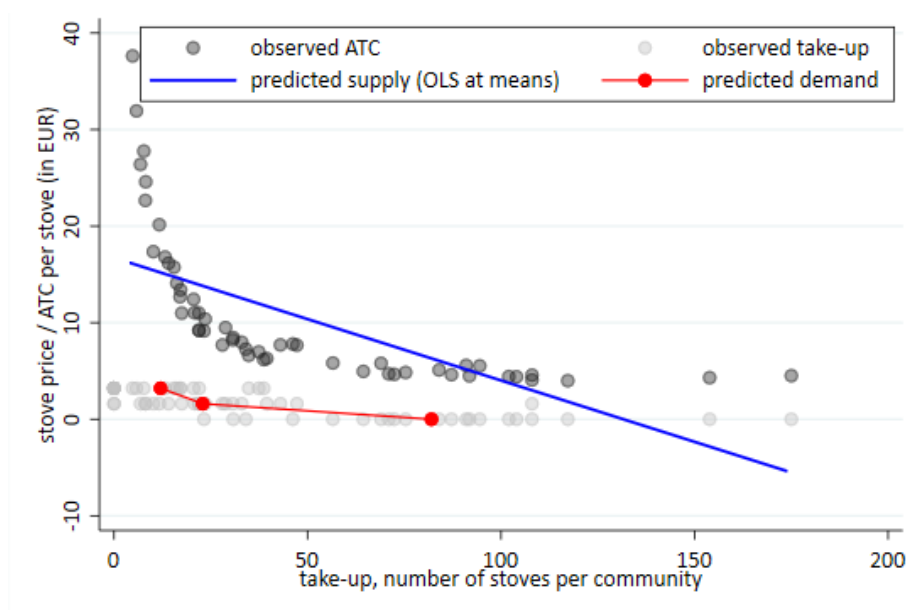
We test if choosing different functional forms of the supply-curve changes our conclusions. Figure A2 illustrates that using a linear supply curve does not alter our conclusions. Supply and demand do not meet at any adoption level.

Figure A2: Linear supply curve

Panel A – supply and demand, community coverage



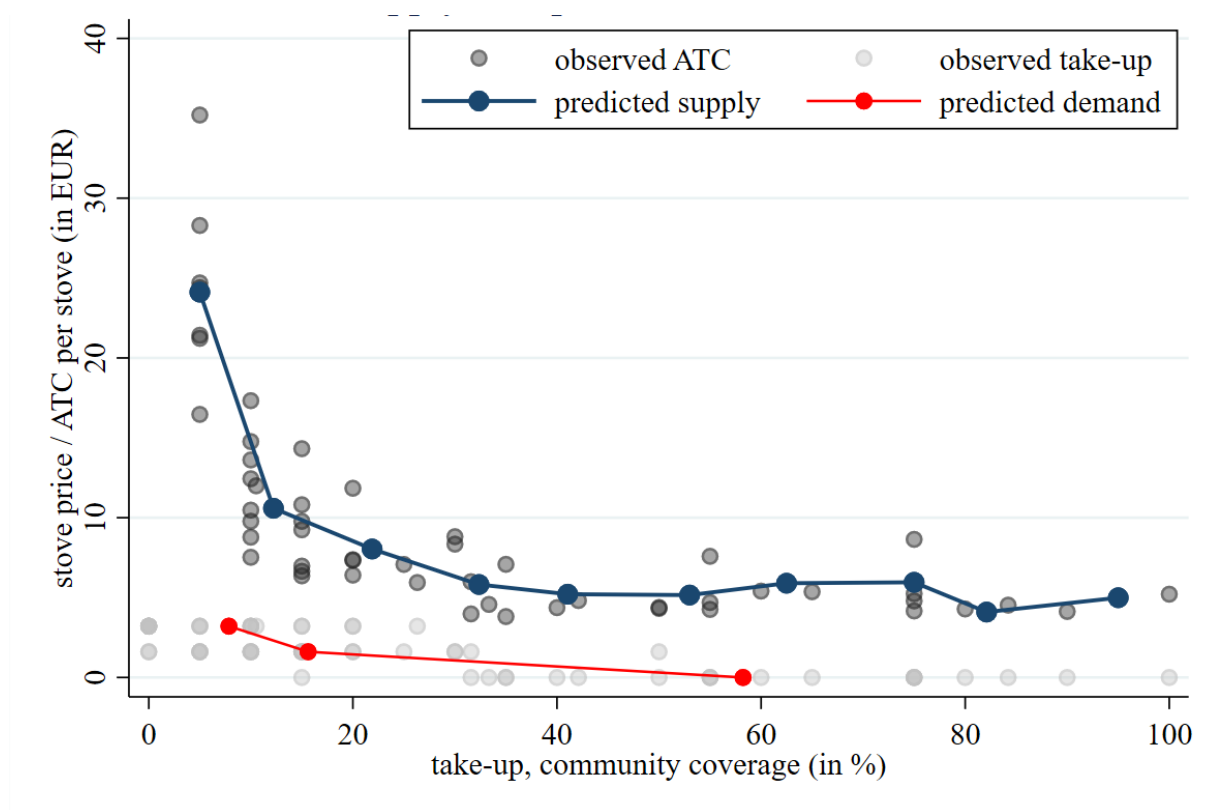
Panel B – supply and demand, number of stoves per community



Appendix F: Supply and Demand for Stoves without district-level supply costs

In order to approximate potential dynamic effects at higher levels of regional or national stove penetration, we re-estimate the ATC per stove without any district-level costs, allowing these to be fully offset by economies of scale. This shifts the average-cost curve downward but does not materially alter the conclusions. Community-level promotion and last-mile distribution costs alone remain sufficient to keep average costs above the willingness to pay.

Figure A3: Supply and Demand for Stoves without district-level supply costs



References:

- Abatable, 2025. A new era for high-quality carbon avoidance: The new floor price for cookstove carbon credits. *Abatable Insights*, 14 May 2025. Available at: <https://abatable.com/blog/a-new-era-for-high-quality-carbon-avoidance-the-new-floor-price-for-cookstove-carbon-credits> (accessed 3 October 2026).
- Agness, D., T. Baseler, S. Chassang, P. Dupas, and E. Snowberg, 2025. Valuing the time of the self-employed. *The Review of Economic Studies* 92(6): 3471–3503. DOI: 10.1093/restud/rdaf003.
- Alem, Y., 2026. Clean cooking in the Global South: A critical synthesis of causal evidence and a future research agenda. *South African Journal of Economics* 94(4): e70037. DOI: 10.1111/saje.70037.
- Anissa, B. P., G. T. Abate, T. Bernard, and E. Bulte, 2021. Is the local wheat market a “market for lemons”? Certifying the supply of individual wheat farmers in Ethiopia. *European Review of Agricultural Economics* 48(5): 1162–1186.
- Atkin, D., and D. Donaldson, 2015. Who’s getting globalized? The size and implications of intra-national trade costs. NBER Working Paper No. 21439.
- Bailis, R., R. Drigo, A. Ghilardi, and O. Masera, 2015. The carbon footprint of traditional woodfuels. *Nature Climate Change* 5(3): 266–272. DOI: 10.1038/nclimate2491.
- Bassi, V., R. Muoio, T. Porzio, R. Sen, and E. Tugume, 2022. Achieving scale collectively. *Econometrica* 90(6): 2937–2978.
- Bensch, G., M. Jeuland, and J. Peters, 2021. Efficient biomass cooking in Africa for climate change mitigation and development. *One Earth* 4(6): 879–890. DOI: 10.1016/j.oneear.2021.05.015.
- Bensch, G., and J. Peters, 2015. The intensive margin of technology adoption: Experimental evidence on improved cooking stoves in rural Senegal. *Journal of Health Economics* 42: 44–63. DOI: 10.1016/j.jhealeco.2015.03.006.
- Bensch, G., and J. Peters, 2020. One-off subsidies and long-run adoption: Experimental evidence on improved cooking stoves in Senegal. *American Journal of Agricultural Economics* 102(1): 72–90. DOI: 10.1093/ajae/aaz023.

- Bensch, G., M. Grimm, and J. Peters, 2015. Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso. *Journal of Economic Behavior & Organization* 116: 187–205.
- Berkouwer, S., and J. Dean, 2022. Credit, attention, and externalities in the adoption of energy efficient technologies. *American Economic Review* 112(10): 3291–3330.
- Berkouwer, S., and J. Dean, 2026. Cooking, health, and daily exposure to pollution spikes. *American Economic Journal: Economic Policy* 18(2): 511–547.
- Bluffstone, R., A. Beyene, Z. Gebreegziabher, P. Martinsson, A. Mekonnen, and M. Toman, 2022. Experience and learning with improved technologies: Evidence from improved biomass cookstoves in Ethiopia. *Environmental & Resource Economics* 81: 271–285.
- Brooks, N., V. Bhojvaid, M. Jeuland, J. Lewis, O. Patange, and S. Pattanayak, 2016. How much do alternative cookstoves reduce biomass fuel use? Evidence from North India. *Resource and Energy Economics* 43: 153–171.
- Do Nascimento Miguel, J., E. Sadoulet, E. Bulte, and T. Bernard, 2026. Buyers’ response to third-party quality certification: Theory and evidence from Ethiopian wheat traders. *American Journal of Agricultural Economics*, in press.
- Foster, A., and M. Rosenzweig, 2022. Are there too many farms in the world? Labor market transaction costs, machine capacities, and optimal farm size. *Journal of Political Economy* 130(3): 636–680. DOI: 10.1086/717890.
- Gebreegziabher, Z., A. D. Beyene, R. Bluffstone, P. Martinsson, A. Mekonnen, and M. A. Toman, 2018. Fuel savings, cooking time and user satisfaction with improved biomass cookstoves: Evidence from controlled cooking tests in Ethiopia. *Resource and Energy Economics* 52: 173–185.
- Grant, M., and M. Startz, 2022. Cutting out the middleman: The structure of chains of intermediation. NBER Working Paper No. 30109.
- Hanna, R., E. Duflo, and M. Greenstone, 2016. Up in smoke: The influence of household behavior on the long-run impact of improved cooking stoves. *American Economic Journal: Economic Policy* 8(1): 80–114. DOI: 10.1257/pol.20140008.

- IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Hayama, Japan: Institute for Global Environmental Strategies.
- Jeuland, M. A., and S. K. Pattanayak, 2012. Benefits and costs of energy-efficient biomass stoves: Assessing the implications of variability in health, forest and climate impacts. *PLoS ONE* 7(2): e30338. DOI: 10.1371/journal.pone.0030338.
- Krishnapriya, P., M. Jeuland, J. Orgill-Meyer, and S. Pattanayak, 2024. Gendered demand for environmental health technologies: Evidence of complementarities from stove auctions in India. *Journal of Behavioral and Experimental Economics* 113: 102295.
- Lee, K., E. Miguel, and C. Wolfram, 2020. Experimental evidence on the economics of rural electrification. *Journal of Political Economy* 128(4): 1523–1565. DOI: 10.1086/705417.
- Levine, D. I., T. Beltramo, G. Blalock, C. Cotterman, and A. M. Simons, 2018. What impedes efficient adoption of products? Evidence from randomized sales offers for fuel-efficient cookstoves in Uganda. *Journal of the European Economic Association* 16(6): 1850–1880.
- Mekonnen, A., A. Beyene, R. Bluffstone, Z. Gebreegziabher, P. Martinsson, M. Toman, and F. Vieider, 2022. Do improved biomass cookstoves reduce fuelwood consumption and carbon emissions? Evidence from a field experiment in rural Ethiopia. *Ecological Economics* 198: 107467.
- Miller, G., and A. Mushfiq Mobarak, 2013. Gender differences in preferences, intra-household externalities, and low demand for energy-efficient biomass stoves. NBER Working Paper No. 18964. DOI: 10.3386/w18964.
- Mobarak, A. M., P. Dwivedi, R. Bailis, L. Hildemann, and G. Miller, 2012. Low demand for nontraditional cookstove technologies. *Proceedings of the National Academy of Sciences* 109(27): 10815–10820. DOI: 10.1073/pnas.1115571109.
- Mortimer, K., C. B. Ndamala, A. W. Naunje, J. Malava, C. Katundu, W. Weston, et al., 2017. A cleaner burning biomass-fuelled cookstove intervention to prevent pneumonia in children under 5 years old in rural Malawi (the Cooking and Pneumonia Study): A cluster randomised controlled trial. *The Lancet* 389(10065): 167–175.

- Munyehirwe, A., J. Ankel-Peters, M. Sievert, E. Bulte, and N. Fiala, 2026. Energy efficiency and local macro rebound effects: Theory and experimental evidence from Rwanda. *The World Bank Economic Review* 40(2): 375–395. DOI: 10.1093/wber/lhaf014.
- National Institute of Statistics of Rwanda (NISR), Ministry of Agriculture and Animal Resources (MINAGRI), and World Food Programme (WFP), 2018. *Rwanda Comprehensive Food Security and Vulnerability Analysis 2018*. Kigali: NISR.
- Pattanayak, S. K., M. Jeuland, J. J. Lewis, F. Usmani, N. Brooks, V. Bhojvaid, A. Kar, L. Lipinski, L. Morrison, O. Patange, and N. Ramanathan, 2019. Experimental evidence on promotion of electric and improved biomass cookstoves. *Proceedings of the National Academy of Sciences* 116(27): 13282–13287. DOI: 10.1073/pnas.1808827116.
- Sievert, M., J. Ankel-Peters, M. Jeuland, L. Lenz, O. Ndiaye, and F. Usmani, 2024. Supply-side constraints to technology adoption: The market for energy-efficient cookstoves in rural Senegal. *Ruhr Economic Papers* No. 1092. DOI: 10.4419/96973269.
- Tol, R. S. J., 2023. Social cost of carbon estimates have increased over time. *Nature Climate Change* 13(6): 532–536. DOI: 10.1038/s41558-023-01680-x.
- UNFCCC, 2025. *Methodological Tool: Default Values for Common Parameters (TOOL33)*. Version 3.0. Bonn: United Nations Framework Convention on Climate Change. Available at: <https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-33-v3.pdf>