RESEARCH ARTICLE

The Efficiency Leap: A Simulation-Driven Approach toward Ethiopian Energy-Efficient Urban Housing

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Abstract

Enhancing the energy efficiency of urban housing is crucial for improving energy access in Ethiopia, where a persistent gap exists between energy demand and supply. The nationwide Integrated Housing Development Program (IHDP), implemented across diverse climatic zones with limited attention to local context and building energy performance, has inadvertently produced thermally uncomfortable and energy-inefficient urban dwellings. This study employs a scenario-based intelligent energy simulation framework to address this inefficiency by identifying energy-saving opportunities in urban housing, pioneering the smart meter data-driven ClimateStudio–EnergyPlus workflow—validated through machine-readable consumption analytics (R^2 = 0.79 in Addis Ababa; 0.64 in Adama) and on-site surveys across temperate highland Addis Ababa and hot-arid Adama. Appliance usage inventory reveals cooking dominance, accounting for 60–62.9% of total loads. Adama's 20% household fan-based thermal coping behavior signals a latent air-conditioning demand projected to surge 31% above baseline in arid lowlands versus 6% in temperate zones as affordability erodes overheating tolerance. Monthly consumption heatmaps reveal unit-size and seasonal interaction effects diverging sharply between cities, with Adama's studio units peaking at approximately 191 kWh/month in the dry season against a stable 150–190 kWh/month range in Addis Ababa. Envelope diagnostics expose a systemic performance gap, wall U-values of 1.61 W/m^{2}K and glazing SHGC of 0.86–0.87 exceeding best-practice targets by three- to fourfold, with Adama's larger glazed area compounding solar heat gain risk in the climate zone least suited to absorb it. Targeting dominant local cooking appliance upgrades yields immediate operational savings of 18–18.9%. Furthermore, these empirical benchmarks recommend region-tailored building envelopes in conjunction with Minimum Energy Performance Standards (MEPS) for cooking appliances, establishing foundational performance data for Ethiopia's unimplemented building codes and informing climate-affordability demand forecasting to achieve policy-aligned efficiency gains.

Keywords: energy efficiency, IHDP housing, smart meter data analytics, intelligent building simulation, latent cooling

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demand, climatic zoning.

1 Introduction

Urbanization in developing countries is happening at an unprecedented pace, and it has severely impacted the global effort to reduce building energy consumption. Ethiopia along with the rest of Sub-Saharan Africa, is at a critical juncture [1]. A rapidly increasing urban population, new middle-class aspirations, and an already overloaded electricity grid are all coming together in Ethiopia to create one of the most difficult environments for building energy use in the world [2]. The environmental and energy consequences of this rapid urbanization are compounding: in Sub-Saharan Africa, rising incomes are projected to drive a highly unequal growth in residential cooling energy demand, with the wealthiest households showing the fastest AC adoption rates [3]. Spatial analysis of Adama's urban expansion further confirms that the city has undergone rapid and accelerating outward growth, driven by the same forces of urbanization and climate change that compound pressure on infrastructure and building energy demand [4]. Improving energy efficiency has been a widely accepted for a long time as a highly cost-effective measure on the demand side to help close the energy access gap in fact, it is sometimes referred to as the "fifth fuel" of the energy transition [5]. Still, such a strategy would rely heavily on having access to real data, locally calibrated benchmarks, and climate-differentiated datasets, which are unfortunately still very limited in Ethiopia [6, 7], in contrast to bottom-up household energy assessments that have begun to emerge in other Global South cities such as Kigali, Rwanda [8].

Integrated Housing Development Program (IHDP), a massive state project aimed at fixing the long-standing urban housing shortage, which was launched in the early 2000s, is the major player in the urban housing sector in Ethiopia. The program has created hundreds of thousands of condominium units around the country, which span vastly different climate zones, for example, the cool subtropical highlands of Addis Ababa (elev. 2,355 m) versus the hot semi-arid rift valley lowlands of Adama (elev. 1,712 m). Most importantly, however, the IHDP was carried out mostly following a uniform design template without considering the various local climates, patterns of occupancy, or regional cultural habits [9]. This rather simplistic tactic resulted in building envelopes with quite poor thermal performance, such as wall U-values of 1.61 W/m^{2}K and glazing U-factors over 5.7 W/m^{2}K, exceeding international best-practice targets by a wide margin [10].

This design disconnect has resulted in many negative effects on the residents' lives. In cities located in temperate highland areas, cooking appliances dominate electricity consumption and their interaction with seasonal occupancy patterns—with residents spending longer periods indoors during cooler months—emerges as a primary driver of thermal discomfort and energy use, as cluster analysis of IHDP housing energy data confirms [11]. On the other hand, in hot-arid lowland cities, the lack of proper passive cooling designs put occupants in a situation where they would have to regularly use electric fans and, with the coming of higher incomes, air-conditioners, thus making a behavioral pattern that sets the stage for a sharp, compounded growth in residential electricity demand. Such projections underscore the urgency of understanding current consumption baselines and efficiency potentials to inform the country's nascent energy efficiency policies, such as the Ethiopian Energy Authority's (EEA) 2019 Energy Efficiency Program (EEP), which aims for substantial savings through MEPS and building codes [12]; yet, as residential electricity demand modelling studies have underscored, the program lacks the granular empirical foundation needed for effective implementation [13]. Nevertheless, as at the time of writing, the residential building code has not been carried out, while no empirical baseline data has been available, thus evidence-based policy is stuck in a stalemate.

On this note, the current paper offers three distinct contributions to the field. Firstly, the authors created and validated the very first simulation workflow: ClimateStudio, EnergyPlus for Ethiopian IHDP residential blocks which was fine-tuned with 2022 smart meter data from 210 housing units located in Addis Ababa and Adama through ASHRAE Guideline 14 criteria [14]. Secondly, it delineates the climate-dependent latent air-conditioning demand trajectories, these trajectories have great implications not only for grid planning but also for investing more in renewable energy capacity and enhancing climate resilience. Finally, the study wisely pinpoints the efficiency changes that have the potential for implementation reduction of operational energy thus giving a quick scalable, culturally cognizant solution which can be used as a platform for Ethiopia's first data-driven residential MEPS. All in all, these contributions lay down the replicable, distinct climate zone-specific quantitative benchmarks which can later be the foundation of building codes, energy labeling, and green building certification of the residential sector in the rapidly developing country.

The specific objectives of the study are to: (i) create and validate calibrated building energy models of IHDP residential blocks in different Ethiopian climatic zones using real smart meter data; (ii) to establish the baseline energy consumption profiles for different appliances at the end-use level in both climatic zones; (iii) to estimate hidden air-conditioning demand under affordability-driven behavioral scenarios; and (iv) to determine the energy saving potential that can be realized through targeted appliance upgrades, thus providing a source of evidence for the implementation of the current Energy Efficiency Program that is yet to be realized in Ethiopia.

2 Energy Efficiency in Ethiopian Urban Buildings

2.1 Ethiopia's Energy Landscape

Ethiopia's energy sector is marked by a significant paradox. The country possesses a vast potential for renewable energy, especially hydropower, which makes up about 90% of the total electricity generation capacity of the country. However, the country's per-capita electricity access is still one of the lowest in the world [15]. For instance, in 2023, only around 50% of Ethiopians had access to electricity, and those using clean cooking solutions were less than 6%. The shortage of electricity in Ethiopia is still in the shadow of an almost total reliance on biomass for energy, which accounts for about 88% of the total national energy consumption and has caused problems such as worsening deforestation, indoor air pollution, and health issues [16].

Nonetheless, the transition of household energy sources into urban areas is gaining pace. Since 2010, the population of Ethiopia's urban areas has been increasing by over 4% annually, and the electrification of formal urban housing has experienced a sharp rise with urban households now accounting for nearly 52% of the national electricity supply, a share that increased by 36.5% from 2017 to 2021 [9, 12]. As they get connected to electricity, households are gradually leaving behind biomass for cooking by using electric appliances, acquiring refrigerators, and, especially in warm places, getting electric fans and air conditioners. If it remains unmanaged, such a shift—already evident in the behavioral changes documented among electrified urban households—could accelerate appliance acquisition and peak-hour demand in ways that stretch Ethiopia's grid infrastructure [17].

2.2 The IHDP Housing and Its Design Challenges

The Integrated Housing Development Program (IHDP) kicked off in 2005 and is a public housing project in line with Sub-Saharan Africa's most ambitious housing programs. By 2020, the program had brought to the residents of Addis Ababa alone more than 400,000 condominiums, and further developments are being made in cities such as Adama, Dire Dawa, Hawassa, Gondar, and Mekelle [18, 19]. IHDP's preferred designs were standard G+3 to G+7 concrete block structures with minor envelope changes between climate zones. The lack of climate-responsive design is a major disadvantage of IHDP lowland hot-arid cities' housing: all materials considered, the same wall construction, glazing specifications, and window-to-wall ratios used in the cool 15°C-mean-temperature highlands are also the ones used in cities where mean temperatures regularly exceed 24°C and cooling degree days are much higher [20].

Some recent thermal comfort checkups confirmed that the inhabitants of free-running houses in IHDP, Jimma, can bear an indoor operative temperature of 32 to 36 degrees Celsius during hot seasons. The main reason is that they cannot buy air conditioners due to lack of money [21]. This is a form of behavioral compliance although residents have gathered a huge latent cooling demand which will get materialized when incomes are up and cooling appliances are affordable. Knowing this change is essential for both grid planning and implementing efficiency measures that can match and reduce the demand before it is established.

2.3 The Ethiopian Energy Efficiency Program

According to the Ethiopian Energy Authority (EEA) 2019 Energy Efficiency Program, there are five main intervention areas for the local residential and building sector: (i) Minimum Energy Performance Standards for electrical appliances, starting with injera mitads (the culturally very popular electric griddle to make injera flatbread), electric stoves, refrigerators, air conditioners, and lighting; (ii) mandatory building energy codes focusing on the building envelope in commercial and residential buildings; (iii) voluntary energy performance certification; (iv) utility demand-side management programs; and (v)

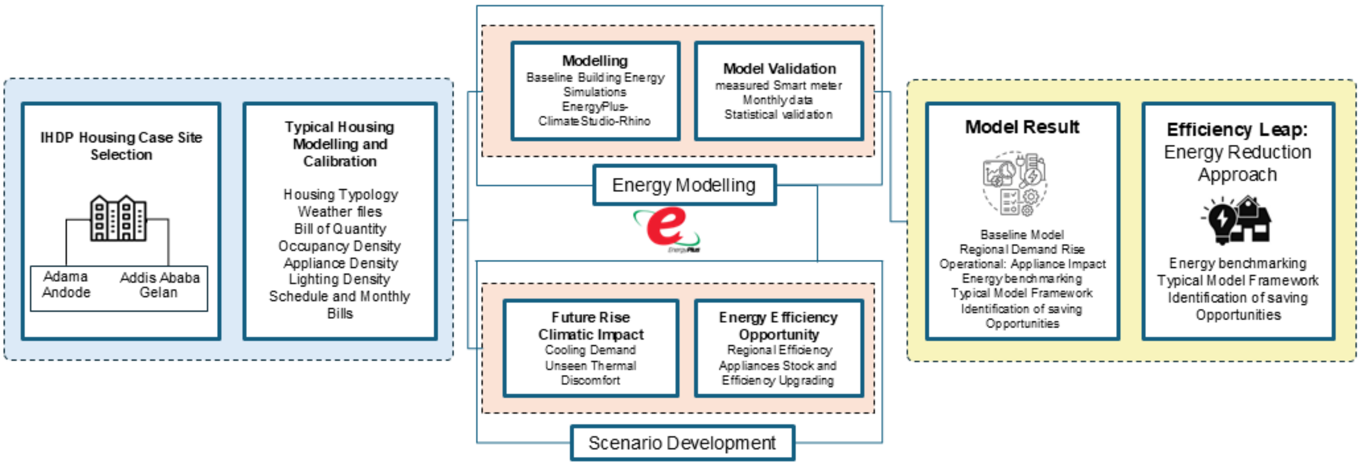

Figure 1. Study Flowchart, Research flow work from Case housing selection to conclusion.

capacity building for energy auditors and building professionals [12]. Significantly, the EEP estimates that MEPS for injera mitads and stoves alone could save 23,442 GWh cumulatively up to 2030, the greatest single efficiency measure of the entire program, thereby demonstrating the importance of electric cooking for the culture of Ethiopian electrified households [22].

Besides this appealing program, actual work has gone by slowly. Until 2023, the residential building code was not yet in force and the appliance labeling and certification were very basic [23]. One of the main structural problems is that there are no empirical residential energy benchmarks: you can neither fix reasonable, enforceable efficiency standards nor prove compliance, without proper baseline data for actual energy use patterns at the level of end-use, household type, and climate zone. This work fills this hole in literature.

2.4 Building Energy Simulation in Data-Scarce Contexts

Intelligent Building Performance Simulation (BPS) combined with smart meter data analytics has become one of the main tools in providing empirical energy benchmarks where real data are not sufficiently available [24]. The EnergyPlus engine is a product of the U.S. Department of Energy that performs heat transfer, air flows, internal gains, and HVAC system performance simulations every hour [25]. However, the degree to which BPS results can be trusted is highly dependent on whether or not model calibration has been done against measured data and the extent to which ASHRAE Guideline 14 calibration protocol has been adhered to [14], and how accurate the schedules fed to the model for occupancy, appliance usage, and metabolic loads are. In developing countries, these schedules are usually undocumented and require a special field survey. Hence, this study responds to this issue by doing a well-organized household survey of 210 units thereby documenting not only the occupancy patterns, the list of appliances, but also the usage behaviors including those cultural practices like the communal injera baking event that results in large and very short spans of cooking load.

The combination of ClimateStudio with the EnergyPlus engine gives a parametric, Rhino 3D-native environment. This permits quick changes of model parameters and facilitates scenario drafting, which makes it an excellent choice to conduct the multi-zone comparative analysis found in this paper [26]. Based on the authors' knowledge, they have not found any previous publication that has combined a ClimateStudio, EnergyPlus workflow calibrated against smart meter data in the Ethiopian residential sector.

3 Methodology

The research chose to use a multi-staged, bottom-up Building Performance Simulation (BPS) method with scenario-based analysis, which was organized into four consecutive phases: (i) site selection and case building documentation; (ii) household survey and appliance inventory; (iii) parametric energy model construction and smart meter calibration; and (iv) scenario simulations for future demand trajectories and appliance upgrade potentials (Figure 1).

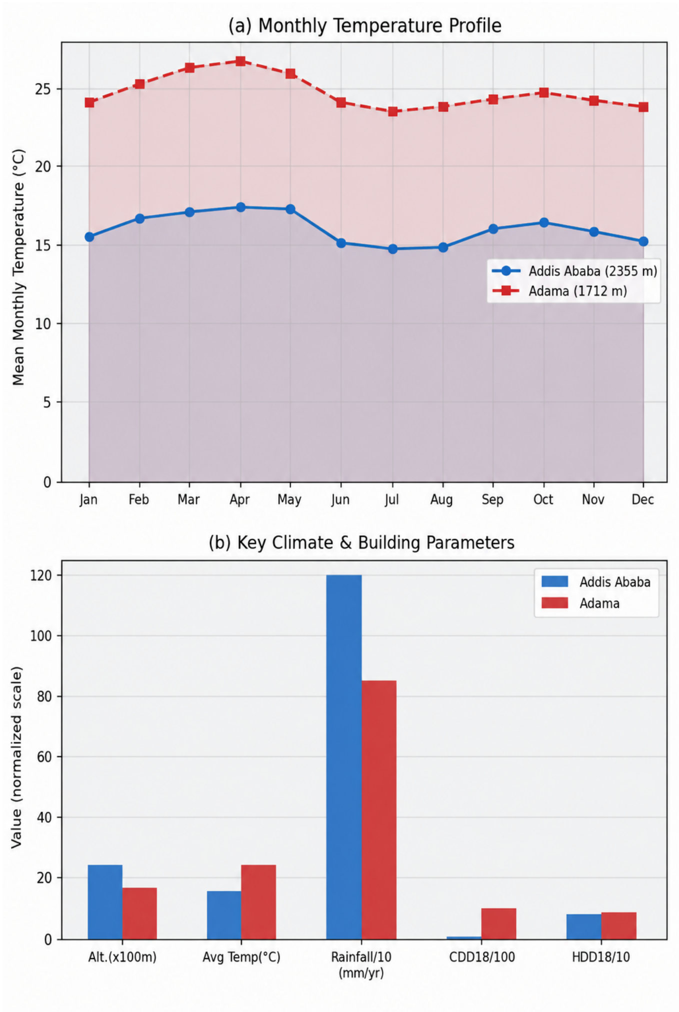

Figure 2. Study Area Climate Context: Monthly Temperature Profiles and Key Climate-Building Parameters for Addis Ababa and Adama.

3.1 Study Area and Case Building Selection

Ethiopia covers a wide range of climatic conditions (Figure 2). These range from mild subtropical highlands (Köppen classification Cwb) to hot semi-arid lowlands (Köppen BSh), with altitude being the main factor determining temperature [20]. Two cities were chosen to illustrate the ends of this range: Addis Ababa (9.0°N, 38.7°E; elevation 2,355 m) the national capital and the largest single urban IHDP project in the country and Adama (8.5°N, 39.3°E; elevation 1,712 m) the main city of the regional hot rift valley, which is 99 km southeast of Addis Ababa by road. These two cities represent the main climatological difference between Ethiopian IHDP deployments. Additionally, they correspond to the climate zonation structure of EEA's Energy Efficiency Action Plan [23].

The case housing type, which is named M units for intermixing balanced diversity within single-block structures, is taken from Gelan IHDP housing sites in Addis Ababa, the city that is anticipated to have 70% of its formal housing stock consisting of both Government and IHDP houses. Besides this, it has a subtropical highland climate [18, 27, 28]. The second source is the Andode housing estates in Adama, which lie 99 km to the southeast at an elevation of 1,712 m. The prevailing climate is hot semi-arid, and remote sensing analyses confirm that Adama exhibits pronounced land surface temperature elevation and urban heat island intensity [29, 30], compounding the thermal stress on building envelopes in a climate zone already classified as BSh under the Köppen system [31]. These locations make a direct comparison of envelope, appliance, and future possible energy demand rise across climatic gradients (Figure 3).

3.2 Household Survey and Appliance Inventory

A detailed field survey was carried out of 210 housing units. To assist with analysis, the units were first broken down by bedroom typology (studio, one-bedroom, two-bedroom, three-bedroom) and then further by site. The survey instrument comprised three main modules: (i) physical building characterization, which accounted for verification of envelope materials, accurate measurement of windows, assessment of infiltration, and evaluation of shading conditions; (ii) occupancy profiling, i.e., determining household size, enumerating daily routines, noting seasonal changes and cultural events influencing energy consumption; and (iii) appliance inventory, which took into consideration household appliance ownership levels, rated power, frequency of usage, and estimated hours of operation for each device category. A special focus was put on the appliance inventory of the 'injera mitad', the electric ceramic griddle used to bake injera, the staple Ethiopian flatbread, because of its high-electricity consumption (usually 3.5 kW) and societal usage patterns that result in very large cooking loads that are temporally highly clustered.

The utility company provided monthly electricity consumption figures for the year 2022 for each of the surveyed units. Those data were derived from smart meters installed by the Ethiopian Electric Utility (EEU) and thus are very reliable. In fact, the metered data were the main calibration data set for the energy models. To obtain data on fan usage in terms of quantity and hours, field observation and interviews were combined to produce such results since the devices were not running on sub-metered circuits and

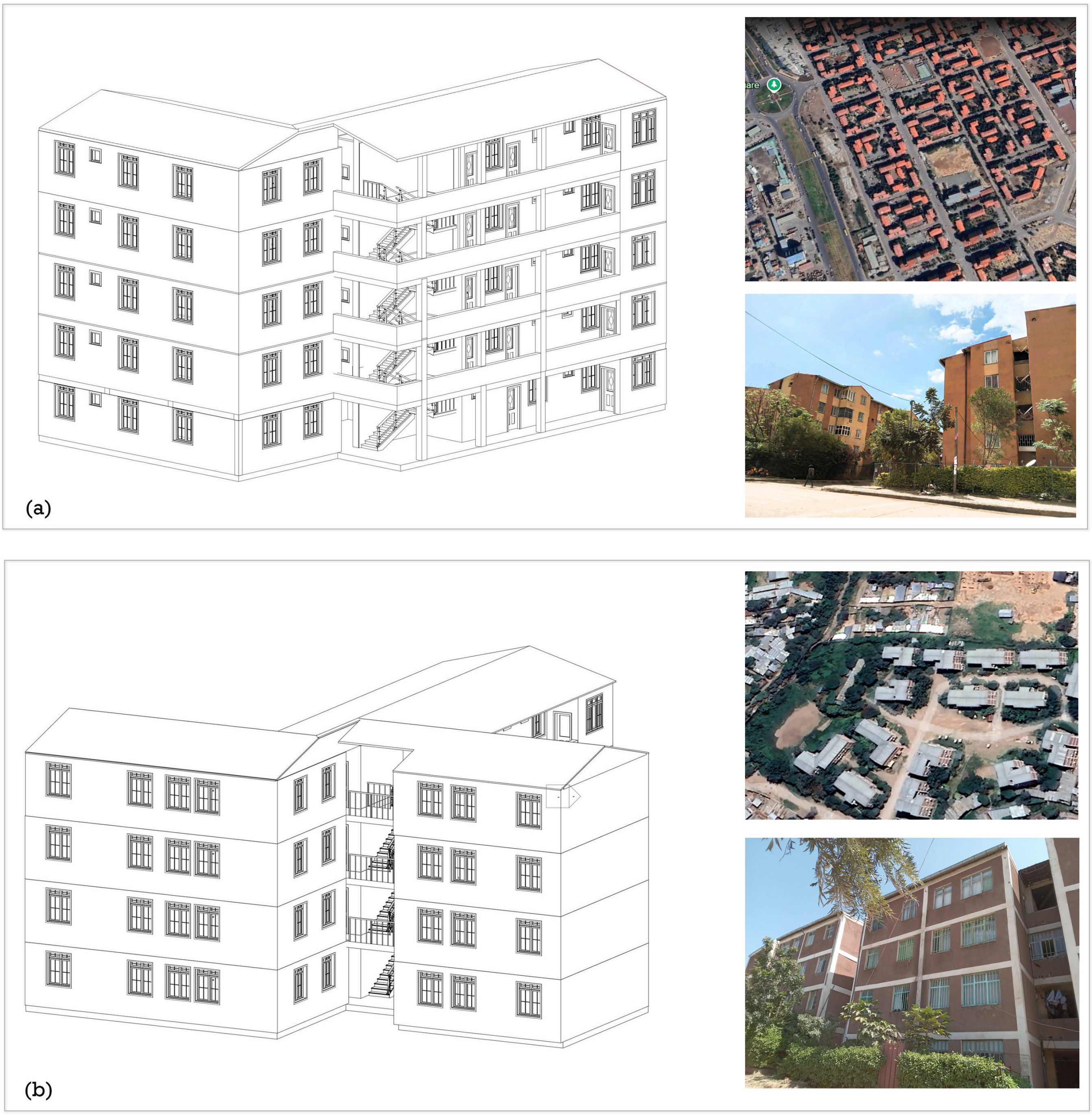

Figure 3. Study area and Case Buildings M1 IHDP Typology; (a) Addis Ababa, (b) Adama.

therefore there was no access to usage data. In Adama city, only 20% of the households were observed to own a fan, and the average operation during the day (in this case, afternoon) was about 4 hours during months when the temperature is most uncomfortable (April, October), thus agreeing with field observations.

3.3 Building Energy Modeling Framework

Parametric Building Energy Models (BEMs) were generated by the ClimateStudio platform integrated with Rhinoceros 3D (Rhino), where the simulation calculations were done using EnergyPlus 8.8 [25, 26]. The geometric 3D model in Rhino for the case buildings was based on architectural drawings from the Federal Ministry of Urban Development and Housing and was checked against the field measurements. Thermal zoning was done based on each unit, where each flat was a separate thermal zone, and the corridors and stairs were given appropriate boundary conditions.

The resulting energy models for both cities are illustrated in Figure 4, showing the detailed 3D representation of the building geometry, thermal zoning, and surrounding context used for the EnergyPlus simulations.

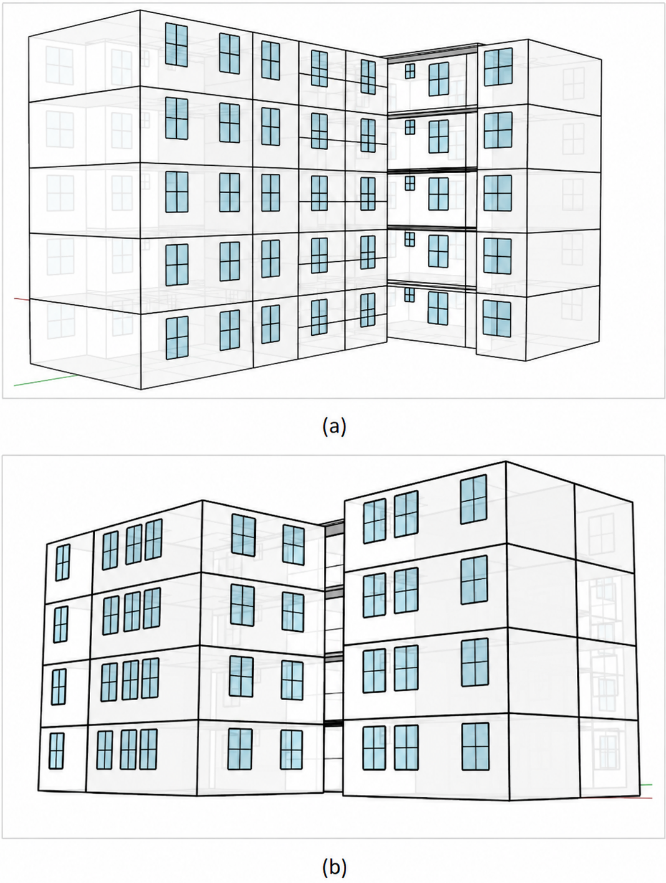

Figure 4. Developed Energy Model of the Case Buildings: (a) Addis Ababa , (b) Adama Model.

The assignment of material properties was based on the documentation of the construction and the on-site verification of the material specifications for the walls of the concrete block, the floors of the ceramic tiles, the single-clear glazing units, and the roofing of corrugated metal sheets which are the main features of IHDP construction. Key envelope parameters are provided in Table 1. The weather data were obtained from EnergyPlus weather files (EPW) for Addis Ababa Bole International Airport and Adama, and local humidity adjustments and solar radiation were made based on site-specific-records wherever available. The operational schedules for occupancy, lighting, appliance use, and ventilation were directly taken from the household survey data.

3.4 Model Calibrations

After that, the model calibration followed the ASHRAE Guideline 14-2014 protocol for the monthly calibration of whole-building energy models [14]. The main calibration measure was Mean Bias Error (MBE), calculated for twelve months in 2022 and $|MBE| \leq 5\%$ was the required level of acceptance for monthly calibration (Table 2). In addition, the Normalized Bias Error (NBE) and the Root Mean Square Error (RMSE) were also computed for the model's secondary validation performance. At the very beginning, the model runs totally predicted the consumption in both cities, which is a consistent phenomenon of the "performance gap" well documented in literature whereby energy models as-designed always overestimate the consumption compared to actual behavior [32].

Calibrating the models involved repeated adjustments of: (i) the appliance usage schedules to thus more closely mirror the survey behavior documentation; (ii) the air leakages that were changed based on the blower door test results; (iii) the metabolic rates of the occupants; and (iv) the fan and lighting partial-use fractions.

3.5 Scenario Development

Two potential future scenarios were outlined based on the adjusted baseline models:

- **Scenario 1:** Latent Cooling Demand Trajectory: This scenario depicts the gradual installation of room air conditioners as household income grows and people become less tolerant to heat. The scenario was set based on the fact that 20% of high-income households in Adama were found to have fans, which were used for 4 hours during midday, and the adoption of air conditioning was projected to follow an electrification trend driven by income that is similar to the one witnessed in Sub-Saharan African cities [5]. This scenario measures the additional energy demand that would be generated if full air-conditioning is adopted at the fan-use levels currently observed, thus representing a conservative lower-bound estimate of latent cooling demand.

- **Scenario 2:** Appliance Upgrade Potential: This scenario estimates the extent to which operational energy can be saved by switching the existing inefficient 'injera mitads' and local stoves with efficient ones. The assumption of efficiency improvement of 30% energy reduction comes from the laboratory tests of the high-efficiency electric 'mitads' prototypes by [33], the same number is supported by the field-trial data

Table 1. Summary of input parameters for energy simulation models.

PARAMETER	UNIT	ADDIS ABABA (MODEL 1)	ADAMA (MODEL 2)
Location	–	Addis Ababa (9.0°N, 38.7°E)	Adama (8.5°N, 39.3°E)
Climate Zone	–	Subtropical Highland (Cwb)	Hot Semi-Arid (BSh)
Building Stories	No.	5 (G+4)	4 (G+3)
Housing Units	No.	25	28
Roof Area	m^2	200.74	268.13
Ground Floor Area	m^2	200.74	268.13
Gross Floor Area	m^2	1,003.68	1,072.53
Total Window Area	m^2	161.81	172.17
Wall U-value	W/m^2K	1.61	1.61
Glazing U-Factor	W/m^2K	5.71	5.77
Glazing SHGC	–	0.86	0.87
Floor Tile U-Factor	W/m^2K	1.81	1.81
Metal Sheet Roof U-Factor	W/m^2K	1.64	1.64
Occupant Density	P/m^2	0.10	0.11
Appliance Load Density	W/m^2	20.32	16.69
Lighting Load Density	W/m^2	1.59	1.10
Heating/Cooling System	–	None (fans only)	None (fans only)

Note: No mechanical HVAC system is installed in case buildings. Partial electric fan use was documented in Adama (20% household penetration).

Table 2. Sample household monthly electricity consumption (kWh) – 2022 smart meter data.

Month	Adama				Addis Ababa			
	Studio	1-Bed	2-Bed	3-Bed	Studio	1-Bed	2-Bed	3-Bed
Jan	184.1	193.6	229.4	236.9	58.8	141.9	179.2	306.8
Feb	97.0	168.9	218.2	224.2	157.0	103.0	185.5	284.5
Mar	138.7	169.7	297.9	279.7	167.2	135.0	189.4	280.8
Apr	117.8	179.6	218.4	211.9	159.0	134.0	208.4	282.6
May	166.7	206.1	229.1	192.2	160.0	136.3	218.2	288.8
Jun	172.2	215.4	335.9	223.6	159.7	168.8	229.0	258.4
Jul	190.9	201.4	274.2	263.1	153.3	188.6	222.0	214.5
Aug	149.5	226.9	296.4	282.4	171.3	195.0	252.5	127.6
Sep	159.3	229.0	212.1	285.0	152.1	168.3	117.0	121.9
Oct	152.6	223.1	211.9	233.1	154.7	218.6	128.8	129.6
Nov	159.3	188.5	190.9	247.6	152.3	205.7	156.4	118.3
Dec	147.1	205.2	205.0	262.0	161.8	249.1	210.5	123.3

of Ethiopian Energy Authority's own MEPS preparatory studies.

4 Results and Discussion

Calibrated models show that IHDP households in the two cities have a standard baseline electricity consumption of about 240–290 kWh per household per month, which is largely in line with the utility company records for similar formal housing typologies in East African cities, but quite higher than informal settlement consumption, thus reflecting the complete appliance package usually associated with formal housing provision [34]. Figure 5 Stacked bars show simulated end-use disaggregation; lines show measured versus simulated total consumption. R^2 = 0.79, NBE < 1%, RMSE < 15 kWh.

In Addis Ababa, the monthly household energy consumption is very consistent, fluctuating between 219 and 261 kWh per month on average, and there is almost no seasonal variation. This consumption

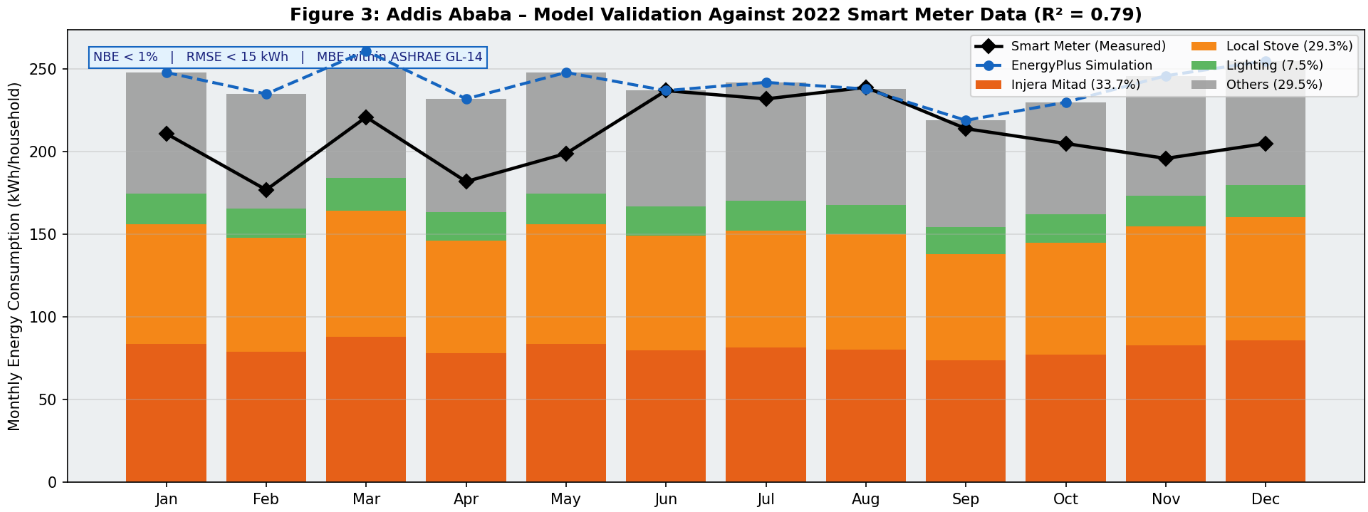

Figure 5. Addis Ababa – Model Validation Against 2022 Smart Meter Data.

trend perfectly fits with the city's subtropical highland climate characterized by mild temperatures throughout the year therefore, without heating or cooling because of these conditions, appliance use is by far the biggest contributor rest to electricity demand. Besides, the two peaks of cooking each day are very visible in the stacked consumption profiles. The evening loads are as high as around 60 kWh monthly and are mostly due to the 'injera mitad' and stove usage. The 'injera mitad' alone accounts for 33.7% of the whole household electricity consumption, which is a combination of its high-power rating (3.5 kW) and its regular use by the culture.

In Adama, Model validation Figure 6 shows Elevated "others" category (gray) reflects electric fan thermal coping. $R^2 = 0.64$, NBE < 1%, RMSE < 15 kWh. The lowest consumption level is 9.5% more than that of Addis Ababa and the average is 215 to 260 kWh each month for most of the year. Only during the October to December discomfort season is there a very significant increase and this is when the day temperatures go above 28°C continuously. The share of cooking appliances has not changed as they still dominate the electricity consumption (60.0% together), but the 'others' category that comprises electric fans and other thermal coping loads has increased by 15 percentage points as compared to those of Addis Ababa and that category has gone up to about 25% of the total consumption during the months of peak discomfort. The raised 'others' component, coupled with the detected 20% fan usage rate, clearly shows that people need thermal comfort, and these needs are being met now by rather inefficient, low energy-consuming methods. Hence, the upscaling of energy use will be very fast once air conditioners become available.

4.1 Appliance Stock Characterization

Appliance stock characterization reveals that cooking appliances are the single largest category of electrical appliances in both cities, together constituting 62.9% of the total electricity consumption in Addis Ababa and 60.0% in Adama. The cooking dominance is a major structural characteristic of the energy profile of Ethiopian urban households, and it is one that sets them apart very much from similar households in South Asian or East Asian cities, where cooking accounts for a much smaller share of electricity use.

The injera mitad alone accounts for 33.7% (Addis Ababa) and 30.3% (Adama) of household electricity, a significant concentration of energy usage in a single traditional appliance. Interviews on the ground confirmed that most families have two mitads (one large for communal baking and another smaller for daily use) and that injera baking sessions, generally lasting 2 to 4 hours, are held several times a week (Figure 7).

The local stove represents a further 29.3% (Addis Ababa) and 29.7% (Adama), which corresponds to its almost universal use for cooking side dishes. Refrigerator possession was shown to be at the highest level in Addis Ababa (around 40% penetration), thereby accounting for ~19.5% of electricity uses among households that own them, whereas in Adama fan ownership was the most popular (20% of households, which during hot months account for around 15% of electricity use among the households owned).

The harmony between the two cities in terms of the

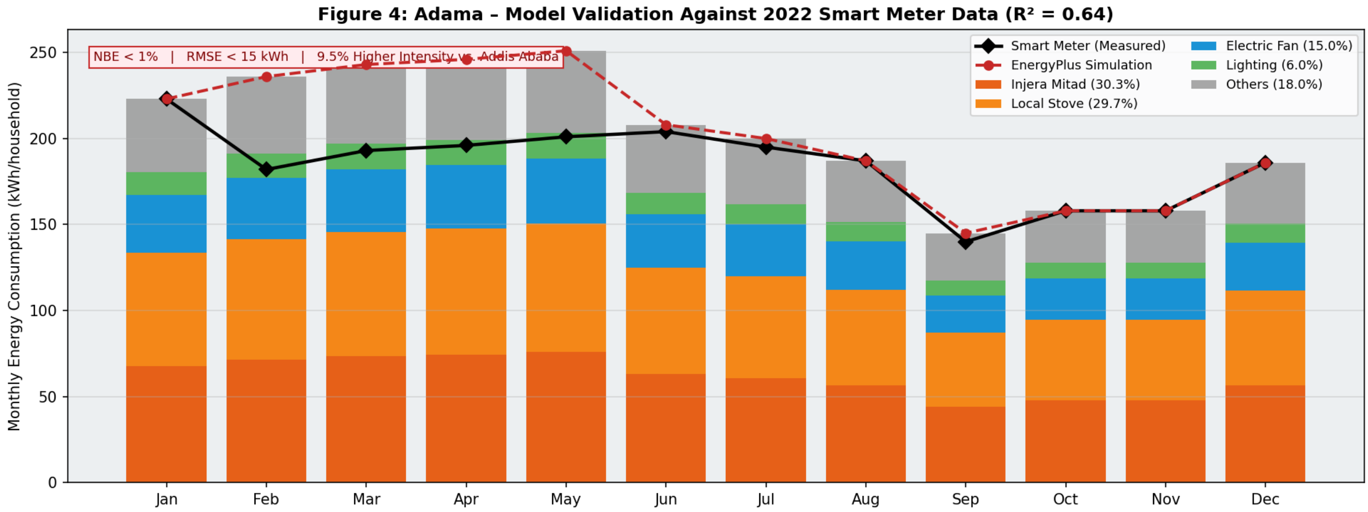

Figure 6. Adama – Model Validation Against 2022 Smart Meter Data.

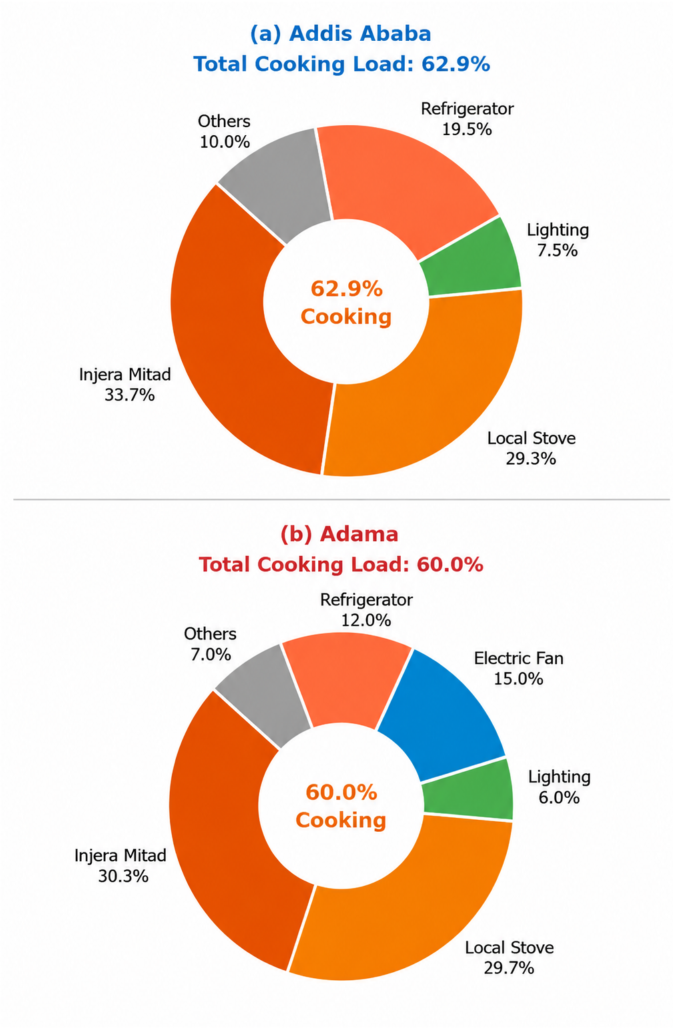

Figure 7. Appliance Energy End-Use Share – IHDP Housing Baseline Consumption (2022). Inner annotation shows combined cooking load share. Note the additional 15% fan load in Adama versus near-zero in Addis Ababa.

share of cooking appliances (60, 63%) is a remarkable result that highlights the cultural commonality of these energy loads throughout Ethiopia's various major climatic zones . This harmony also gives a strong reason for MEPS: making injera mitads and stoves more efficient through technology upgrades brings savings across the entire national IHDP housing stock that are proportionate, irrespective of the climatic zone, and without the need for climate-specific policy instrument calibration.

Figure 8 illustrates the simulated electric energy usage (kWh/month) monthly and further disaggregated by unit types, Studio, 1-Bedroom, 2-Bedroom, and 3-Bedroom, throughout the two cities. In Addis Ababa (blue scale), the consumption pattern rises linearly with the unit size: while studio units consume 150–190 kWh/month on average, 3-bedroom ones use 220–290 kWh/month, thus, directly reflecting the increase in the number of occupants and the density of electrical appliances. The heatmap pinpoints a remarkably steady seasonal variation for all the units, which is in line with the mild temperate climate of Addis Ababa, where month-to-month fluctuations hardly go beyond 15% for any given unit type. The highest levels recorded in 2-bedroom apartments from June to August (up to 252.5 kWh/month in August) correspond to the rainy season changes in occupancy and increased indoor cooking activities when access to outdoor areas is limited.

In Adama (red scale), similar scaling with unit size is observed, but the seasonal pattern is much more significant, especially in studio and 1-bedroom units. Studio electricity consumption in Adama significantly declines from the peak experienced in

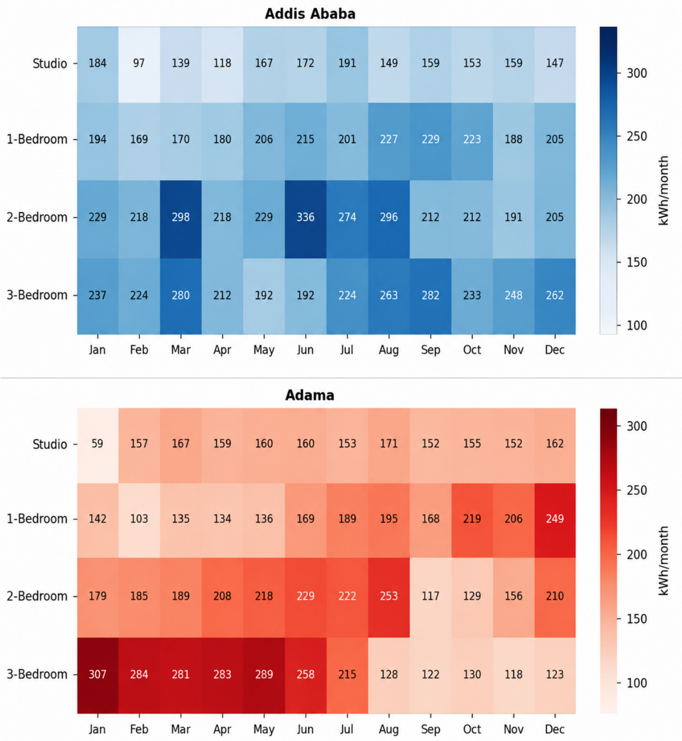

Figure 8. Monthly Smart Meter Consumption Heatmap by Household Type (kWh, 2022). Larger units show higher consumption in both cities; Adama exhibits stronger seasonal variation, particularly in studio units.

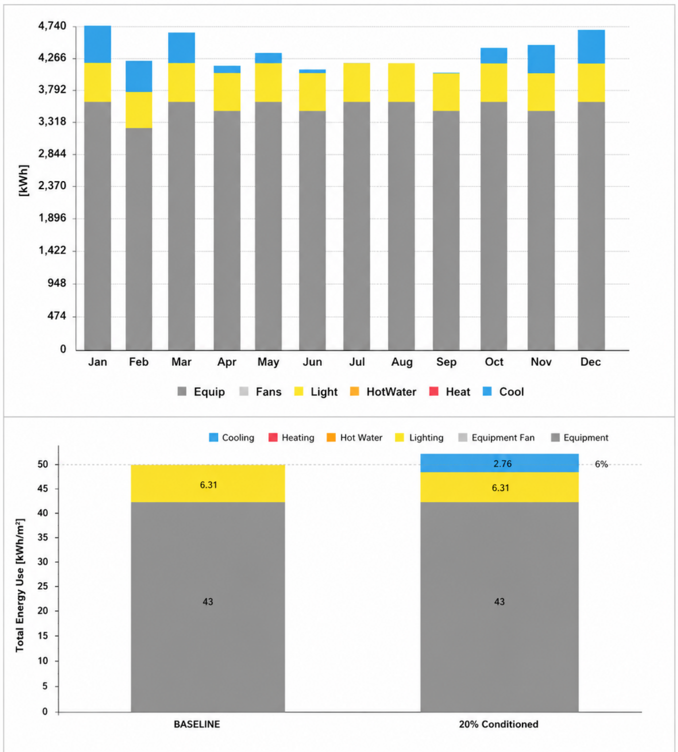

Figure 9. Addis Ababa ClimateStudio projection for Latent Cooling Demand rise.

January (˜184.1 kWh) to the trough in February (~97.0 kWh), which is the consequence of the very distinct thermal discomfort cycle of the hot-arid climate and the fan-based coping behavior that is mostly concentrated among smaller, less-ventilated dwelling units. On the contrary, three-bedroom units in Adama register their highest energy consumption during the first quarter (January: 236.9 kWh/month; March: 279.7 kWh/month), when the combination of large family numbers and total appliance usage during the dry hot season result in peak demand. The heatmap comparison of the two cities supports the conclusion that unit size and seasonality have varying effects depending on the climate zone, and hence, there might be a need for introducing policy instruments such as tiered tariff structures or setting different MEPS thresholds for various unit types to cater to the diverse demand pattern.

4.2 Scenario 1: Latent Air-Conditioning Demand Trajectories

The latent cooling demand scenario discloses very different space cooling demand paths for the two climatic zones. The projected air-conditioning adoption in Addis Ababa results in an incremental increase of only around 6% above the baseline by 2036, because the city is naturally mildly thermally buffered so that space cooling is hardly a physiological need even without mechanical systems (Figure 9).

On the other hand, the scenario in Adama is a 31% increase over the baseline of residential electricity demand by 2036 caused by the combination of the baseline outdoor heat stress being high (average monthly temperatures persistently above 23°C) and the recorded behavioral willingness to buy cooling devices when the income levels are sufficient (Figure 10).

By comparing the two sets of projection charts side-by-side in Figure 11, the climate-driven divergence in latent cooling demand is clearly visible through these two sets of projection charts, as seen in the figures.

As for Addis Ababa (temperate), the area of shaded latent AC demand expands only slightly over the 2022, 2036 period, and the scenario of affordability erosion reaches only a level that is 6% above the 2022 baseline level by 2036.The closeness of the shaded corridor to the flat baseline confirms that the energy consequence of AC adoption is limited by the mild highland climate even if incomes rise and thermal tolerance is eroded. To illustrate this, the adoption curve in Addis Ababa is not very steep and linear which means that the demand

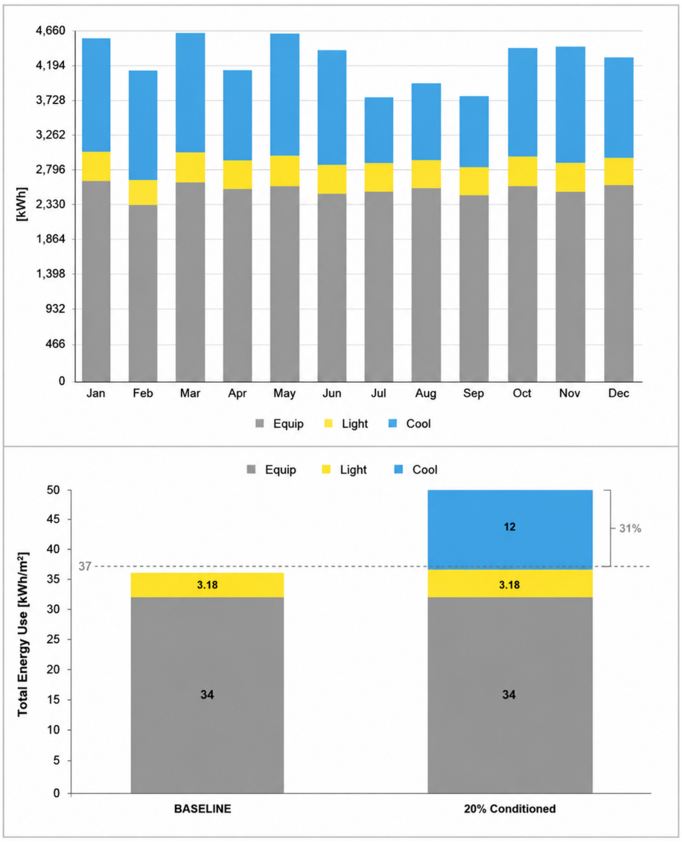

Figure 10. Adama ClimateStudio projection for Latent Cooling Demand rise.

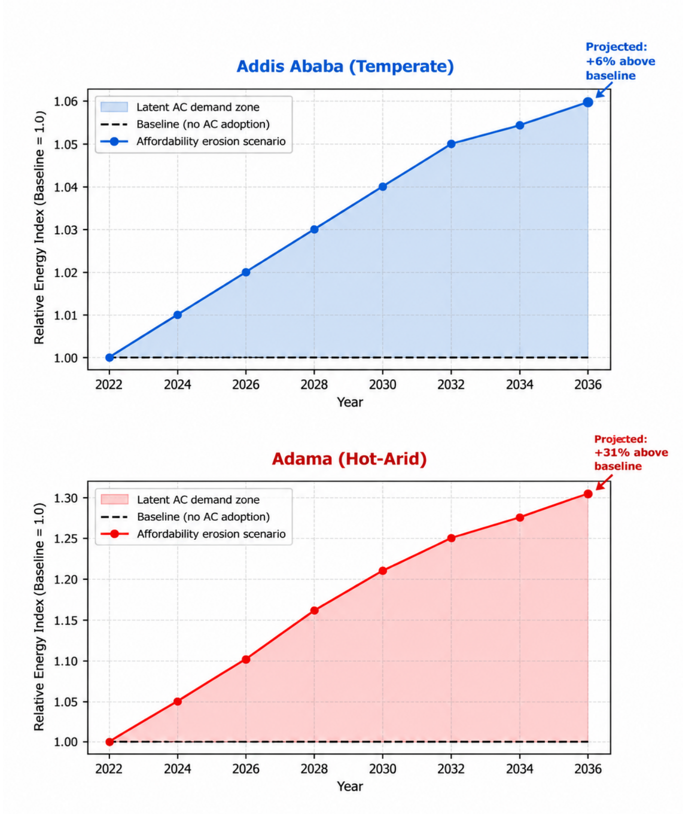

Figure 11. Latent Air-Conditioning Demand Projections Under Affordability-Driven Adoption Scenarios (2022–2036). The shaded zone represents the latent demand corridor; dashed line shows baseline without AC adoption.

growth, if any, will be gradual and can be handled within the current grid capacity planning.

On the other hand, the Adama forecast shows a completely different behavior: the affordability erosion scenario is depicted as a sharply accelerating curve, going as high as 31% over the 2022 baseline by 2036. The increasing shaded area, the latent AC demand corridor, indicates that air conditioning penetration even at a low level amongst the population that currently uses fans only can result in a rapidly increasing demand for energy that will be depleted one after another. This non-linearity is due to two factors: firstly, the already high thermal stress in Adama and secondly, the behavioral readiness for mechanical cooling which can be inferred from the 20% fan ownership rate recorded during the 2023 survey. As a result, these charts show very well that the main risk for uncontrolled growth of demand for cooling is in hot-arid cities like Adama and at the same time the most cost-effective grid protection measure for local authorities is to carry out pre-emptive envelope improvements in such locations.

This finding is in line with the recent study on the thermal comfort measurement data of the same IHDP housing in the Jimma city [21] have reported that the occupants of a hot climate must bear indoor operative temperatures of 32–36°C for their thermal comfort needs because of cost constraints, but they strongly prefer mechanical cooling. Assuming that this AC-readiness is true for all the estimated 80,000 IHDP units in hot-climate cities of Ethiopia, the uncontrolled electrification of space cooling alone could add between 350 and 500 GWh of annual electricity demand to the national grid, by 2036, this is an increment exceeding the annual output of several of Ethiopia's smaller hydropower plants.

The policy implications are drastic: the interventions aimed at improvement of the passive thermal performance of IHDP envelopes in the arid lowland cities should be considered urgently, as a grid-protection measure, not only a comfort upgrade. In particular, reducing the solar heat gain coefficient (SHGC) of the glazing from the present 0.86, 0.87 to below 0.4, along with providing external shading and natural ventilation pathways, can significantly reduce the heat inside the building during the hottest time of the day, therefore, increase the time span when the occupants can stay comfortably without mechanical cooling, thus lowering the rate of AC adoption.

4.3 Scenario 2: Appliance Upgrade Savings

An upgrade from inefficient cooking appliances to high-efficiency ones, especially using an energy-efficient injera mitad that consumes 30% less energy than the current stock, is shown in the appliance upgrade scenario to provide total operating savings of 18.9% in Addis Ababa and 18.0% in Adama (Table 3). These savings result from the 30% efficiency increase being offset against the cooking appliance share (62.9% and 60.0% respectively) that has been documented: $0.629 \times 0.30 = 18.87\% \approx 18.9\%$ (Addis Ababa); $0.600 \times 0.30 = 18.0\%$ (Adama), as explored saving on each appliance consumption in Figure 12.

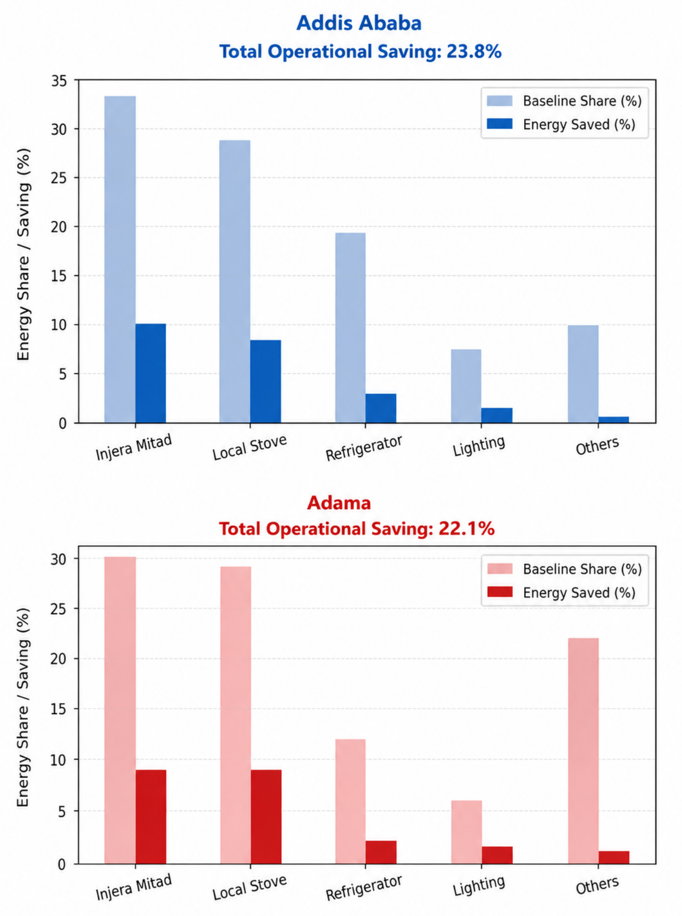

Figure 12. Operational Energy Savings from Targeted Appliance Upgrades. Light bars: baseline appliance share; dark bars: energy savings achieved per appliance category assuming 30% efficiency gain for cooking appliances.

These savings are substantial and come with significant immediacy. In contrast to envelope retrofits that require changing the physical structure of buildings and exposing multi-family units to occupancy barriers from a logistical and financial standpoint, the replacement of appliances can be done through the implementation of regulatory tools (MEPS) that influence new purchases and through focused subsidy or exchange programs. According to the EEA's EEP projections, MEPS for injera mitads may lead to 23,442 GWh of cumulative national savings by 2030 [12], a number that becomes reliable from the empirical cooking dominance evidence in the current research.

Besides direct energy savings, upgrading injera mitads and using efficient local stoves is a good way to achieve most co-benefits: a decrease in waste heat rejection from appliances leads to fewer internal heat gains; thus, room temperature is lowered and the running of fans is reduced both in frequency and intensity in hot-climate cities therefore, the latent cooling demand trajectory Scenario 1 identified is indirectly taken care of. The mutual benefit of appliance efficiency and passive cooling performance really points out the necessity of well-thought-out, multi-lever efficiency strategies coordinated to give simultaneous attention to both the appliance and envelope aspects of IHDP housing.

4.4 Building Envelope Performance Gap

Envelope performance assessment clearly demonstrates that the construction of IHDP is nowhere near the level of the international efficiency standards. Walls with heat transfer coefficients (U-values) of 1.61 W/m^{2}K have a very poor comparison with the 0.30, 0.45 W/m^{2}K band recommended by ASHRAE 90.1-2022 for tropical and subtropical climates (Figure 13). Single-clear glass having U-factors of 5.71, 5.77 W/m^{2}K and Solar Heat Gain Coefficient (SHGC) of 0.86, 0.87 is undoubtedly the biggest drawback of Adama. Here, unregulated solar gain through the south- and west-facing windows is the main reason for overheating in the afternoons. Furthermore, the continuous use of corrugated metal sheet roofing, a high-conductance, low-mass material, contributes to the daytime heat gain problem at the lower-altitude locations.

Figure 13(a) shows the measured envelope U-values for both Addis Ababa and Adama plotted against the best-practice target thresholds recommended under ASHRAE 90.1-2022 for similar climate types. The difference is uniform and significant for all five envelope components. The walls have U-values of 1.61 W/m^{2}K in both cities, which are about 3.5 to 5 times higher than the best-practice range of 0.30 to 0.45

Table 3. Appliance shares and projected operational savings from 30% efficiency improvement.

City	Cooking Appliance Share (%)	Efficiency Gain Basis [33]	Total Operational Saving
Addis Ababa	62.9% (Mitad 33.7% + Stove 29.3%)	0.629 * (30%) = 18.87%	18.9%
Adama	60.0% (Mitad 30.3% + Stove 29.7%)	0.600 * (30%) = 18.0%	18.0%

Note: Efficiency improvement factor based on [33] laboratory testing of high-efficiency electric *mitad* prototypes.

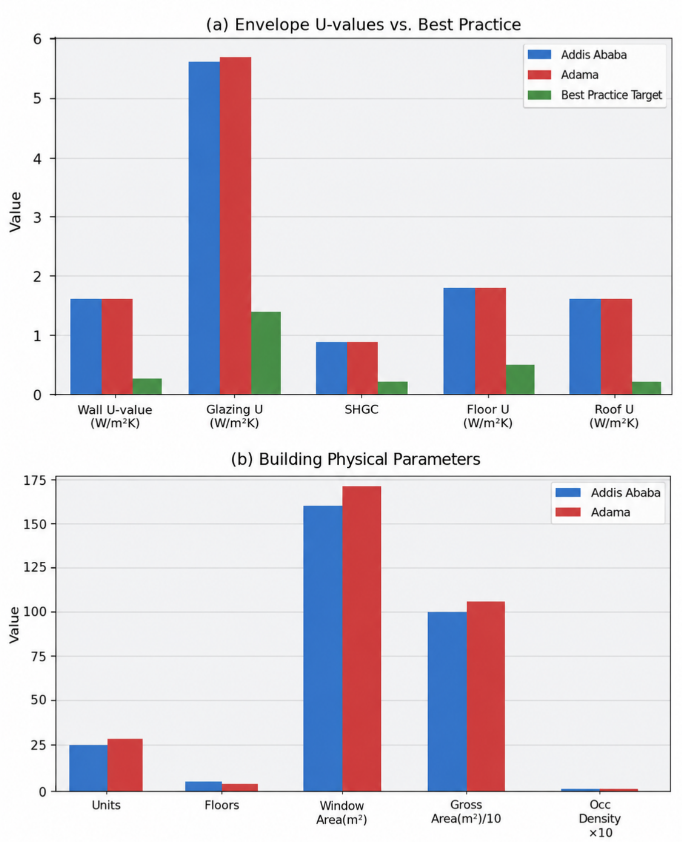

Figure 13. IHDP Building Envelope Performance vs. Best Practice Benchmarks (a) and Physical Building Parameters Comparison (b). Current envelope U-values substantially exceed best-practice thresholds for both cities.

W/m^{2}K, implying that the current walls in the IHDP are almost non-insulated by international standards. The glazing U-values of 5.71 to 5.77 W/m^{2}K are four times higher than the best practice, while the Solar Heat Gain Coefficient (SHGC) values of 0.86, 0.87, in comparison with sub-0.25 target, signify that solar radiation penetrating the glazing is hardly inhibited. Likewise, floor and roof U-values surpass the targets, though the roof performance gap is especially Adama's concern because of the intense solar radiation that falls on horizontal surfaces at low altitude.

Figure 13(b) displays the physical building parameters of the case buildings simulated, thus providing a reference to the envelope performance data. The model consists of mid-rise G+4 to G+6 blocks with a comparable gross floor area (approximately 1000-1050 m^2) and a similar number of floors (4-5 storeys) for both cities, which is proof of the typicality of the IHDP constructions. Window area is appreciably larger in Adama (172 m^2) than in Addis Ababa (162 m^2), an irrational design decision for a hot-arid climate directly exacerbating the SHGC-induced overheating risk quantified in subplot (a). Occupant density, adjusted by a factor of 10, is slightly higher in Adama, which leads to an increase in internal heat gain per unit. The joint reading of both subplots thus indicates that the IHDP design template not only neglects to achieve efficiency standards in absolute terms, but in the case of Adama, it violates climate-responsive design principles by installing bigger glazed areas in the climate zone least capable of handling solar gain.

Furthermore, the result indication is consistent with the idea that a further reduction of wall U-attainable W/m^{2}K by means of externally applied insulation combined with the replacement of single-clear glass with low-e double-pane units ($U \approx 1.4$ W/m^{2}K, SHGC ≈ 0.25) would result in peak indoor temperatures going down by around 3–4°C in Adama, sufficiently cool to mean no space cooling would be required on about 65% of discomfort-season days, and the AC adoption trigger temperature threshold would be reduced to a setpoint that is actually attainable. The evidence presented here further supports the argument for the building code to include zonal-specific envelope prescriptions: The code for Addis Ababa can emphasize lightweight constructions that rely on internal gains to minimize heating energy (due to the very limited heating requirement), whereas the code in Adama should make it a requirement for the use of solar-control glazing and roof insulation at the very least as performance levels that must be met.

5 Conclusion

This research introduces the calibrated, smart meter-validated EnergyPlus simulation workflow coupled with ClimateStudio, specifically for Ethiopian IHDP residential housing. The study includes two IHDP housing in divergent climatic zones, i.e., the temperate highland of Addis Ababa and the hot-arid climate of Adama. Besides, the study tackles the major issue of lack of empirical energy benchmarks, which for a long time have been hindering the implementation of the ambitious Ethiopian Energy Efficiency Program.

The main outcomes of the research are:

- Historically, the dominant cooking appliances in Ethiopian households (injera mitad for baking traditional flatbread and local electric stove) use up to 60–62.9% of the total electricity consumption. Herein, those appliances are viewed as the single most influential efficiency lever, which is also culturally consistent, in the Ethiopian residential sector.
- Energy use per unit area of the city of Adama is 9.5% more than that of Addis Ababa at the starting point level. The main reasons behind this are the heavily degraded building envelope that results in high thermal stress, cooling, and thermal comfort fan use which ultimately leads to increase of more than 15% in the "others" category consumption during the discomfort months.
- In the moderate climates of the Highlands, the increase in latent cooling demand will only be 6% relative to the present level. However, in the hot-arid lowland, it will be 31%. The use of cooling as driven by higher disposable income will thus, one way or another brings this divergence, which at the same time can be very relevant to the national grid expansion planning.
- The result of converting cooking appliances into more energy-efficient ones will be almost instantaneous cross-zone operational savings to the level of 18.0 to 18.9 percent. The outcome can be seen as making a very convincing and continuous case for MEPS implementation.

These energy benchmarks of real-world buildings are the basis for a two-fold set of policy recommendations. Appliance regulations: the finding that cooking loads take up most of the energy (60-63%) confirms that the EEA's focus on injera mitad and stove MEPS is the single most effective health sector intervention; the 18% savings estimate can therefore serve as the empirically supported savings claim in the MEPS justification document. Building codes: the highly divergent latent cooling patterns across the two climatic zones, i.e., 6% and 31% relative to the baseline, provide very strong grounds for climate-specific envelope requirements: thin- and glassed-roof insulating code mandates enforced strictly in Adama and other similar hot-arid cities, while codes in the highland cities could mainly focus on the thermal mass, airtightness, and daylighting.

The geographical limitations of this study, in addition to the exclusion of the embodied carbon and lifecycle aspects and not considering climate change projections in the demand scenarios, are some of the limitations of this article. Further studies can develop the validated BPS framework across all Ethiopian climatic zones and utilize RCP weather data to illustrate the impact of warming climate on cooling demand pathways. Moreover, they can implement behavioral modeling for occupants' heterogeneous responses as reported across different household income levels. The main immediate avenue to the policy impact is the integration with Ethiopia's national building energy code development, through the provision of the statistical benchmark datasets of the zone-specifics that are generated here.

To sum up, besides other findings, this article has demonstrated how empirically calibrated building energy simulation coupled with smart meter data and culturally aware appliance inventories can yield the kind of climate-differentiated, housing-typology-specific energy benchmarks that the Ethiopian energy efficiency policy machinery so desperately needs. The efficiency jump is within reach, only if it is enabled by the type of evidence which is at the very beginning by the present article.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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