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Cleaner Cooking, Persistent Firewood: Household Fuel Transition, Stacking and Avoided Emissions in Honduras, 2013–2025

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Abstract

Household firewood combustion is a major source of air pollution, greenhouse gases and forest pressure in Central America. We examine the clean cooking transition in Honduras using twelve rounds of the national household survey (2013–2025; 72,447 households). We model the primary cooking fuel, decompose the decline in firewood use, analyze directly measured fuel stacking, test the role of the real price of liquefied petroleum gas (LPG) and quantify firewood demand and emissions. The share of households cooking primarily with firewood fell from 55.6% in 2013 to 37.7% in 2025. Urban residence (−36.0 percentage points), grid electricity (−24.2 points) and income were the strongest correlates of lower firewood use. Changes in household characteristics explain only 19.6% of the 16.2-point decline since 2017. Between 13% and 16% of households stacked fuels, devoting 54–58% of their cooking time to biomass stoves. The real LPG price moved almost in parallel with the time trend, and no robust price association was found. Relative to a counterfactual with the 2017 fuel–stove mix, the transition avoided about 1.9 Mt of firewood and 1.0 Mt CO_2e (net of LPG) in 2025 (1.6–2.2 Mt of firewood under alternative assumptions). Addressing persistent stacking and rural access can consolidate these gains.

Keywords: household air pollution; clean cooking; fuel stacking; firewood; LPG subsidy; energy transition; greenhouse gas emissions; decomposition analysis; Honduras; SDG 7

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1. Introduction

Billions of people still cook with polluting fuels and technologies, and household air pollution from solid fuels remains one of the leading environmental risk factors for disease worldwide [1,2]. Residential woodfuel use also has environmental consequences. Where harvesting exceeds regrowth, it contributes to forest degradation and net carbon dioxide emissions, and incomplete combustion releases methane, nitrous oxide, carbon

monoxide and fine particles, including short-lived climate forcers such as black carbon [3–5]. Field measurements in Honduras have documented high particle emission factors from traditional wood-burning stoves [6]. Randomized trials in neighbouring Guatemala and elsewhere show that cleaner cooking reduces exposure, although near-exclusive LPG use did not improve birth weight in a recent multi-country trial [7].

Honduras is one of the most firewood-dependent countries in Latin America. National assessments estimate that more than one million households cook with biomass and that over 200,000 improved stoves have been disseminated in the last two decades [8]. Regional projections suggest that, without additional policies, a large share of rural households will remain unable to afford clean cooking by 2030 [9]. The country has also implemented one of the most visible LPG price interventions in the region. Since February 2022, the retail price of the 25-lb (11.3 kg) LPG cylinder has been frozen by executive decree, and the government absorbs the difference from the import-parity price [10,11]. At the macroeconomic level, recent assessments find that the relationship between growth and CO_2 emissions in Honduras is not driven by the expansion of renewable energy [12], and that decoupling across Central America is associated with the electricity generation mix rather than with income growth itself [13]. Because national CO_2 statistics usually exclude biomass combustion, residential firewood use remains a largely unexamined component of the country's emissions and low-carbon development agenda.

Two strands of literature frame the analysis, reviewed in detail in Section 2. The energy ladder model predicts that households move from solid fuels to modern fuels as incomes rise. The fuel stacking view, in contrast, emphasizes that households add new fuels and devices without abandoning traditional ones [14–16]. Throughout this article, fuel stacking refers to the combined use of biomass and clean (LPG or electric) stoves by the same household. A growing body of evidence shows that stacking is the norm rather than the exception, and that the persistence of traditional stoves can erode the environmental and health gains of clean fuel adoption [17,18]. Empirical studies of fuel choice in Latin America identify income, education, urbanization, start-up costs and fuel prices as the main determinants [19–21]. Regional analyses show that LPG subsidies have accelerated the move away from solid fuels, but firewood persists among poorer rural households even where LPG is cheap [22,23].

Despite this literature, three gaps remain for Central America. First, most evidence relies on single cross-sections and cannot separate changes in household characteristics from other changes over time. Second, stacking is rarely measured directly in nationally representative data. Third, studies seldom connect household fuel choices with an explicit accounting of firewood demand and emissions at the national scale. This study addresses these gaps for Honduras using twelve rounds of the national Permanent Multipurpose Household Survey (EPHPM) between 2013 and 2025. We ask five questions: (RQ1) What household and contextual factors explain the choice among firewood, LPG and electricity as the primary cooking fuel? (RQ2) How much of the recent decline in firewood use is explained by changes in household characteristics? (RQ3) How prevalent and intense is fuel stacking, and which households stack? (RQ4) Is the real price of LPG measurably associated with firewood use? (RQ5) What are the implications of the observed transition for national firewood demand and emissions?

The study contributes new results, not only new data. First, it shows that changes in household characteristics, the drivers emphasized by the energy ladder model, explain only about one fifth of the decline in firewood use since 2017; most of the transition reflects changes in how households with given characteristics choose fuels or factors outside the models. Second, it measures the intensity of stacking in nationally representative data, from cooking hours by stove type, which is rare in the literature (Section 2.1); stacking

households still devote more than half of their cooking time to biomass stoves, and their profile differs from that of exclusive biomass users. Third, it shows that a uniform national LPG price that moves almost in parallel with the time trend cannot identify a price effect, a methodological lesson for evaluations of generalized subsidies. Fourth, it links measured stove portfolios, rather than the primary fuel alone, to a counterfactual accounting of firewood, greenhouse gas and $PM_{2.5}$ emissions with explicit uncertainty and sensitivity analysis. Together, these steps offer a replicable approach to assessing household energy transitions with routine household surveys: harmonize repeated rounds, separate composition from other changes, measure stacking directly and translate observed stove portfolios into environmental outcomes.

Figure 1 summarizes the conceptual framework. Household characteristics and the context in which households live, including access to electricity and the price of LPG, shape the cooking portfolio: the primary fuel, the stove used and the extent to which traditional and clean stoves are combined. The portfolio in turn determines firewood demand and household exposure, and through them the environmental and health outcomes of residential cooking. Each research question addresses one link of this chain.

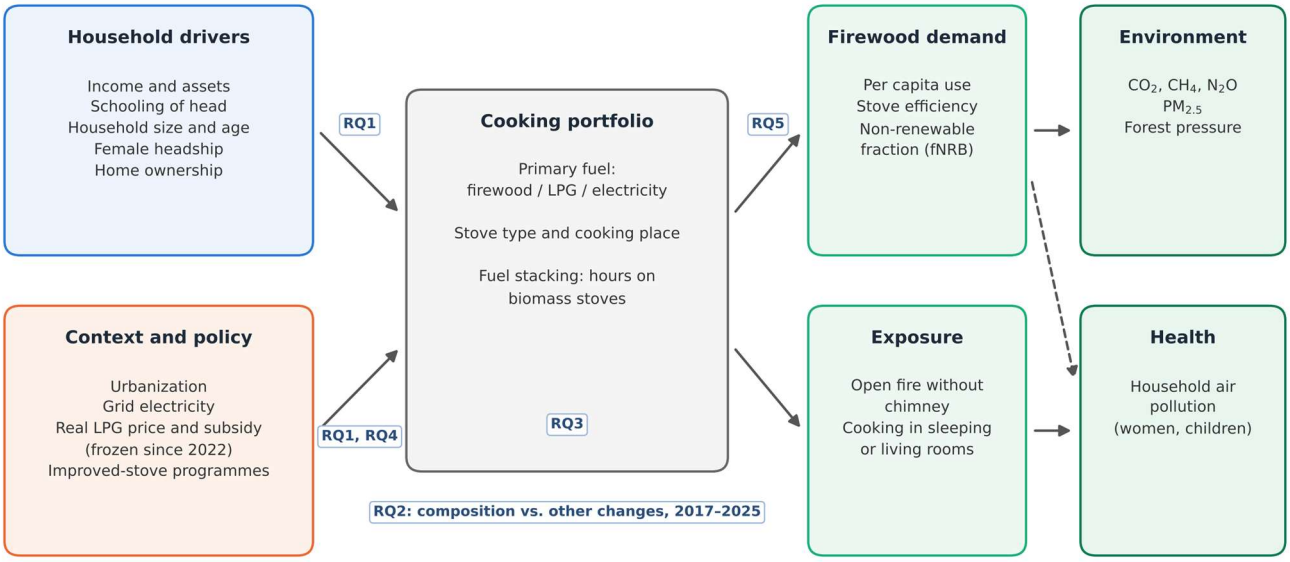


Figure 1. Conceptual framework of the study and research questions (RQ1–RQ5). The dashed arrow indicates that fine particles emitted by firewood combustion also affect health through ambient air pollution.

2. State of the Art

To position the study, we reviewed the literature indexed in Scopus with four search blocks applied to titles, abstracts and keywords: (i) household energy transitions, the energy ladder and fuel stacking; (ii) cooking fuels in Latin America and the Caribbean; (iii) LPG prices, subsidies and access programs; and (iv) the environmental impacts of residential biomass use. The searches were run on 8 October 2026 and restricted to articles and reviews in English published from 2010 onwards; the complete search strings are given in Table S2. We restricted the search to Scopus and to English to obtain consistent metadata for the bibliometric maps. This choice under-represents Spanish-language journals, regional databases such as SciELO and Redalyc, and reports of regional agencies, so the scarcity of Central American records reflects coverage as well as research effort. We therefore use the corpus to map the international literature and complement it with regional studies and reports in Sections 2.2–2.4 [8,9,24]. After removing duplicates by DOI and title, the corpus contains 1864 records (1743 articles and 121 reviews) from 613 sources, led by Energy for

Sustainable Development (131 records), Energy Policy (69) and Renewable and Sustainable Energy Reviews (38). Output has grown steadily, from 19 records in 2010 and 57 in 2016 to 203 in 2024, and 79% of the corpus has been published since 2018 (Figure 2). Studies focused on Latin America and the Caribbean remain scarce, with at most 12 records per year.

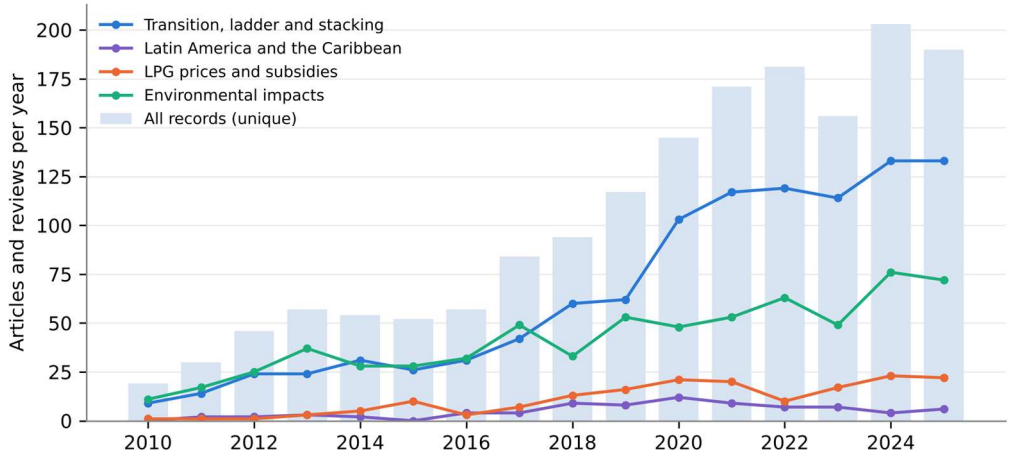


Figure 2. Articles and reviews per year in the Scopus corpus, 2010–2025, by search block. Bars show unique records after removing duplicates across blocks; a record can belong to more than one block. The 205 records published by October 2026 and three in-press records dated 2027 are excluded from the figure.

Figure 3 shows the keyword co-occurrence network of the full corpus built with VOSviewer (version 1.6.21) [25], retaining keywords with at least 15 occurrences after merging synonyms and removing generic indexing terms and country names with a thesaurus file. Three main clusters emerge. The first and largest (red) links firewood, LPG, charcoal and household energy with energy transition, energy policy, energy access, fuel choice and energy stacking, and with environmental themes such as deforestation, greenhouse gas emissions, climate change and sustainable development. The second (blue) groups combustion, emission factors, emission inventories, particulate matter, black carbon and air quality, and reflects the literature that measures emissions. The third (green) is centred on household air pollution and its health effects, including respiratory disease, pregnancy outcomes, blood pressure and mortality, mostly studied with cross-sectional and cohort designs. The overlay map (Figure 3b) shows that emission factors, emission inventories and fuelwood consumption belong to the older part of the corpus (average publication year around 2018–2019), whereas energy transition, energy stacking, sustainable development and cohort-based health studies are the most recent themes (2021–2022). Within the first cluster, stacking lies at the policy end, away from the greenhouse gas and deforestation nodes: of the 156 records that mention stacking in the title, abstract or keywords, only 18 also quantify greenhouse gas emissions, deforestation or non-renewable biomass.

The bibliometric results shaped the design of the study. The first cluster places fuel choice, energy access and stacking at the centre of the transition literature, which motivates the fuel choice and stacking models (RQ1 and RQ3), and its links with energy policy and LPG motivate the price analysis (RQ4). The separation between stacking and the greenhouse gas and deforestation nodes, with only 18 of 156 stacking records quantifying these outcomes, motivates linking measured stove portfolios to an environmental accounting (RQ5). The second cluster supplies the emission factors and inventory methods used as parameters in that accounting (Section 3.7), and the third, centred on exposure and health, motivates the high-exposure indicator. Finally, the overlay map shows that energy transition

and stacking are the most recent themes of the corpus, which motivates following the transition over time with repeated survey rounds (RQ2).

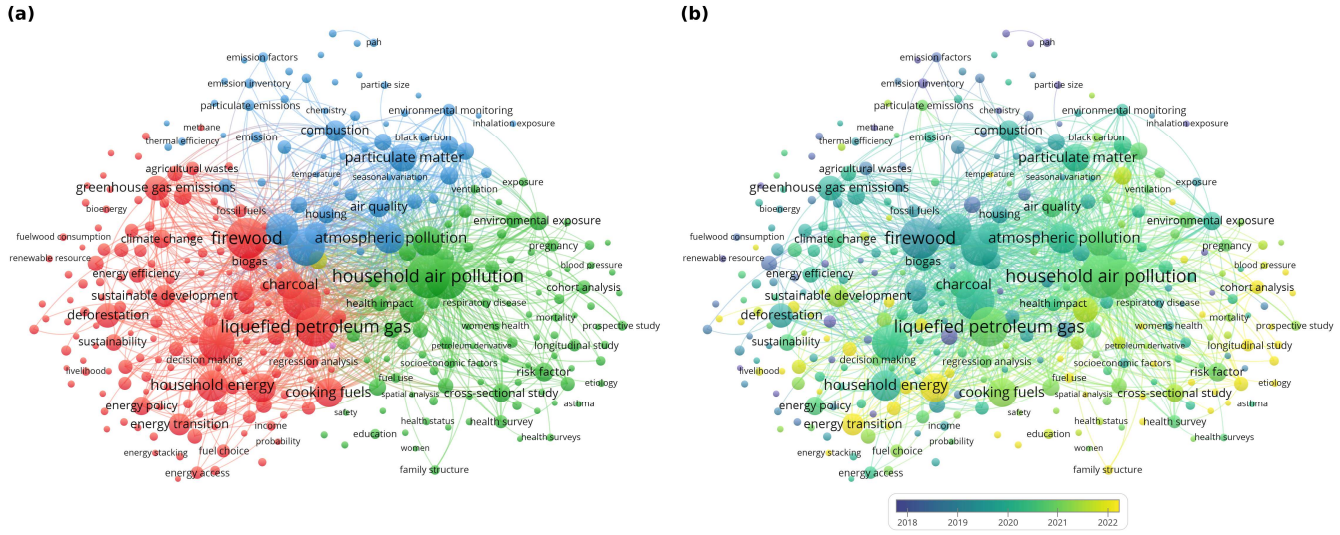


Figure 3. Keyword co-occurrence in the Scopus corpus: (**a**) network map, with colours indicating clusters; (**b**) overlay map, with colours indicating the average publication year of the records using each keyword. Node size is proportional to the number of occurrences and links represent co-occurrence in the same record. Maps produced with VOSviewer [25] using all keywords, full counting, a minimum of 15 occurrences per keyword and a thesaurus that merges synonyms and removes generic indexing terms and country names.

2.1. Energy Ladder and Fuel Stacking

The energy ladder model describes a sequential substitution of traditional biomass by transition fuels and then by LPG, natural gas or electricity as incomes rise. A meta-analysis of household choice models found that socioeconomic characteristics dominate empirical work, while the external decision context—prices, supply and policy—has received much less attention [15]. The fuel stacking model, first articulated for rural Mexico [14], holds instead that households add new fuels without abandoning traditional ones. Evidence from several regions supports stacking as the norm. In India, stacking in cooking increased between 1987 and 2010 because LPG did not replace biomass, and higher income no longer reduced cooking stacking by 2010 [26]. In rural China, the share of households using a single energy type fell from 28% in 1992 to 11% in 2012 [27]. In Mexico, fuelwood use remained almost constant for four decades despite the expansion of LPG, because a large share of rural households combined both fuels on a long-term basis [28]. A systematic review of 92 studies describes adoption and disadoption of fuels and stoves as a dynamic process shaped by technological, socioeconomic, market, institutional and biophysical factors [29].

Stacking also matters for measurement. Indicators based on the primary fuel overstate clean energy use: rural Chinese households used on average 3.4 cooking energy carriers in 2012 [30], and mixed use can add up to 40% to cooking energy demand [27]. Whether stacking erodes the benefits of clean fuels depends on which devices are combined. In controlled cooking cycles in rural Mexico, $PM_{2.5}$ concentrations exceeded the WHO interim target whenever an open fire was part of the combination, but not when an efficient chimney stove was combined with LPG [31]. Most studies, however, measure stacking with small samples, stove-use monitors or self-reported secondary fuels [32]; nationally representative measures of the intensity of stacking, such as the time spent on each stove, remain rare.

2.2. Determinants of Cooking Fuel Choice in Latin America

Reviews of adoption studies identify income, education and urban residence as positive correlates of clean fuel use in most studies, whereas the roles of prices, household size and gender are less clear [19]. Latin American evidence broadly confirms this pattern. In Colombia, multinomial models estimated with living standards surveys for 2010–2016 identify education, income and household type as the main determinants [33]. In Ecuador, the poorest, Indigenous and worse-housed households were the least likely to adopt induction stoves and continued to prefer firewood despite highly subsidized LPG [34]. In Peru, regional dependence on solid fuels is associated with elevation, forest cover, urbanization, poverty and female literacy [35]. Migration and remittances have ambiguous effects: in rural Mexico, sending a migrant to the United States reduced reliance on firewood collection and increased gas purchases [36], whereas in Guatemala firewood remained preferred despite higher incomes because of its cost, experience and cooking methods [37]. A scoping review of 143 publications on rural Latin America concludes that firewood remains resilient and is increasingly stacked with LPG, and that programs focused on single fuels or stoves have not displaced open fires [38]. For Central America, the only regional assessment projected that, without additional policies, 40–50% of rural Guatemalans and Hondurans would still find clean fuels or stoves unaffordable in 2030 [9].

2.3. LPG Prices, Subsidies and Access Programs

Cross-country evidence for Latin America indicates that LPG subsidies have accelerated the transition from solid fuels once socioeconomic development and urbanization are controlled for [22], and Brazil's long-run replacement of fuelwood by LPG was driven by urbanization together with price regulation and subsidies [39]. Generalized subsidies, however, do not ensure exclusive use. After more than three decades of cheap LPG in Ecuador, more than three quarters of surveyed rural households used wood weekly [23], and half of rural households still relied on firewood for some cooking or heating needs [40]. Firewood use was also associated with personal $PM_{2.5}$ exposures above the WHO interim target even where LPG was the primary fuel [32]. In Chiapas, Mexico, almost all households that received LPG stoves continued to use firewood, mainly to make tortillas, and the cost of LPG was the main barrier to exclusive use [41]. Targeted programs show similar patterns: Peru's FISE program reached all districts of the country, but more than 95% of surveyed households in Puno stacked LPG with biomass and fewer than 5% used it exclusively [42]. Outside the region, stacking is the prevailing pattern among LPG adopters in rural India [43], and subsidized connections did not translate into primary or exclusive LPG use among beneficiaries [44]. Conversely, the removal of subsidies can reverse the transition: in Ghana, price increases of 50% for LPG and 20% for diesel raised the share of households mainly using firewood by 3 percentage points [45]. Few studies examine how a prolonged price freeze interacts with income and firewood use using repeated nationally representative data.

2.4. Environmental Consequences of Residential Firewood Use

The environmental benefits of the transition depend on how much firewood is displaced and whether it is harvested non-renewably. Fuelwood harvesting is a chronic source of forest degradation in densely populated tropical landscapes [46], but the fraction of non-renewable biomass (fNRB) varies widely in space. Spatially explicit estimates imply that the emission reductions of cookstove offset projects are 41–59% lower than the projects expect [47]. A recent comparison of offset methodologies found over-crediting by a factor of 9.2, with fNRB, stove usage and stacking among the main sources of misalignment [48]. The MoFuSS model, tested in western Honduras, was developed to account for the spatiotemporal effect

of fuelwood harvesting on non-renewable biomass [49]. At the national scale, improved access to LPG displaced about 7.2 Mt of fuelwood in India between 2001 and 2011, but the net climate benefit depended strongly on the assumed fNRB and on the inclusion of short-lived pollutants [50]. In Mexico, scenario modelling showed that a strategy based only on LPG does not deliver the largest mitigation because of stacking with open fires, whereas combining LPG with efficient wood stoves in regions with high fNRB does [51]. Improved stoves can reduce wood use—by 59% in a Guatemalan field experiment [52]—but in a meta-analysis only clean fuels consistently brought kitchen $PM_{2.5}$ to the WHO interim target or below [53]. For Honduras, an exergy and forest stock model projected that continued reliance on wood would exhaust forest stocks by 2050 [54]. A randomized trial of the Justa chimney stove reduced geometric mean personal and kitchen $PM_{2.5}$ by 32% and 56%, respectively [55], although it did not significantly reduce glycated haemoglobin [56].

2.5. Research Gaps

Table 1 summarizes the empirical studies most comparable to ours. Three limitations stand out. First, Honduras is almost absent from the literature: only 7 of the 1864 records mention the country, and none uses nationally representative household data; they are stove trials [55,56], forest or energy models [49,54] or regional projections [9]. Second, Latin American studies of fuel choice rely on one or a few cross-sections [33,34] and do not separate the contribution of changing household characteristics from that of other changes. Third, studies that measure stacking and studies that quantify environmental outcomes rarely overlap, and national accounting exercises rely on the primary fuel or on expenditure data rather than on direct measures of stove use [50]. The last column of Table 1 summarizes the main methodological limitation of each study. Our design responds to these limitations in three ways: twelve repeated nationally representative rounds and a decomposition replace single cross-sections; stacking intensity is measured from cooking hours by stove type rather than from reported secondary fuels; and the environmental accounting uses observed stove portfolios, with uncertainty and sensitivity analysis, rather than the primary fuel alone. This study addresses the three gaps for a Central American country.

Table 1. Selected empirical studies on household cooking fuel transitions and their environmental implications, with the main methodological limitation of each study.

Study	Country and Data	Period, Design and Method	Stacking Measured	Environmental Accounting	Main Finding	Methodological Limitation Addressed Here
Cheng and Urpelainen [26]	India; National Sample Survey	1987 and 2010; two cross-sections, two-stage model	Yes (reported fuels)	No	Cooking stacking increased; income no longer reduced it by 2010	Two cross-sections; stacking from reported fuels, intensity not measured
Zhu et al. [27]	China; national rural energy survey	1992–2012; descriptive	Yes (all carriers)	Energy use	Single-fuel households fell from 28% to 11%; mixed use adds up to 40% to cooking energy	Descriptive; no household-level determinants
Singh et al. [50]	India; expenditure surveys and census	2001–2011; fuelwood displacement accounting	No	GHG and SLCP; fNRB scenarios	7.2 Mt fuelwood displaced; net benefit sensitive to fNRB	Primary fuel and expenditure data; stacking not measured

Table 1. *Cont.*

Study	Country and Data	Period, Design and Method	Stacking Measured	Environmental Accounting	Main Finding	Methodological Limitation Addressed Here
Mani et al. [44]	India; panel of rural households, six states	2014–2015 and 2018; panel regressions	Primary vs. exclusive use	No	Subsidized connections did not ensure primary or exclusive LPG use	Stacking inferred from primary vs. exclusive use; no emissions
Greve and Lay [45]	Ghana; household data	Subsidy removal; quasi-experimental	No	GHG in cost–benefit	LPG (+50%) and diesel (+20%) price increases raised firewood use by 3 pp	Single policy change; stacking not measured
Pérez et al. [33]	Colombia; living standards survey	2010–2016; multinomial logit	No	No	Education, income and household type are main determinants	Cross-sections; change over time not decomposed
Davi-Arderius et al. [34]	Ecuador; official household surveys	2015–2017; probit and multinomial logit	No	No	Poorest and Indigenous households keep firewood despite subsidized LPG	Short period; no decomposition or emissions
McLean et al. [35]	Peru; regional data	Cross-section; regression	No	No	Elevation, forest cover, poverty and female literacy shape solid fuel use	Regional aggregates; no household data
Gould et al. [40]	Ecuador; 808 peri-urban and rural households	Cross-section; survey	Yes (reported)	No	Half of rural households use firewood after decades of cheap LPG	Small sample; single cross-section
Troncoso and Soares da Silva [22]	Latin America and the Caribbean; countries	Cross-country regression	No	No	LPG subsidies accelerated the transition from solid fuels	Country-level data; no household heterogeneity
Pachauri et al. [9]	Guatemala, Honduras, Nicaragua	Discrete choice model; scenarios to 2030	No	GHG of subsidy scenario	40–50% of rural Hondurans unable to afford clean cooking in 2030	Simulated scenarios rather than observed transitions
Ver Beek et al. [54]	Honduras; national energy data	1971–2013; exergy and forest stock model	No	Forest stocks, GHG	Continued reliance on wood would exhaust forest stocks by 2050	Aggregate energy data; no household behaviour
This study	Honduras; EPHPM, 12 national rounds	2013–2025; multinomial logit, decomposition, Monte Carlo	Yes (cooking hours by stove)	Firewood, GHG, $PM_{2.5}$; fNRB uncertainty	See Sections 4 and 5	Repeated cross-sections, not a panel; firewood quantities not observed (Section Limitations)

fNRB, fraction of non-renewable biomass; GHG, greenhouse gases; SLCP, short-lived climate pollutants; pp, percentage points; EPHPM, Permanent Multipurpose Household Survey.

3. Materials and Methods

Figure 4 summarizes the methodological workflow. Twelve rounds of the national household survey were harmonized into a single household-level dataset and combined with a reconstructed LPG price series and a set of emission parameters. Five analytical modules address the five research questions: a multinomial model of the primary cooking fuel (RQ1), a decomposition of the 2017–2025 decline in firewood use (RQ2), a model of fuel stacking measured from cooking hours (RQ3), an analysis of LPG prices (RQ4) and a Monte Carlo accounting of firewood demand and emissions (RQ5).

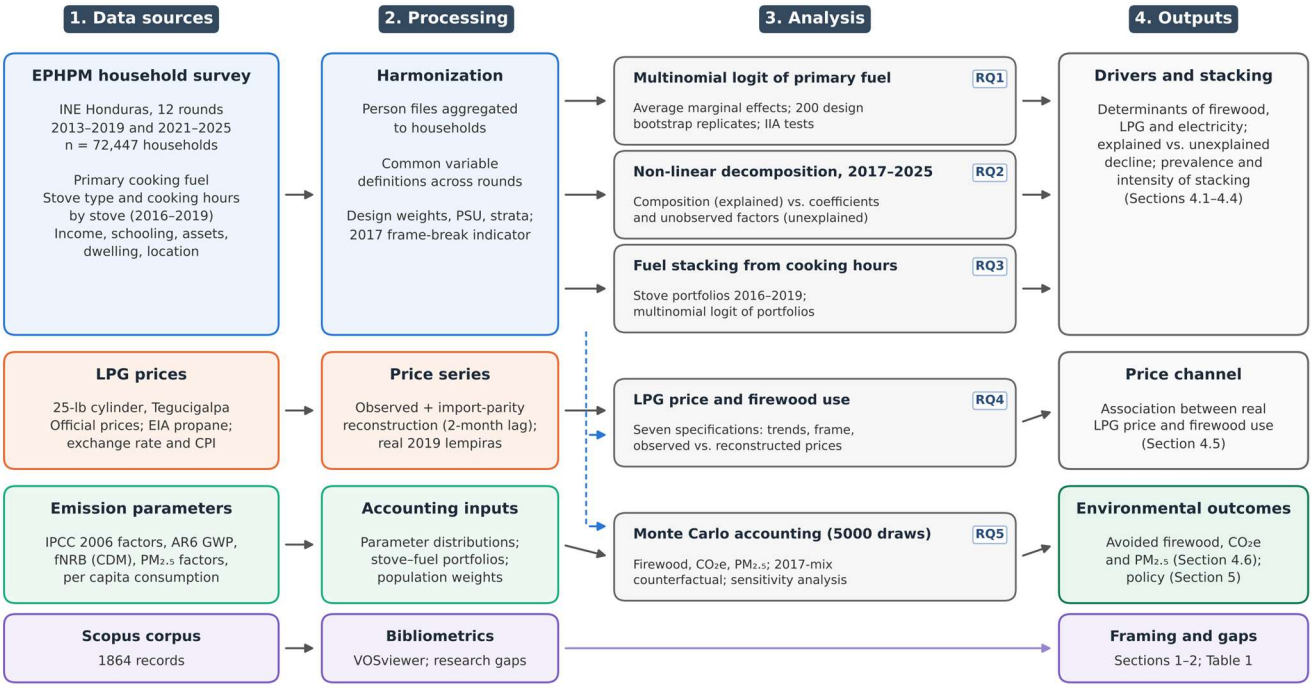


Figure 4. Methodological workflow of the study. Each row links a data source with its processing step, analytical module and results; dashed blue arrows indicate that the harmonized household data also feed the price analysis and the environmental accounting. RQ, research question; EPHPM, Permanent Multipurpose Household Survey; fNRB, fraction of non-renewable biomass; GWP, global warming potential.

3.1. Data Sources and Harmonization

We use the household and person microdata of the EPHPM conducted by the National Institute of Statistics of Honduras (INE) for 2013–2019 and 2021–2025; no round was fielded in 2020. The EPHPM is a probabilistic, stratified, two-stage area survey in which census segments are selected first and dwellings second; results are expanded with design weights equal to the inverse of the selection probabilities [57]. All files were harmonized to one record per household (n = 72,447), with variables recoded to common definitions across rounds (Table 2). Households that do not cook (1.7% of the sample) were excluded from the analysis of cooking fuel.

Four features of the data required particular care. First, the sampling frame was updated from the 2001 to the 2013 population census; in the microdata the change appears in 2017, when the number of sampling domains increases from four to five [57]. We therefore include an indicator for the post-2017 frame in all pooled models and conduct the main decomposition within the new frame (2017–2025). Second, the public microdata contain no households from the departments of Gracias a Dios and Islas de la Bahía in any round except 2024 (270 households), and department codes are not released for 2022 and 2023. The remaining 16 departments therefore form the common territory of the survey, and

the 2017–2025 comparisons, the decomposition and the environmental counterfactual use identical geographic coverage. As a stability test, we recomputed the main trends for the common territory and after reweighting every round to the 2017 distribution of households by department and area (Section 4.1). The change of frame limits the comparability of levels before and after 2017: the 2014–2016 rounds give more weight to some departments, such as Cortés (28% of weighted households, against 21% in 2017), so the jump in firewood use between 2016 and 2017 reflects sample composition rather than a change in cooking practices, and comparisons spanning 2013–2025 should be read as indicative. At constant territorial composition the 2013–2025 decline is about 13 rather than 18 percentage points (Section 4.1); for this reason, the decomposition and the environmental counterfactual are restricted to the 2017–2025 rounds of the new frame, and all pooled models include the frame indicator. Third, the value labels of the cooking-place variable in 2013–2017 invert the categories 'patio' and 'living room', but the data follow the same coding as later rounds (more than 89% of households in category 4 cook with firewood in every year), so no recoding was applied. Fourth, labour income was stored as text in 2014–2017 and was converted to numeric values before aggregation.

Table 2. Cooking fuel, stoves and household characteristics, selected years (survey-weighted).

Indicator	2013	2016	2017	2019	2021	2023	2025
Households in sample (*n*)	7198	6108	5356	5689	5008	5241	7731
Cooking households (millions, weighted)	1.87	1.96	2.03	2.17	2.27	2.53	2.73
Firewood as primary fuel (%)	55.6	48.1	53.1	51.9	48.6	42.4	37.7
LPG as primary fuel (%)	24.9	30.9	28.2	31.2	35.7	39.7	46.3
Electricity as primary fuel (%)	17.3	18.1	15.8	14.8	13.7	16.3	15.0
Urban households (%)	49.0	56.6	56.2	56.7	56.3	57.7	58.4
Grid electricity (%)	81.5	87.8	86.9	88.7	90.0	91.0	92.3
Household size (persons)	4.54	4.42	4.35	4.19	4.15	3.82	3.65
Schooling of head (years)	6.4	6.9	6.5	6.9	6.7	6.4	7.2
Female-headed (%)	32.9	33.9	32.8	33.6	37.2	38.8	38.8
Traditional stove without chimney (%) [a]	—	17.4	16.6	12.1	11.6	9.4	7.2
Improved stove, eco-fogón (%) [a]	—	7.8	8.5	5.9	3.2	1.6	1.9
High exposure (%) [a,b]	—	21.4	21.1	15.4	14.4	12.6	9.5

[a] Stove type observed from 2019; derived from cooking hours by stove type in 2016–2018; not available before 2016. [b] Household cooking with solid fuel on a stove without chimney or in a room used for sleeping or as a living room. LPG, liquefied petroleum gas.

3.2. Variables

The dependent variable of the fuel choice model is the primary cooking fuel reported by the household, grouped into firewood, LPG and electricity (kerosene, biogas and other fuels, which together account for 1–3% of households in each round, were excluded). Since 2019 the survey records the main type of stove; in 2016–2018 we derive the main stove from a battery of questions that records the hours per day the household cooks with each stove type (improved 'eco-fogón', Lorena stove, traditional stove with chimney, traditional stove without chimney, and electric or gas stove). The derived stove coincides with the observed one in 96.8% of households in 2019, when both are available.

The same battery allows a direct measurement of fuel stacking in 2016–2019. We classify households as using only biomass stoves, only clean (electric or gas) stoves, or both (stacking), and compute the share of cooking hours devoted to biomass stoves. We also construct a high-exposure indicator equal to one when a household that cooks with solid fuel uses a stove without chimney or cooks in a room also used for sleeping or as a living room. The indicator summarizes exposure-relevant cooking conditions; it is used

descriptively and to compare stove portfolios (Section 4.4) rather than modelled, because it is defined only for solid fuel users and largely follows from the stove type. Explanatory variables include urban residence, grid electricity, the sex, age and years of schooling of the household head, household size, the number of children under five and adults aged 65 or more, and per capita labour income (in logs, with an indicator for households without labour income). All incomes are expressed in constant 2019 lempiras using the consumer price index [58]. Total per capita income and household assets (refrigerator, television, motorcycle, car and computer) are used in the decomposition and stacking models, where they are available in all relevant rounds.

3.3. Fuel Choice Model

The probability that household i in year t chooses fuel $j \in \{\text{firewood, LPG, electricity}\}$ is modelled with a multinomial logit:

$$P(Y_{it} = j \mid X_{it}) = \exp(X_{it}\beta_j + \delta_{jt}) / \Sigma_k \exp(X_{it}\beta_k + \delta_{kt}), \quad (1)$$

where X_{it} is the vector of covariates, δ_{jt} are year fixed effects and firewood is the base category ($\beta_{\text{firewood}} = 0$). We report average marginal effects (AMEs), computed as discrete changes for binary variables and numerical derivatives for continuous variables, averaged with the survey weights. Standard errors are obtained with 200 subsampling bootstrap replicates of the survey design, with census segments as primary sampling units and strata defined by year and urban–rural area [59]. The 2024 file does not include the segment identifier; for that year each household is treated as its own cluster. The independence of irrelevant alternatives (IIA) assumption is assessed with Hausman–McFadden tests [60] and Small–Hsiao tests [61], omitting each alternative in turn; the Small–Hsiao test is repeated over 50 random splits of the sample. Because these tests often give conflicting results and have poor size properties [62], we also estimate a binary logit of firewood versus clean fuels, which does not rely on IIA, and compare its AMEs with those of Equation (1). Further checks re-estimate Equation (1) without the demographic controls and for the common territory of 16 departments (Section 4.2). Because the tests are contradictory, they neither confirm nor reject IIA with confidence. The assumption matters mainly for the relative probabilities of LPG and electricity; for the main outcome of the study, the use of firewood versus clean fuels, the IIA-free binary logit gives practically the same AMEs (Section 4.2), so the conclusions on firewood use do not depend on IIA, whereas the AMEs on the split between LPG and electricity should be read with more caution. Models were estimated with the nnet package [63].

3.4. Decomposition of the Decline in Firewood Use

To separate the contribution of changing household characteristics from other changes, we decompose the difference in the probability of using firewood between 2017 (A) and 2025 (B) with a non-linear Oaxaca–Blinder decomposition based on a pooled logit with year effects as the reference coefficient vector β^* [64,65]:

$$\overline{P}_A - \overline{P}_B = \left[\overline{F}(X_A\beta*) - \overline{F}(X_B\beta*)\right] + \left\{\left(\overline{P}_A - \overline{P}_B\right) - \left[\overline{F}(X_A\beta*) - \overline{F}(X_B\beta*)\right]\right\}, \quad (2)$$

where $\overline{F}$ denotes the weighted mean of the logistic function over each sample. The first term is the part explained by characteristics and the second the unexplained part. The contribution of each covariate k to the explained part is obtained with Yun's weights, $W_k = \left(\overline{X}_{Ak} - \overline{X}_{Bk}\right)\beta*_k / \Sigma_m \left(\overline{X}_{Am} - \overline{X}_{Bm}\right)\beta*_m$ [66]. Restricting the comparison to 2017–2025 keeps the sampling frame constant, both years cover the same 16 departments, and per capita income is expressed in constant 2019 lempiras so that inflation is not counted as income growth. Both predicted means in the explained term are computed with the pooled

coefficients and the year effect fixed at its 2017 (reference) value, so the 2025 year effect belongs to the unexplained part; as a check, both predictions are also evaluated at the 2025 year effect. The unexplained component combines changes in the coefficients (how households with given characteristics choose fuels), factors that changed over time but are not in the model, such as prices, supply networks, remittances or the COVID-19 shock, and limitations of the method, such as omitted variables and the logistic functional form. It is therefore not interpreted as a change in household behaviour.

3.5. Fuel Stacking Model

For 2016–2019 we estimate a multinomial logit of the three-category stove portfolio (only biomass, stacking, only clean) with year and department fixed effects, total per capita income, home ownership and dirt floor in addition to the demographic covariates, and report AMEs with design-based standard errors.

3.6. LPG Prices

We assembled the nominal retail price of the 25-lb LPG cylinder in Tegucigalpa for the survey months from official statistics of the Directorate General of Hydrocarbons reported by CEPAL [24] and from dated press reports of the regulated price structure (Appendix A, Table A1). No reliable price could be found for May 2013 and June 2015. Because Honduras sets fuel prices by import parity, we reconstructed these values with a calibration model in which the domestic price depends on the Mont Belvieu propane spot price two months earlier [67], converted at the official exchange rate [58]:

$$P_t = a + b \cdot (PMB_{t-2} \times e_t) + u_t, \quad (3)$$

estimated on 35 verified market prices for 2014–2020 (15 dated press reports and 20 quarterly CEPAL observations). The lag was selected by leave-one-out cross-validation. Prices were deflated to 2019 lempiras with the consumer price index [58]. Because the price varies only across survey rounds, its association with firewood use is estimated with household-level logit models that replace year effects with the log real price, a linear trend and the frame indicator, and with year-level regressions of composition-adjusted firewood probabilities (from Equation (1)) on the same terms with heteroskedasticity-robust errors. The year-level estimates provide a conservative view of the uncertainty of an aggregate regressor. Over the twelve survey rounds, the log real price and the linear trend are strongly correlated ($r = -0.94$; variance inflation factor of 25 given the trend and the frame indicator, and 22 within 2017–2025), so the price coefficient is weakly identified. The specifications therefore test whether any price association survives these controls; they do not estimate a price elasticity.

3.7. Environmental Accounting

Annual firewood use of household i with a biomass main stove s is estimated as

$$W_i = c \times N_i \times 365 \times (1 - \sigma_s) + c \times N_i \times 365 \times h_i, \quad (4)$$

where c is per capita firewood consumption, N_i household size, σ_s the fuel saving of stove type s relative to a traditional open fire, and h_i the share of cooking hours on biomass stoves for households whose primary stove is clean (stacking; measured in 2016–2019 and held at its 2016–2019 mean afterwards). Emissions of non-renewable CO_2, CH_4 and N_2O are computed with the IPCC default net calorific value and emission factors for residential wood combustion [68], a fraction of non-renewable biomass (fNRB) drawn between 0.26 and 0.36 (mean 0.31), the range of the national (0.33) and subnational default values for Honduras [69], and 100-year global warming potentials [70]; fine particulate matter ($PM_{2.5}$)

uses the field emission factor measured in Honduran kitchens [6]. Emissions from LPG are added for LPG-using households. Parameter uncertainty is propagated with 5000 Monte Carlo draws (Appendix B, Table A2), and results are expanded to the national level with the survey weights. The resulting 95% intervals reflect uncertainty in the parameters only; they do not include the sampling error of the survey estimates or systematic bias in the literature values. Avoided firewood and emissions in 2025 are computed against a counterfactual in which the 2025 population, by urban and rural area, retains the fuel–stove composition and per capita use observed in 2017. Because the EPHPM does not record firewood quantities, a single per capita range spanning the Honduran estimates is applied to all biomass households, and differences between households enter through household size and stove type. We assess the main assumptions with a one-at-a-time sensitivity analysis (Section 4.6): fixed fNRB values of 0.20, 0.33, 0.50 and 1.00; higher fuel savings for chimney and Lorena stoves; the lower and upper halves of the per capita range; economies of scale in household size; lower per capita use in urban than in rural households; alternative stacking intensities after 2019; and the inclusion of electricity used for cooking, assuming 1–3 kWh per day per electric-cooking household and the grid emission factor of 0.61 t CO_2/MWh [71]. Electricity is excluded from the main estimate because the share of households cooking with electricity was similar in 2017 and 2025 (15.8% and 15.0%).

3.8. Software, Reproducibility and Use of Generative AI

Data harmonization, the price reconstruction and most figures were implemented in Python (version 3.13) and the statistical models and the map in R (version 4.3.3) [59,63]; department boundaries were taken from Natural Earth [72]. The bibliometric indicators in Section 2 were computed in Python, and the keyword maps were produced with VOSviewer [25]. The price series is reported in Appendix A and Table S1, and the aggregated data underlying all tables and figures are provided as Dataset S1. Generative artificial intelligence (Claude Sonnet 5.5) was used to verify price sources, for editorial assistance, grammar correction, drafting, and refining the English text. The authors take full responsibility for the content of the manuscript.

4. Results

4.1. Trends in Cooking Fuels and Stoves

The share of households cooking primarily with firewood declined from 55.6% in 2013 to 37.7% in 2025, while LPG rose from 24.9% to 46.3% and became the main cooking fuel at the national level in 2024 (Figure 5, Table 2). Electricity remained between 13% and 19%. The transition was concentrated in the second half of the period: within the new sampling frame, firewood use declined from 53.1% in 2017 to 37.7% in 2025. In urban areas firewood fell to 13.9%, whereas in rural areas it still reached 71.1% in 2025. The jump in rural firewood use between 2016 and 2017 coincides with the change of sampling frame and is not interpreted as a behavioural change. The stability test supports this reading (Appendix D): when every round is reweighted to the 2017 distribution of households by department and area, firewood use remains between 51.3% and 54.0% in 2013–2019 and falls to 38.6% in 2025. At constant territorial composition, the decline is therefore about 13 points and concentrated after 2019. Restricting 2024 to the common territory changes the firewood share from 38.2% to 38.6% and the LPG share from 44.5% to 43.0%, so LPG also overtook firewood in 2024 within the 16 departments.

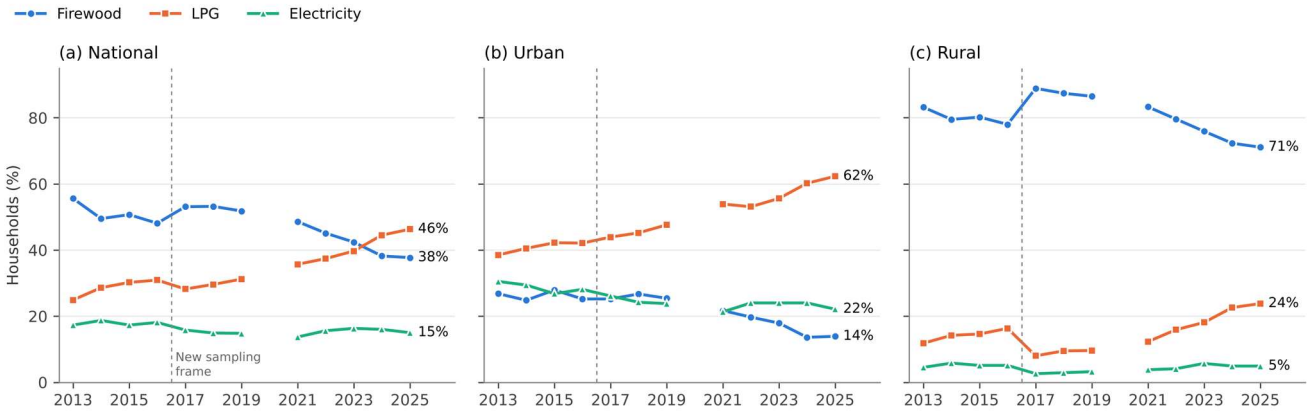


Figure 5. Primary cooking fuel in Honduras, 2013–2025: (**a**) national; (**b**) urban; (**c**) rural. Survey-weighted shares of households that cook. The dashed line marks the change of sampling frame (2017); no survey was conducted in 2020.

The decline was generalized across the territory. Between 2017 and 2025 the share of households using firewood fell in all sixteen departments covered by the survey, by between 9.9 percentage points in Francisco Morazán and 28.2 points in Olancho (Figure 6). The largest reductions occurred in Olancho, Yoro, Valle and Santa Bárbara (24–28 points), whereas the smallest changes occurred in the most urbanized departments, Francisco Morazán and Cortés, where firewood use was already low, and in the western highlands (Lempira, La Paz and Intibucá; 11–14 points), where it was highest. As a result, the spatial gradient widened in relative terms: in 2025 firewood was the primary cooking fuel for 10.8% of households in Cortés, which includes San Pedro Sula, but for 79.2% in Lempira and for more than two thirds of households in Intibucá and La Paz.

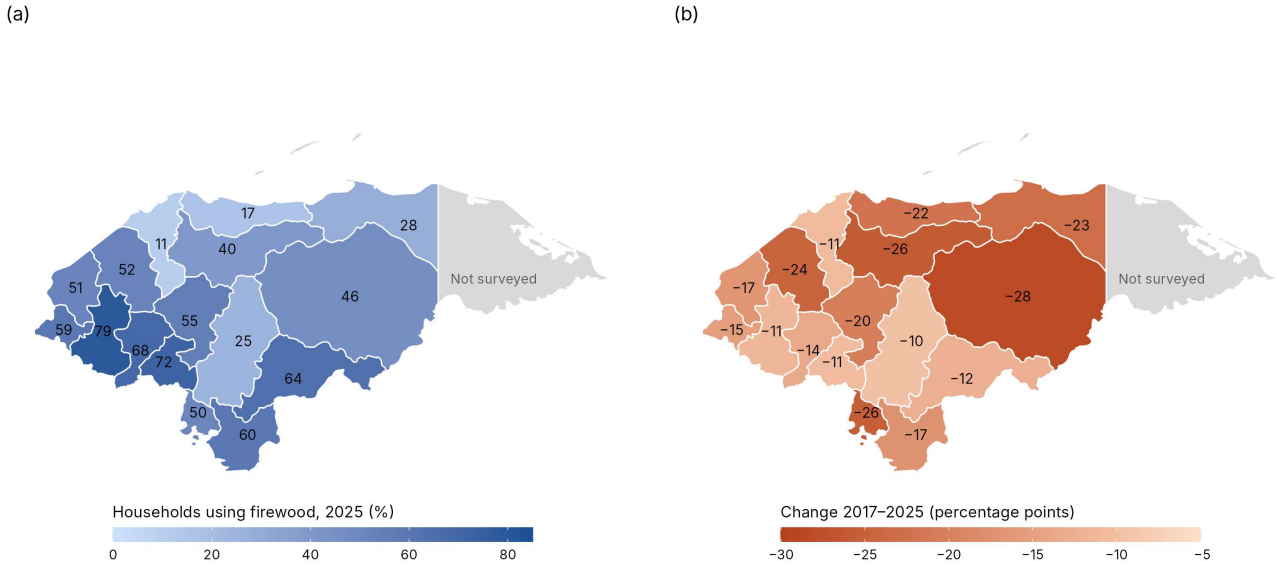


Figure 6. Households using firewood as the primary cooking fuel by department: (**a**) share in 2025 (%); (**b**) change between 2017 and 2025 (percentage points). Survey-weighted estimates. Gracias a Dios and Islas de la Bahía (grey) are not covered by the EPHPM in 2017 and 2025. Boundaries from Natural Earth [72].

Stove technology and exposure also improved. The share of households using a traditional stove without chimney declined from 16.6% in 2017 to 7.2% in 2025, and the share of households classified as highly exposed fell from 21.1% to 9.5% (Table 2). The decline in firewood use was particularly pronounced among the poorest households (Figure 7): in

the bottom income quintile the share fell from 91.4% in 2019 to 59.5% in 2025, compared with a decline from 15.9% to 11.2% in the top quintile. The income gradient therefore narrowed, but firewood remained the main cooking fuel for most households in the two lowest quintiles.

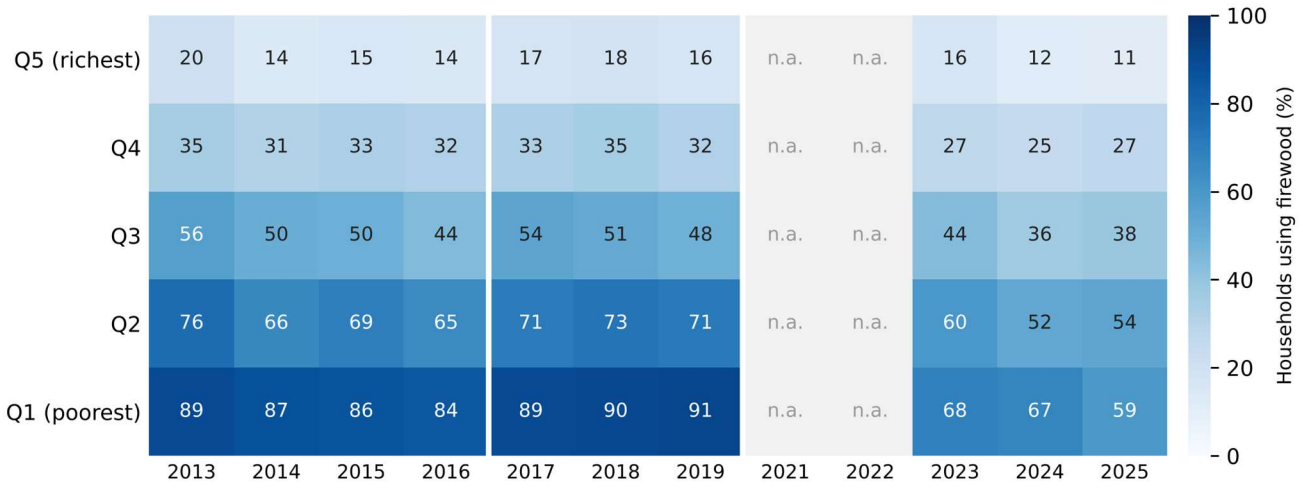


Figure 7. Households using firewood as the primary cooking fuel by quintile of per capita household income, 2013–2025 (%, survey-weighted). Quintiles are defined within each survey round. White lines separate the 2001-frame rounds (2013–2016), the 2013-frame rounds before the pandemic (2017–2019) and the post-pandemic rounds; n.a.: income quintile not available in the public files for 2021 and 2022.

4.2. Determinants of the Primary Cooking Fuel

Table 3 and Figure 8 report the AMEs of the multinomial logit (n = 67,688; McFadden pseudo-R^2 = 0.28; 67.5% of households correctly classified). Living in an urban area reduces the probability of using firewood by 36.0 percentage points and increases the probability of using LPG by 24.4 points. Access to grid electricity reduces firewood use by 24.2 points, with gains for both LPG (15.1 points) and electricity (9.0 points). A one-unit increase in log per capita labour income reduces firewood use by 7.6 points, and each additional year of schooling of the household head reduces it by 2.3 points. Female-headed households are 2.3 points less likely to use firewood, and households with young children are less likely to use firewood and more likely to use LPG. Larger households and older heads are more likely to rely on firewood. The IIA tests are inconclusive, as is common in large samples [62]. The Hausman–McFadden test does not reject IIA when electricity is omitted (negative statistic) but rejects it when firewood or LPG is omitted ($p < 0.001$), whereas the Small–Hsiao test does not reject IIA at the 5% level in any of 50 random splits when firewood or electricity is omitted and in 70% of them when LPG is omitted. A binary logit of firewood versus clean fuels, which does not rely on IIA, gives practically the same AMEs on firewood use as Equation (1) (urban area −36.0, grid electricity −23.8, log labour income −7.6 and schooling −2.3 points; Appendix D). Without the demographic controls, the AMEs of urban residence, grid electricity and income become −42.6, −26.0 and −10.7 points: they keep their sign and ranking but increase in magnitude, because without controls they partly capture the correlated effects of schooling and household composition. Restricting the sample to the common territory leaves the AMEs practically unchanged (Appendix D).

Table 3. Average marginal effects on the probability of each primary cooking fuel (percentage points), 2013–2025.

Variable	Firewood	LPG	Electricity
Urban area	−36.0 (0.5)	+24.4 (0.6)	+11.6 (0.4)
Grid electricity	−24.2 (0.9)	+15.1 (1.1)	+9.0 (0.7)
Log labour income per capita	−7.6 (0.2)	+4.7 (0.3)	+2.9 (0.2)
Schooling of head (years)	−2.3 (0.1)	+0.6 (0.1)	+1.6 (0.0)
Female-headed household	−2.3 (0.4)	+1.6 (0.4)	+0.8 (0.3)
Age of head (10 years)	+1.7 (0.1)	−2.4 (0.2)	+0.7 (0.1)
Household size (persons)	+1.7 (0.1)	−1.3 (0.1)	−0.4 (0.1)
Children under 5 (number)	−1.7 (0.3)	+2.1 (0.4)	−0.3 (0.3)
Adults aged 65+ (number)	−1.1 (0.4)	+0.0 (0.5)	+1.1 (0.3)

Survey-weighted multinomial logit with year fixed effects and an indicator for households without labour income; income in constant 2019 lempiras; $n = 67{,}688$; McFadden pseudo-$R^2 = 0.28$. Standard errors in parentheses from 200 subsampling bootstrap replicates of the survey design. All effects except adults aged 65+ on LPG and children under 5 on electricity are significant at $p < 0.05$.

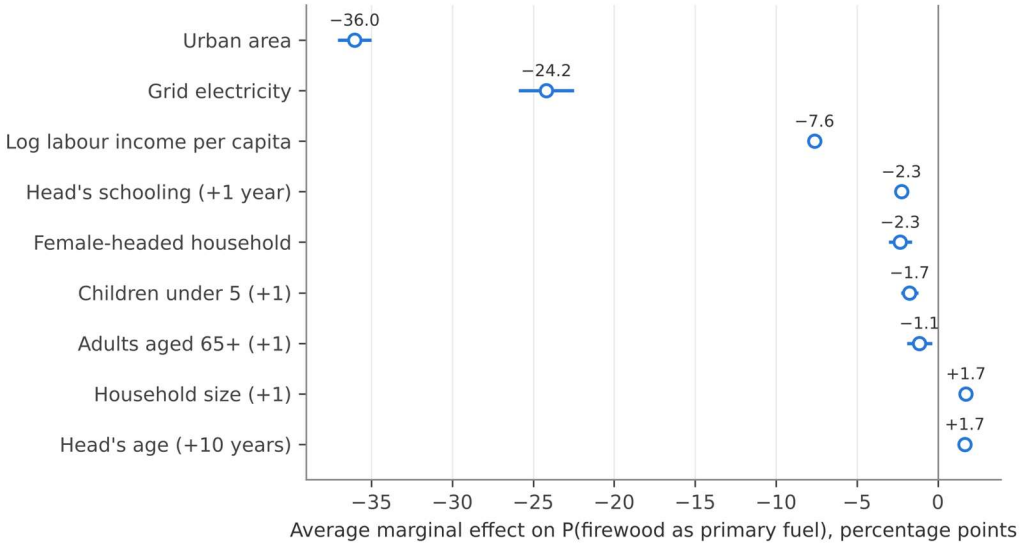


Figure 8. Average marginal effects on the probability of using firewood as the primary cooking fuel. Horizontal lines are 95% confidence intervals from 200 bootstrap replicates of the survey design. Multinomial logit with year fixed effects and income in constant 2019 lempiras, 2013–2019 and 2021–2025 ($n = 67{,}688$).

4.3. Decomposition of the 2017–2025 Decline

In the decomposition sample, the probability of using firewood fell by 16.2 percentage points between 2017 and 2025 (Figure 9; full results in Appendix C, Table A3). With income in constant prices, changes in observed characteristics explain 3.2 points (19.6% of the gap), while 13.0 points (80.4%) remain unexplained. Among the explained components, the largest contributions come from smaller households (8.3% of the gap), refrigerator ownership (6.0%), schooling (5.0%) and urbanization (4.0%); real per capita income rose only modestly (0.10 log points) and contributed 2.4%. Expansion of grid electricity contributed only 1.9%, reflecting the already high coverage reached by 2017. Evaluating both predictions at the 2025 year effect raises the explained share to 24.8%, whereas nominal income would have raised it to 31.5% by counting inflation as income growth. Consistently, the composition-adjusted probability of firewood use derived from the year effects of Equation (1) declines from 52.6% in 2019 to 41.6% in 2025. The unexplained component should not be read as a change in household behaviour alone: it also captures changes in coefficients and in unobserved factors such as prices, supply networks and remittances,

as well as the limitations of the decomposition (Section 3.4). Because the EPHPM does not observe preferences or cooking practices, the decomposition cannot separate changes in household behaviour from the effects of unobserved factors: both are contained in the unexplained component, which is therefore an upper bound on any behavioural change rather than an estimate of it.

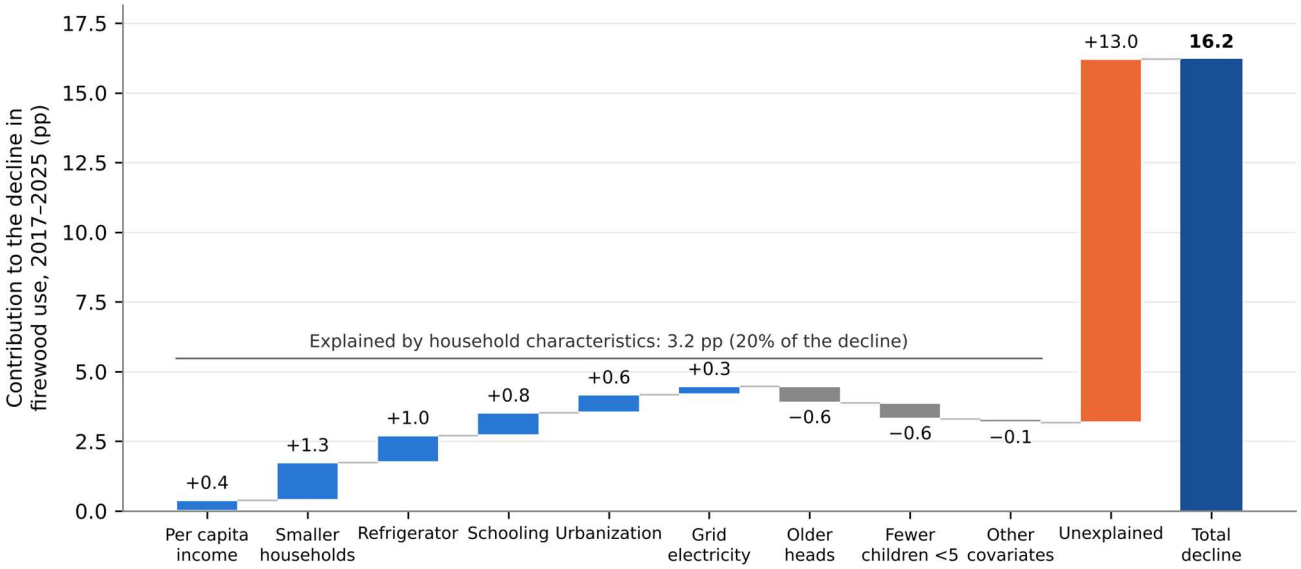


Figure 9. Non-linear decomposition of the 2017–2025 decline in the probability of using firewood (16.2 percentage points). Blue bars are covariates whose change reduced firewood use, grey bars covariates whose change increased it, and the orange bar is the unexplained component (change in coefficients and unobserved factors). Pooled coefficients with the year effect fixed at its 2017 value and income in constant 2019 lempiras; detailed estimates in Table A3.

4.4. Fuel Stacking

Direct measurement of stove use shows that stacking is widespread and stable (Table 4). Between 12.9% and 16.2% of households used both biomass and clean stoves in 2016–2019, and these households devoted 54.5–58.0% of their cooking hours to biomass stoves. In 2019, slightly more than half of stacking households reported LPG or electricity as their primary fuel, so that classifications based on the primary fuel alone understate the persistence of biomass use.

Table 4. Stove portfolios measured from cooking hours by stove type, 2016–2019 (survey-weighted).

Year	Households (*n*)	Only Biomass (%)	Stacking (%)	Only Clean (%)	Biomass Share of Cooking Hours, Stackers (%)
2016	5891	40.8	13.9	45.3	56.0
2017	5141	43.3	16.2	40.5	57.7
2018	5719	45.9	13.7	40.4	58.0
2019	5340	45.5	12.9	41.6	54.5

Portfolios defined from the hours per day the household cooks with each stove type. Biomass stoves: eco-fogón, Lorena, traditional with and without chimney; clean stoves: electric or gas.

The determinants of stacking differ from those of exclusive biomass use (Table 5). Grid electricity (+4.5 points), home ownership (+3.3 points), income (+1.9 points per log unit), household size (+0.9 points per member) and the age of the head (+1.2 points per decade) increase the probability of stacking, whereas a dirt floor reduces it (−6.4 points). In contrast, exclusive biomass use is associated with rural residence, lack of electricity, low income and

precarious housing. Stacking is therefore characteristic of households in transition rather than of the poorest households.

Table 5. Average marginal effects on the probability of each stove portfolio (percentage points), 2016–2019.

Variable	Only Biomass	Stacking	Only Clean
Urban area	−23.1 (0.9) *	−0.1 (0.8)	+23.2 (1.0) *
Grid electricity	−21.9 (2.0) *	+4.5 (1.3) *	+17.4 (2.5) *
Log per capita income	−8.6 (0.3) *	+1.9 (0.3) *	+6.7 (0.4) *
Schooling of head (years)	−1.5 (0.1) *	−0.3 (0.1) *	+1.8 (0.1) *
Female-headed household	−2.0 (0.6) *	+0.8 (0.6)	+1.1 (0.6)
Age of head (10 years)	+1.3 (0.2) *	+1.2 (0.2) *	−2.5 (0.2) *
Household size (persons)	+1.0 (0.1) *	+0.9 (0.1) *	−1.9 (0.2) *
Children under 5 (number)	−1.5 (0.4) *	−0.9 (0.5)	+2.4 (0.5) *
Adults aged 65+ (number)	−2.5 (0.6) *	−0.0 (0.6)	+2.5 (0.6) *
Home owner	+1.4 (0.6) *	+3.3 (0.6) *	−4.7 (0.6) *
Dirt floor	+19.4 (1.5) *	−6.4 (1.1) *	−13.0 (1.8) *

Survey-weighted multinomial logit with year and department fixed effects, 2016–2019 (n = 22,091). Standard errors in parentheses from 200 design bootstrap replicates; * $p < 0.05$.

Comparing Tables 3 and 5 makes the contrast explicit. Urban residence, the strongest correlate of using firewood as the primary fuel (Table 3), has no association with stacking (−0.1 points), and income, grid electricity and home ownership, which reduce exclusive biomass use, increase the probability of stacking. A dirt floor, a marker of precarious housing, raises exclusive biomass use by 19.4 points but lowers stacking by 6.4 points. Policies guided only by the correlates of the primary fuel would therefore miss many households that still cook part of the time with biomass.

Stacking also matters for exposure. In 2016–2019, 30.2% of stacking households met the high-exposure criterion, almost as many as among households using only biomass stoves (34.1%) and far more than among clean-only households (0.3%); stacking households accounted for 21.4% of all highly exposed households. Compared with biomass-only households, stacking households were less likely to cook on a stove without chimney (20.3% vs. 28.2%) but more likely to cook in a room used for sleeping or as a living room (25.8% vs. 8.5%).

4.5. LPG Prices and Firewood Use

The calibration model of Equation (3) explains 71% of the variation in verified prices, with a leave-one-out root mean squared error of 15.1 lempiras (5.0%). The reconstructed prices were L268.9 for May 2013 (95% prediction interval 239.9–298.0) and L241.5 for June 2015 (212.3–270.6). In real terms, the cylinder price fell from about L342 (2019 lempiras) in 2013 to L247 in 2016, rose to a local peak of L301 in 2018, and then declined by 42% to L173 in 2025, as the nominal price was kept at L238.13 while consumer prices continued to rise (Figure 10). Without the subsidy, the cylinder cost L313.35 in Tegucigalpa in late January and early February 2022, before the frozen price took effect on 7 February [10,73]. The real decline improved affordability: for the median household in the poorest quintile, one cylinder represented 60.8% of monthly per capita income in 2019 and 31.8% in 2025. However, most households were unaware of the subsidy: in 2025, 71.5% of firewood users and 60.1% of LPG users reported not knowing that fuels were subsidized. This finding is relevant for policy design, but it does not help to identify the price effect.

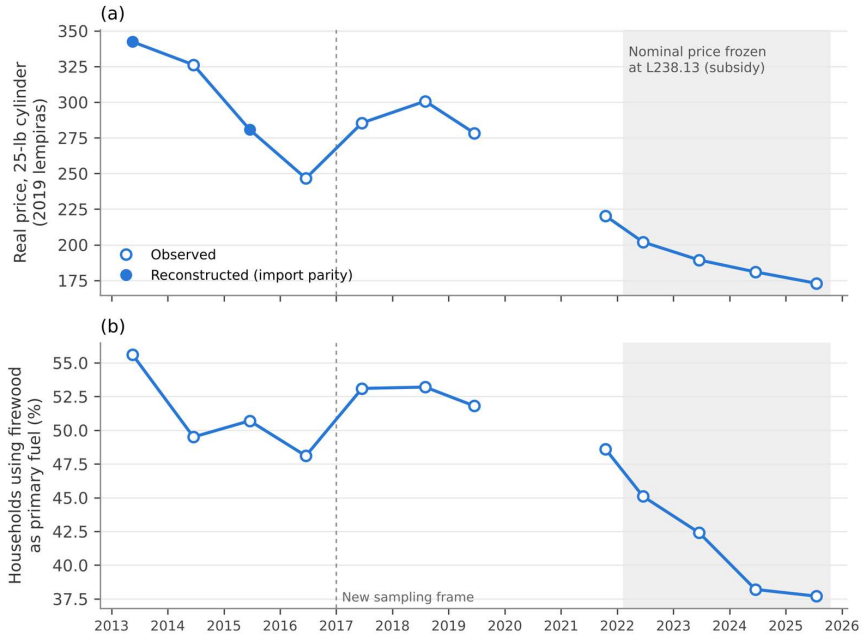


Figure 10. (**a**) Real price of the 25-lb LPG cylinder in Tegucigalpa (2019 lempiras); filled markers are reconstructed by import parity. (**b**) Share of households using firewood as the primary cooking fuel. Markers are placed at the survey month. The shaded area marks the period with a frozen nominal price (from 7 February 2022); the dashed line marks the change of sampling frame.

Despite the visual co-movement, the econometric evidence on the price channel is not robust (Table 6). With all twelve rounds, a linear trend and the frame indicator, the association between the real LPG price and firewood use is close to zero, whether the reconstructed or only the observed prices are used. Only within the new sampling frame (2017–2025) is a positive association observed (+1.16 percentage points of firewood use per 10% increase in the LPG price; $p = 0.07$), and the corresponding year-level estimate is imprecise. Since the real price and the time trend move almost in parallel ($r = -0.94$; variance inflation factor of about 25), the data do not allow the price effect to be separated from other time-varying factors. This limitation is inherent to a uniform national price series: departmental data on LPG distribution networks or retail availability, which could provide spatial variation, were not available for the study period.

Table 6. Association between the real LPG price and the probability of using firewood.

Specification	*n*	Change in P(Firewood) per +10% Real LPG Price (pp)	SE	*p*
(1) Households, 12 rounds (2013 and 2015 reconstructed); trend + frame	67,688	−0.16	0.45	0.72
(2) Households, 10 rounds with observed prices; trend + frame	55,208	+0.12	0.49	0.81
(3) Households, 12 rounds, fully reconstructed series; trend + frame	67,688	−0.54	0.44	0.22
(4) Households, 2017–2025 (same frame); trend	44,286	+1.16	0.63	0.07
(5) Year-level, 12 rounds; trend + frame	12 years	−0.23	0.97	0.81
(6) Year-level, 12 rounds, reconstructed series; trend + frame	12 years	−0.59	0.70	0.40
(7) Year-level, 2017–2025; trend	8 years	+1.27	0.87	0.15

Household-level models: survey-weighted logit with the covariates of Table 2 (income in constant 2019 lempiras), with standard errors from 200 design bootstrap replicates (which understate the uncertainty of a regressor that varies only across years). Year-level models: OLS of composition-adjusted firewood probabilities on the log real price with heteroskedasticity-robust (HC1) standard errors. Frame: indicator for the 2013-census sampling frame (2017 onwards).

4.6. Firewood Demand and Emissions

National residential firewood use is estimated at 6.6 Mt in 2017 (95% interval 4.3–8.9) and 5.4 Mt in 2025 (3.6–7.5), with associated biomass emissions of 4.5 and 3.7 Mt CO_2e, respectively, and $PM_{2.5}$ emissions of about 56 and 46 kt (Table 7, Figure 11). The wide intervals mainly reflect uncertainty in per capita consumption, which is common to all years; differences between years are estimated much more precisely. These intervals reflect parameter uncertainty only (Section 3.7). Had the 2025 population kept the fuel–stove composition of 2017, residential firewood use would have been 1.9 Mt higher (1.3–2.5 Mt; 25.8% of counterfactual use). The avoided biomass emissions of 1.3 Mt CO_2e are partly offset by 0.3 Mt CO_2e from additional LPG use, giving net avoided emissions of 1.0 Mt CO_2e per year (0.5–1.6). Avoided $PM_{2.5}$ emissions amount to 16 kt (9–25 kt). Stacking households accounted for 2.4–5.7% of residential firewood use in 2016–2019, equivalent to 0.11–0.26 Mt CO_2e per year.

Table 7. Residential firewood use and emissions, 2017 and 2025, and avoided amounts relative to the 2017 fuel–stove mix (means and 95% Monte Carlo intervals).

Indicator	2017	2025	Avoided in 2025 vs. 2017 Mix
Households with biomass main stove (millions)	1.14	1.03	—
Residential firewood (Mt/year)	6.6 (4.3–8.9)	5.4 (3.6–7.5)	1.9 (1.3–2.5)
Biomass GHG emissions (Mt CO_2e/year)	4.5 (2.9–6.4)	3.7 (2.4–5.3)	1.3 (0.8–1.8)
LPG CO_2 emissions (Mt/year)	0.26 (0.18–0.34)	0.58 (0.40–0.76)	−0.28 (0.19–0.36) [a]
Net GHG emissions avoided (Mt CO_2e/year)	—	—	1.0 (0.5–1.6)
$PM_{2.5}$ emissions (kt/year)	56 (31–88)	46 (26–73)	16 (9–25)

Means and 95% intervals from 5000 Monte Carlo draws (parameters in Table A2). GHG: non-renewable CO_2, CH_4 and N_2O with 100-year global warming potentials. The counterfactual applies the 2017 fuel–stove composition and per capita use, by urban and rural area, to the 2025 population. [a] Additional LPG emissions in 2025 (negative avoided amount).

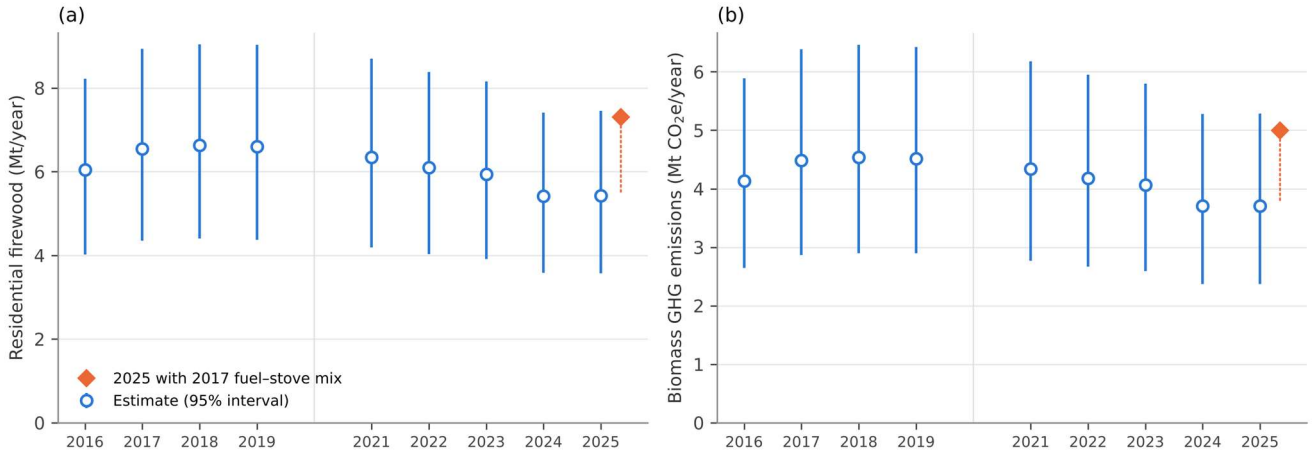


Figure 11. (**a**) Residential firewood use and (**b**) greenhouse gas emissions from biomass cooking in Honduras, 2016–2025. Vertical lines show 95% Monte Carlo intervals; diamonds show 2025 values under the 2017 fuel–stove composition.

Table 8 shows how the avoided amounts in 2025 respond to the main assumptions. Avoided firewood ranges from 1.55 to 2.22 Mt across the scenarios. It is most sensitive to per capita consumption and to economies of scale in household size, and moderately sensitive to stacking after 2019: if stacking households had halved their biomass use after 2019, avoided firewood would be 2.03 Mt, and if they had increased it by 50%, 1.73 Mt. Higher fuel savings for chimney and Lorena stoves hardly change the result (1.86 Mt), because these stoves were used in both years. Net avoided emissions depend strongly on

fNRB, the most influential assumption of the accounting: 0.65 Mt CO_2e with fNRB = 0.20, 1.08 Mt with the national default of 0.33, 1.63 Mt with 0.50 and 3.27 Mt in the upper bound in which all harvested wood is non-renewable, a fivefold range. Avoided firewood and $PM_{2.5}$ do not depend on fNRB, but the net carbon benefit should be read as conditional on the assumed non-renewability of harvested wood. Including electricity for cooking adds only 0.02 Mt CO_2e in 2025 relative to the counterfactual and reduces the net benefit from 1.01 to 0.99 Mt CO_2e. Finally, the national totals refer to the 16 departments covered by the survey. In 2024, the only round that includes them, households in Gracias a Dios and Islas de la Bahía used about 15% more firewood per person than in the rest of the country; because these departments held 1.8% of the national population in the 2013 census (153,352 of 8,303,771 inhabitants) [74], including them would raise national firewood use and emissions by roughly 2%.

Table 8. Sensitivity of the avoided firewood, net greenhouse gas emissions and $PM_{2.5}$ emissions in 2025 to the main assumptions (means and 95% Monte Carlo intervals). Net avoided GHG emissions are highly sensitive to fNRB.

Scenario	Avoided Firewood (Mt)	Net GHG Avoided (Mt CO_2e)	Avoided $PM_{2.5}$ (kt)
Main estimate (Table 7)	1.88 (1.25–2.54)	1.01 (0.53–1.56)	16 (9–25)
fNRB = 0.33 (national default)	1.88 (1.25–2.54)	1.08 (0.60–1.57)	16 (9–25)
fNRB = 0.20	1.88 (1.25–2.54)	0.65 (0.31–1.00)	16 (9–25)
fNRB = 0.50	1.88 (1.25–2.54)	1.63 (0.98–2.32)	16 (9–25)
fNRB = 1.00 (upper bound)	1.88 (1.25–2.54)	3.27 (2.09–4.54)	16 (9–25)
Chimney/Lorena saving U(0.10, 0.30)	1.86 (1.24–2.53)	1.00 (0.52–1.54)	16 (9–25)
Chimney/Lorena saving U(0.15, 0.25)	1.86 (1.24–2.53)	1.00 (0.52–1.54)	16 (9–25)
Per capita use U(2.5, 3.85) kg/day	1.55 (1.22–1.90)	0.79 (0.49–1.11)	13 (8–19)
Per capita use U(3.85, 5.2) kg/day	2.22 (1.87–2.58)	1.24 (0.90–1.61)	19 (13–26)
Economies of scale in household size [a]	1.61 (1.07–2.20)	0.83 (0.41–1.30)	14 (8–22)
Urban use −20%, rural use +10%	1.76 (1.17–2.39)	0.93 (0.47–1.44)	15 (8–24)
Stacking after 2019 halved	2.03 (1.36–2.75)	1.11 (0.60–1.70)	17 (10–27)
Stacking after 2019 +50%	1.73 (1.15–2.34)	0.90 (0.46–1.41)	15 (8–23)
No stacking after 2019	2.18 (1.46–2.95)	1.22 (0.67–1.85)	19 (10–29)
Electricity for cooking included [b]	1.88 (1.25–2.54)	0.99 (0.51–1.54)	16 (9–25)

Net avoided GHG emissions vary about fivefold with fNRB (0.65–3.27 Mt CO_2e), whereas avoided firewood and $PM_{2.5}$ do not depend on fNRB. One parameter or assumption is changed at a time; all others as in Table A2. Stacking scenarios change the biomass share of cooking hours of clean-stove households in 2025 relative to its 2016–2019 mean. [a] Household firewood use proportional to household size raised to 0.75, normalized at 4.35 persons. [b] 1–3 kWh per day per household cooking with electricity and 0.61 t CO_2/MWh [71].

5. Discussion

The Honduran experience between 2013 and 2025 combines a substantial clean cooking transition with persistent reliance on biomass. Firewood remained the primary fuel for more than one million households in 2025, and seven in ten rural households still cooked mainly with wood. The strong associations of firewood use with rural residence, electricity access, income and education are consistent with previous evidence for Guatemala and other developing countries [16,19,20], and with the role of start-up costs and access identified in the region [21,22].

Two findings qualify the energy ladder interpretation. First, about four fifths of the decline in firewood use since 2017 is not explained by changes in income, education, household size, urbanization or electrification. This unexplained component is consistent with changes that affected households with similar characteristics, among which the real decline in the LPG price and the improvement in affordability for the poorest quintile stand out, but it also includes changes in coefficients, unobserved factors and the limitations of the method, and it cannot be attributed to any single cause. The concentration of the decline

among low-income households after 2019 points in the same direction. However, our formal tests do not identify a robust price effect, because the real price and the time trend move almost together over the period. The appropriate conclusion is that the evidence is compatible with an important role for affordability, but other contextual factors—such as remittances [36,37], the expansion of LPG distribution networks, the COVID-19 shock or changes in firewood availability and prices—cannot be ruled out with these data. Evidence from Ghana, where the removal of LPG subsidies increased the use of firewood [45], and from Brazil, where price regulation and subsidies accompanied the long-run substitution of fuelwood by LPG [39], makes the price channel plausible; identifying it in Honduras would require spatial or temporal variation in prices that a uniform national price does not provide.

Second, stacking is common, stable and concentrated among households in transition. Stackers devote more than half of their cooking time to biomass stoves even when they report LPG as their main fuel. This is consistent with the 'everybody stacks' evidence [17,18] and with studies from Ecuador and India showing that subsidized LPG coexists with continued firewood use [23,40,43]. The intensity of stacking is also similar to that observed in Chiapas, Mexico, where households that had received LPG stoves cooked about 58% of their food with LPG while almost all continued to use firewood [41]. It follows that indicators based only on the primary fuel, such as those used to monitor SDG 7, overstate the extent of the clean cooking transition [30]. Because only clean fuels used almost exclusively bring household exposure close to health-based targets [7,53], and because improved biomass stoves often deliver smaller gains in everyday use than in controlled tests [75], the persistence of biomass in stacking households limits the environmental and health dividends of the transition. Our accounting suggests that stacking represented up to 6% of residential firewood use, a modest share at the national level but a relevant one for indoor exposure in the affected households.

From an environmental perspective, the transition avoided about 1.9 Mt of firewood and 1.0 Mt CO_2e in 2025 relative to a counterfactual with the 2017 fuel–stove mix. These estimates rely on parameters from the literature and on a fraction of non-renewable biomass between 26% and 36% (mean 31%) [69]. With the national default of 33%, net avoided emissions would be 1.08 Mt CO_2e, and across all the scenarios of Table 8 avoided firewood remains between 1.6 and 2.2 Mt; the carbon benefit would be larger in departments with higher non-renewability and lower where woodfuel harvesting is sustainable [3,4,47]. Unlike many offset methodologies, which have been shown to over-credit emission reductions partly because of how they treat fNRB, stove usage and stacking [48], our accounting uses observed stove portfolios, including the biomass share of stackers. The $PM_{2.5}$ emissions avoided are likely to be more important for local air quality and health than the avoided greenhouse gas emissions are for national totals, and avoided black carbon emissions, not quantified here, would add to the near-term climate benefit [5].

The results suggest three policy implications, which are consistent with the evidence but were not tested as policy effects. First, because no robust price association was found, this study does not establish that the generalized LPG price freeze reduced firewood use. The freeze is costly—the Central Bank reports fuel subsidies of about 27.4 billion lempiras in 2022–2025, of which LPG is a part [76]—and largely invisible to beneficiaries; whether targeted and salient support for rural and low-income households could achieve similar environmental gains at lower fiscal cost is a hypothesis that deserves evaluation [9,22]. Second, interventions could address stacking explicitly, for example by supporting the adoption of LPG for the cooking tasks that are still performed with wood, such as tortilla preparation, or by combining clean fuels with high-efficiency biomass stoves where full substitution is not feasible, as suggested by field evidence from Guatemala and Mexico [17,31,52] and by scenario analyses for Mexico, which identify this combination as the most effective

for climate mitigation [51]. Third, rural electrification and access to LPG distribution are likely to remain necessary conditions for further progress in the most firewood-dependent areas. Electric cooking can complement LPG, but its climate benefit depends on the generation mix, which regional evidence identifies as the main driver of decoupling in Central America [13,54].

Limitations

This study has several limitations. The EPHPM does not record the quantity or expenditure on firewood, so household firewood use is estimated with literature parameters rather than observed; the Monte Carlo intervals quantify parameter uncertainty but neither survey sampling error nor possible biases in those parameters, which Table 8 explores with alternative assumptions. Stacking is measured directly only in 2016–2019, and the stacking contribution for later years is extrapolated; alternative stacking scenarios change avoided firewood by at most 0.31 Mt. The change of sampling frame in 2017 limits comparisons across the whole period, the public microdata do not cover Gracias a Dios and Islas de la Bahía (except in 2024), and the 2024 file lacks the cluster identifier. The IIA tests are inconclusive, although a binary model that does not rely on IIA gives the same results for firewood use. The bibliometric review is limited to English-language records in Scopus and under-represents the regional and Spanish-language literature. Health outcomes are only available in a few rounds and were not analyzed. Two LPG prices were reconstructed and survey months had to be assumed for some rounds; however, the main conclusion on the price channel holds with observed prices only. Finally, the results are associations from repeated cross-sections and should not be interpreted as causal effects.

6. Conclusions

Between 2013 and 2025, the share of Honduran households cooking primarily with firewood fell from 55.6% to 37.7% (about 13 points at constant territorial composition), LPG became the main cooking fuel, and the share of households exposed to the most polluting cooking conditions halved. Three groups of results should be distinguished. The statistically supported results are the decline in firewood use, its strong association with urban residence, electricity access and income, the small share of the 2017–2025 decline explained by changes in household characteristics (about one fifth), and the prevalence and intensity of fuel stacking among households in transition. The environmental benefits are model-based estimates that rest on parameters from the literature: relative to the 2017 situation, the transition avoided about 1.9 Mt of firewood (1.6–2.2 Mt under alternative assumptions) and 1.0 Mt CO_2e per year, a carbon benefit that depends strongly on the non-renewable fraction of harvested wood. Finally, the effectiveness of the LPG subsidy was not established: the decline coincided with a sharp real fall in the price of LPG under a generalized subsidy, but the association between the price and firewood use was not robust, so any role of the subsidy remains a hypothesis for future evaluation. Consolidating these gains is likely to require policies that reach the rural poor, address the cooking tasks that still rely on wood, and monitor stove use rather than only the primary fuel.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13110601/s1, Table S1: Price of the 25-lb LPG cylinder at the time of each EPHPM round, with sources and calibration data; Table S2a: Scopus search strings used for the bibliometric analysis; Table S2b: Records in the bibliometric corpus; Dataset S1: Aggregated data underlying all tables and figures of the article.

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Abbreviations

The following abbreviations are used in this manuscript:

AME	Average marginal effect
CDM	Clean Development Mechanism
CO_2e	Carbon dioxide equivalent
EPHPM	Encuesta Permanente de Hogares de Propósitos Múltiples (Permanent Multipurpose Household Survey)
fNRB	Fraction of non-renewable biomass
IIA	Independence of irrelevant alternatives
INE	Instituto Nacional de Estadística (National Institute of Statistics)
LPG	Liquefied petroleum gas
$PM_{2.5}$	Fine particulate matter (diameter ≤ 2.5 µm)
SDG	Sustainable Development Goal

Appendix A

Table A1 reports the LPG price series used in Section 4.5. Observed prices correspond to the regulated price structure for Tegucigalpa in or near the survey month; 2016–2017 values are quarterly averages reported in US dollars by CEPAL [24] converted at the annual average exchange rate [58]. Values for 2013 and 2015 are reconstructed with Equation (3). The nominal price was frozen at L238.13 from February 2022 [10,11]. The full list of sources for each observation is provided in Table S1.

Table A1. Price of the 25-lb LPG cylinder in Tegucigalpa at the time of each survey round.

Year	Survey Month	Nominal Price (L)	Real Price (2019 L)	Basis
2013	May	268.92	342.3	Reconstructed (95% PI 240–298)
2014	June [a]	271.95	326.2	Regulated price, May 2014
2015	June [a]	241.47	280.8	Reconstructed (95% PI 212–271)
2016	June	217.84	246.6	CEPAL, Q2 (USD 9.54)
2017	June [a]	262.12	285.5	CEPAL, Q2 (USD 11.16)
2018	July–August	288.12	300.7	Regulated price, June–July 2018
2019	June [a]	278.24	278.2	Regulated price, January–June 2019
2021	October	238.13	220.3	Regulated price with subsidy
2022	June [a]	238.13	201.9	Frozen price (decree 01-2022)
2023	June	238.13	189.3	Frozen price
2024	June	238.13	181.0	Frozen price
2025	July	238.13	173.0	Frozen price

[a] Main round of the survey (INE convention 'EPHPM junio'); exact fieldwork month not documented. PI, prediction interval. Reconstruction: P = 188.1 + 4.43 × (Mont Belvieu propane price two months earlier × exchange rate); R^2 = 0.71; leave-one-out RMSE = L15.1 (n = 35).

Appendix B

Table A2 lists the parameters and distributions used in the Monte Carlo accounting of Section 3.7.

Table A2. Parameters of the environmental accounting.

Parameter	Value or Distribution	Source
Per capita firewood use, open fire (kg/person/day)	Uniform (2.5, 5.2)	[8,9]
Fuel saving, improved stove (eco-fogón)	Uniform (0.40, 0.60)	[8,52]
Fuel saving, traditional stove with chimney or Lorena	Uniform (0, 0.20)	Assumption
Net calorific value of wood (MJ/kg)	15.6	[68]
Emission factors, residential wood (g/MJ)	CO_2 112; CH_4 0.300; N_2O 0.004	[68]
Fraction of non-renewable biomass, Honduras	Uniform (0.26, 0.36), mean 0.31; national default 0.33	[69]
Global warming potential (100 years)	CH_4 27.0; N_2O 273	[70]
$PM_{2.5}$ emission factor (g/kg wood)	8.5 × Uniform (0.7, 1.3)	[6]
LPG use of LPG households (25-lb cylinders/month)	Uniform (0.75, 1.5)	Assumption
LPG net calorific value (MJ/kg); CO_2 factor (g/MJ)	47.3; 63.1	[68]
Electricity for cooking (sensitivity only)	1–3 kWh/day per household; 0.61 t CO_2/MWh	Assumption; [71]

Appendix C

Table A3 reports the detailed results of the non-linear decomposition summarized in Figure 9.

Table A3. Non-linear decomposition of the change in the probability of using firewood, 2017–2025.

Component	Percentage Points	SE	Share of Change (%)
Total change (2017–2025)	16.2	1.1	100.0
Explained by characteristics	3.2	0.7	19.6
Unexplained	13.0	1.0	80.4
Log per capita income	0.4	0.1	2.4
Household size	1.3	0.2	8.3
Refrigerator	1.0	0.2	6.0
Schooling of head	0.8	0.2	5.0
Urban area	0.6	0.2	4.0
Grid electricity	0.3	0.1	1.9
Age of head	−0.6	0.1	−3.6
Children under 5	−0.6	0.2	−3.6
Other covariates [a]	−0.1	—	−0.8

Non-linear decomposition with pooled logit coefficients and Yun weights; income in constant 2019 lempiras; year effect fixed at its 2017 value (with the 2025 year effect the explained part is 4.0 points, 24.8%; with nominal income it is 5.1 points, 31.5%); survey-weighted; standard errors from 200 design bootstrap replicates. Contributions of individual covariates are indented. [a] Female head, adults aged 65+, television, motorcycle, car and computer.

Appendix D

Table A4 reports the stability test of the main trends described in Section 3.1, and Table A5 the robustness checks of the fuel choice model described in Section 3.3.

Table A4. Households using firewood and LPG as the primary cooking fuel under alternative territorial samples (%, survey-weighted).

Year	Firewood: All Rounds as Published	Firewood: Common Territory [a]	Firewood: 2017 Composition [b]	LPG: As Published	LPG: Common Territory [a]	LPG: 2017 Composition [b]
2013	55.6	55.6	51.7	24.9	24.9	27.4
2014	49.5	49.5	52.2	28.6	28.6	26.2
2015	50.7	50.7	54.0	30.2	30.2	26.8
2016	48.1	48.1	52.1	30.9	30.9	27.3
2017	53.1	53.1	53.1	28.2	28.2	28.2
2018	53.2	53.2	52.8	29.6	29.6	29.1
2019	51.8	51.8	51.3	31.2	31.2	30.6
2021	48.6	48.6	48.4	35.7	35.7	34.3
2022	45.1	45.1	n.a.	37.4	37.4	n.a.
2023	42.4	42.4	n.a.	39.7	39.7	n.a.
2024	38.2	38.6	39.5	44.5	43.0	42.0
2025	37.7	37.7	38.6	46.3	46.3	44.6

[a] Excluding Gracias a Dios and Islas de la Bahía, which appear only in 2024 (270 households). [b] Households reweighted to the 2017 distribution by department and urban–rural area (16 departments); not available for 2022 and 2023, when department codes are not released. Shares are computed with unrounded values.

Table A5. Robustness of the average marginal effects on the probability of using firewood as the primary cooking fuel (percentage points).

Variable	(1) Main Model (Table 3)	(2) Binary Logit, Firewood vs. Clean Fuels	(3) Without Demographic Controls	(4) Common Territory, 16 Departments
Urban area	−36.0 (0.5)	−36.0 (0.5)	−42.6 (0.5)	−36.2 (0.5)
Grid electricity	−24.2 (0.9)	−23.8 (0.9)	−26.0 (1.0)	−23.8 (0.9)
Log labour income per capita	−7.6 (0.2)	−7.6 (0.2)	−10.7 (0.2)	−7.6 (0.2)
Schooling of head (years)	−2.3 (0.1)	−2.3 (0.1)	—	−2.3 (0.1)
Female-headed household	−2.3 (0.4)	−2.3 (0.4)	—	−2.3 (0.4)
Age of head (10 years)	+1.7 (0.1)	+1.6 (0.1)	—	+1.7 (0.1)
Household size (persons)	+1.7 (0.1)	+1.7 (0.1)	—	+1.7 (0.1)

Table A5. *Cont.*

Variable	(1) Main Model (Table 3)	(2) Binary Logit, Firewood vs. Clean Fuels	(3) Without Demographic Controls	(4) Common Territory, 16 Departments
Children under 5 (number)	−1.7 (0.3)	−1.8 (0.3)	—	−1.8 (0.3)
Adults aged 65+ (number)	−1.1 (0.4)	−1.2 (0.4)	—	−1.2 (0.3)
Households (n)	67,688	67,688	67,688	67,425

Average marginal effects on the probability of using firewood, in percentage points; standard errors in parentheses from 200 design bootstrap replicates. All models include year fixed effects and an indicator for households without labour income; income in constant 2019 lempiras. (2) Binary logit of firewood versus LPG or electricity, which does not rely on the IIA assumption. (3) Omits the sex, age and schooling of the head, household size, children under 5 and adults aged 65+. (4) Excludes the 270 households from Gracias a Dios and Islas de la Bahía in 2024. IIA tests for model (1): Hausman–McFadden $\chi^2(21) = 280.9$ omitting firewood and 236.8 omitting LPG ($p < 0.001$), negative statistic omitting electricity; Small–Hsiao, median p over 50 random splits = 0.97 omitting firewood, 0.13 omitting LPG and 0.83 omitting electricity.

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