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Efficient Energy Mix Model for Households in Dar es Salaam

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Abstract

The study analyses energy consumption in Dar es Salaam and assesses a range of energy sources, including solar power, liquefied petroleum gas (LPG), grid electricity, charcoal, firewood, and natural gas. By analysing the characteristics, costs, and benefits of each energy source, the study proposes an optimal household energy mix that enhances energy security, minimizes environmental impact, and reduces costs. Secondary data on existing energy practices were collected, and various energy mix scenarios were simulated using optimization techniques such as combined heat and power (CHP) systems and load-following strategies to ensure optimal performance while maintaining energy sustainability. Implementing this optimized energy mix model reduces household energy expenses by integrating cost-effective energy carriers and efficient technologies. Households benefit from lower electricity and fuel costs through the use of affordable and sustainable energy sources such as solar power and natural gas. Additionally, demand-side management strategies, like load following, help minimize peak-time energy costs and enhance efficiency. Furthermore, the model encourages investment in local energy infrastructure such as photovoltaic systems and natural gas pipelines networks, fostering economic opportunities like installing solar panel and distribution, job growth through technological innovation in energy efficiency solutions, and reduced dependency on traditional energy sources.

Keywords: Energy mix model, charcoal dependence, cost effective energy, household energy, energy optimization

Introduction

Household energy consumption in urban Tanzania, particularly Dar es Salaam, remains heavily reliant on traditional biomass sources such as charcoal and firewood (Msuya 2011, Mhache 2021). While considered affordable, these sources contribute to deforestation (Mahushi et al. 2021), indoor air pollution, and greenhouse gas emissions (Doggart et al. 2020, Sansavini et al. 2022, URT 2021). Charcoal dominates urban areas (Faraji et al. 2015), while firewood is prevalent in rural settings, highlighting a major energy security issue, as over 90% of households in Tanzania Mainland still depend on biomass for cooking (URT 2021). Despite the availability of cleaner and more efficient energy options such as liquefied petroleum gas (LPG) (Olowolayemo 2023), natural gas, solar power (Lau et al. 2017, Mwakitalima et al. 2023), wind power and grid electricity, their adoption remains limited due to cost perceptions, accessibility constraints, and socio-economic factors (Ishengoma and Igangula 2021, Lusambo and Mbeyale 2021, Inston and Scott 2022, URT 2021).

The household energy mix refers to the combination of energy sources (Hannah and Pablo 2020), including electricity, natural gas, coal, oil, renewable energy (solar, wind, etc.), and biomass, used for various end-uses such as cooking, heating, appliances, lighting, and travel, which can vary due to different influencing factors such as energy content, cost, and appliances affordability (Bongers 2022, Chen et al. 2023). Existing research has focused on individual energy sources but lacks a comprehensive approach to optimizing household energy mixes (Ntiyakunze 2021, Lusambo and Mbeyale 2021, Lokina and Mapunda 2015, Luo et al. 2020, Luo et al. 2021). Table 1 shows potential sources of energy for households in Dar es Salaam (Lusambo and Mbeyale 2021, Inston and Scott 2022, URT 2021).

Table 1: Potential sources of energy for households in Dar es Salaam

Energy carrier	Fuel cost	Energy content		Equivalent energy cost (TSh/kWh)
		MJ/kg	kWh/kg	
Charcoal	1500 TSh/kg	29.4	8.2	182.93
Grid-electricity	350 TSh/kWh	-	-	350
LPG	3833.33 TSh/kg	46.4	12.8	299.48
Natural Gas	1000 TSh/m^3	55.5	11.1 kWh/m^3	90

This study addresses this research gap by developing an optimized energy mix model that integrates multiple energy sources based on cost-effectiveness, sustainability, and energy security. The developed model aims to minimize biomass reliance, promotes cleaner energy transitions (Koepke et al. 2021), reduces environmental impacts, and supports policy development for improved energy access (Yawale et al. 2023) and renewable investment in urban Tanzania.

Materials and Methods

This study develops an optimized household energy mix model integrating various energy carriers, including charcoal, grid electricity, LPG, natural gas, and solar energy, to meet household energy needs such as cooking, lighting, powering appliances, and entertainment as depicted in **Figure 1**. The model is based on a household of six members using various appliances, as outlined in **Table 2**, with energy demand profiles shown in **Table 3.**

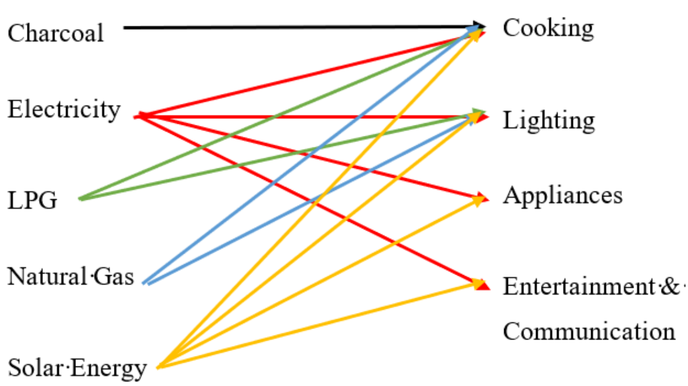

Figure 1: Network Representation of Household Energy Consumption

Energy Source Selection

The selection of energy source for optimization was based on economic viability, energy efficiency, and availability. Solar PV was excluded from the objective function due to inconsistent unit costs, complicating direct economic optimization, but was included in sustainability assessments. LPG was excluded in favor of natural gas, as it offers a lower energy cost. Additionally, when gas is converted into electricity to meet household demands, natural gas remains the superior, cost-effective option over LPG.

Objective Function and Optimization Approach

The objective function was formulated to minimize household energy expenditure while ensuring that daily energy demands were met. Mathematically, this is represented as:

Minimize $Z = \sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij} X_{ij}$ Eqn (1)

where Z is the total cost of the energy expenditure (TSh), m is the number of the energy carriers, n is the number of the energy end-uses, C_{ij} is the unit cost of energy (TSh/kWh) shown in **Table 2** and X_{ij} is the energy consumed (kWh) by households using energy carrier i to meet energy end-use j; numbering of i and j follows sequential order as depicted Figure 1.

The Constraints Requirements

The total energy required to meet particular demand must be greater than or equal to useful energy required for the specific energy end-use. Mathematically, this is expressed as:

$P = \sum_{i=1}^{m}\sum_{j=1}^{n} n_{ij} X_{ij} \geq useful\ energy$ Eqn (2)

Where P represents the energy demand constraint and n_{ij} denotes the efficiency of the appliance for each energy end-use. In cases where multiple energy sources are available to satisfy the same end-use, the source with the lowest useful energy contribution is selected to meet the demand efficiently.

Data Collection and Energy Demand Quantification

Energy demand was estimated using appliance power ratings, household energy survey data, manufacturer specifications and existing literature. Studies from India, China, Japan, and the Netherlands reported daily useful cooking energy ranging from 0.5 to 3.5 MJ per capita. Comprehensive sampling approach ensured data reliability, employing stratified random sampling and structured questionnaires to categorize households by income, location, and energy use behaviours, capturing a diverse range of consumption patterns. Face-to-face interviews with 500 households in urban and peri-urban Dar es Salaam captured energy preferences and cost perceptions, providing a robust dataset for modelling energy consumption and optimizing energy mix decisions (Kichonge et al. 2014).

Cost Trade-Offs in Cooking Energy Sources

A life-time cost analysis evaluated the trade-offs of different cooking energy sources incorporating key financial components: initial investment costs (C_0), annual maintenance (C_m) at 5% of appliance cost, operational costs (C_o), and appliance replacement (C_r) over a 25-year period. The analysis incorporated Tanzania's 3% annual inflation rate for economic realism.

Future costs were adjusted using the standard inflation formula:

$C_t = C_{t-1} \times (1 + i)$ Eqn (3)

Where C_t is the cost in year t, C_{t-1} is the cost from the previous year, and i = 3% is the annual inflation rate. The 25-year cumulative cost enables a direct comparison of energy sources, balancing short-term affordability with long-term savings for informed household policy decision making.

Sensitivity Analysis and Seasonal Variability

Using HOMER Pro software (Fofang and Tanyi 2020), sensitivity analysis simulated energy price fluctuations and their effects on household expenditure. Seasonal variations in energy demand were also analysed particularly during peak periods to assess how external factors influence energy mix decisions overall costs.

Validation of Household Energy Mix Model

Due to challenges in obtaining historical utility records and tracking energy expenditures, the validation process ensured accuracy and reliability. A comparative systematically matched reported household energy costs with estimates from the energy mix model. Households recalled monthly expenditures, which were then cross-referenced with market prices and appliance usage estimates, enhancing the model's credibility (Stoner et al. 2021).

Household Energy Expenditure Survey

The survey provided insights into household energy consumption patterns and the mix of sources used for cooking, lighting, appliances, entertainment, and communication. These patterns were mathematically expressed in Eqn 4 that guiding the energy mix categorization.

$$W = \sum(\text{Energy Carrier}_{\text{Cooking}} + \text{Energy Carrier}_{(\text{Lighting, Appliances, Ent \& Comm})}) \ldots \quad \text{Eqn (4)}$$

Where, Elec – Electricity, Ent – Entertainment, Comm – Communication, W – represents the energy mix patterns. Energy Carrier – Any of the energy carriers like charcoal, LPG, natural gas, electricity, solar PV or any combinations of this energy carried like (Charcoal and LPG, Electricity and solar PV). Given the difficulty of tracking multiple sources for the same end-use (such as cooking), four primary household energy mix scenarios (W_1, W_2, W_3, W_4) were formulated for cost evaluation.

$$W_1 = \text{Charcoal}_{\text{Cooking}} + \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots \quad \text{(Eqn 5)}$$

$$W_2 = \text{LPG}_{\text{Cooking}} + \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots \quad \text{(Eqn 6)}$$

$$W_3 = \text{Natural gas}_{\text{Cooking}} + \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots \quad \text{(Eqn 7)}$$

$$W_4 = \text{Elec}_{\text{Cooking}} + \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots\cdots \quad \text{(Eqn 8)}$$

Household Energy Cost Estimation

Household energy expenditures was calculated for each scenario using standardized energy prices and compared with model-predicted cost

Table. The cost Equations (Eqn 9-12), represents actual energy expenditures (C_1, C_2, C_3, C_4) for different energy mixes.

$$C_1 = 182.93\ \text{Charcoal}_{\text{Cooking}} + 350\ \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots \quad \text{(Eqn 9)}$$

$$C_2 = 299.48\ \text{LPG}_{\text{Cooking}} + 350\ \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots \quad \text{(Eqn 10)}$$

$$C_3 = 90\ \text{Natural gas}_{\text{Cooking}} + 350\ \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots \quad \text{(Eqn 11)}$$

$$C_4 = 350\ \text{Elec}_{\text{Cooking}} + 350\ \text{Elec}_{(\text{Lighting, Appliances, Ent \& Comm})} \cdots\cdots\cdots \quad \text{(Eqn 12)}$$

Cost Estimation of the Energy Mix Model

The predicted annual household energy cost was derived from the lifetime cost breakdown of optimized model (Figure 6) and expressed as:

$$\text{Energy Mix Model Predicted Cost} = \text{Lifetime Cost of Energy Mix Model} / 25\text{yrs} .. \quad \text{Eqn (13)}$$

Comparison and Model Validation

The model's effectiveness was assessed by comparing actual household energy expenditures with predicted cost for the same energy consumption. The percentage cost reduction was calculated as:

$$\text{Cost Reduction (\%)} = \left(\frac{\text{Actual cost} - \text{Predicted cost}}{\text{Actuat cost}}\right) \times 100\ \% \ldots\ldots\ldots\ldots \quad \text{Eqn (14)}$$

Where, Actual cost - represents household actual energy cost. Predicted cost - represents energy mix model predicted cost. This approach validated the model's credibility, enabling meaningful comparisons between projected and actual household energy expenditures.

Results and Discussion

Evaluation of the Household Energy Requirements

Table 3 presents the energy requirements for a household of six persons across different end-uses. Appliance efficiency impacts overall energy consumption, with classifications such as the European Union's A+++ to G scale and the United States of America Energy Star certification. In Tanzania's urban areas, higher-efficiency models are becoming more available due to rising consumer awareness and energy costs. Investing in energy-efficient appliances enhances affordability and reduces long-term operational costs.

Table 3: Estimated energy requirement for different household end-uses in Dar es Salaam

Energy Carrier	Energy end-uses	Devices and Effective Time	Energy requirement (equivalent)	
			(kWh)/day	(kWh)/year
Charcoal	Cooking	Top cover cast iron stove, 2.0 kg/day of charcoal	16.4	5986
Electricity	Cooking	Flat hotplate class A, 3 hours/day on 1.5 kW hotplate	4.5	1642.5
	Lighting	15 LED bulbs of 10W each, 85% energy efficiency, 10 hours/day	1.5	547.5
	Appliances	Kettle (2 litres) of 3.5 kW, 85% energy efficiency, for 20 min/day	1.2	438
		Blender (2 litres) of 1.5 kW 85% energy efficiency, for 10 min/day	0.25	91.25
		Oven (60 litres) of 3.5 kW 75% energy efficiency, for 30 min/day	1.75	638.75
		Electric iron (1.5 kW), 75% energy efficiency, for 30 min/day	0.75	273.75
		Central Air Conditioner of 3.5 kW, 3 hours/day, 50% energy efficiency	10.5	3832.5
		Water heater of class A+ of 4 kW, 1 hour/day of 50% energy efficiency	4	1460
		Hair dryer of 1.5 kW, 10 min/day of 40% energy efficient	0.25	91.25
		Water pump of 1.5 kW, 8 min/day of 50% pump efficiency and motor efficiency of class IE1	0.2	73
		5 fans (44 to 50 inches size of DC motor) of 45 W, 90% energy efficiency, 9 hours/day	2.025	739.13
		Class A+ refrigerator (250 litres) 0.18 kW 50% energy efficiency for 24 hours/day	4.32	1576.8
		Class A+ washing machine (8 kg load capacity) 0.5 kW 50% energy efficiency, 15 min/day	0.125	45.625
	Entertainment & Communication	LED smart TV (50 inches) 0.1 kW class A+, 5 hours/day Home Music System 0.1 kW for 4 hours/day Average router 0.01 kW for 24 hours/day 4 Laptops (0.05 kW for 4 hours/day)	1.94	708.1
LPG	Cooking	Flat hotplate stove, 406.1 g/day	5.2	1898
	Lighting	15 LED bulbs each of 10 W consume 46.6 g of gas for 12 hours	0.6	219
Natural gas	Cooking	Flat hotplate stove, 0.46 m^3/day	5.1	1861.5
	Lighting	15 LED bulbs each of 10 W consume 0.0542 m^3 for 12 hours	0.597	218
Solar energy	Cooking	Flat hotplate class A, 3 hours/day on 1.5 kW hotplate	4.5	1642.5

Energy Carrier	Energy end-uses	Devices and Effective Time	Energy requirement (equivalent)	
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	Total		**94.517**	**34498.81**

Useful Amount of Energy for the End-use Functions

Evaluating appliance efficiency for each end-use enabled the determination of actual energy delivered by the various sources. Table 4 summarises the useful energy derived from different sources.

Table 4: Useful energy requirement for different end-use functions

Energy carrier	Energy end-uses	Energy required (kWh/year)	Appliances efficiency (%)	Useful energy (kWh/year)
Charcoal	Cooking	5986	50	2993
Electricity	Cooking	1642.5	74	1215.45
	Lighting	547.5	85	465.38
	Appliances (washing machines, refrigerator, electric kettle, electric iron, blender, Oven, Fan, Air conditioner, Water pump, Hair dryer, Water heater)	9260.055	75	6945.04
	Entertainment & communication (LED TV, Home Music System, Average router, Laptops)	708.1	90	637.29
LPG	Cooking	1898	64	1214.72
	Lighting	219	85	186.15
Natural gas	Cooking	1861.5	66	1228.59
	Lighting	218	85	185.3
Solar energy	Cooking	1642.5	74	1215.45
	Lighting	547.5	85	465.38
	Appliances (washing machines, Refrigerator, Electric kettle, Iron, blender, Oven, Fan, Air conditioner, Water heater, Hair dryer, Water pump)	9260.055	75	6945.04
	Entertainment and communication (LED TV, Home Music System, Average router, Laptops)	708.1	90	637.29
	Total	**34498.81**		**24334.08**

The energy generated from carriers amounts to 34,498.81 kWh per year, while the total useful energy is 24,334.08 kWh per year. This indicates that 29.46% of the total energy is lost due to inefficiencies in devices, appliances, and machinery. To mitigate these inefficiencies, it is essential to invest in energy-efficient technologies and promote the adoption of high-efficiency devices, appliances, and machines within households.

Load Demand and Profile

The electric load demand covers household appliances used to meet energy needs through electricity. The evaluation of household energy consumption in Table 2 provides a basis for profiling electric energy shown in Figure 2

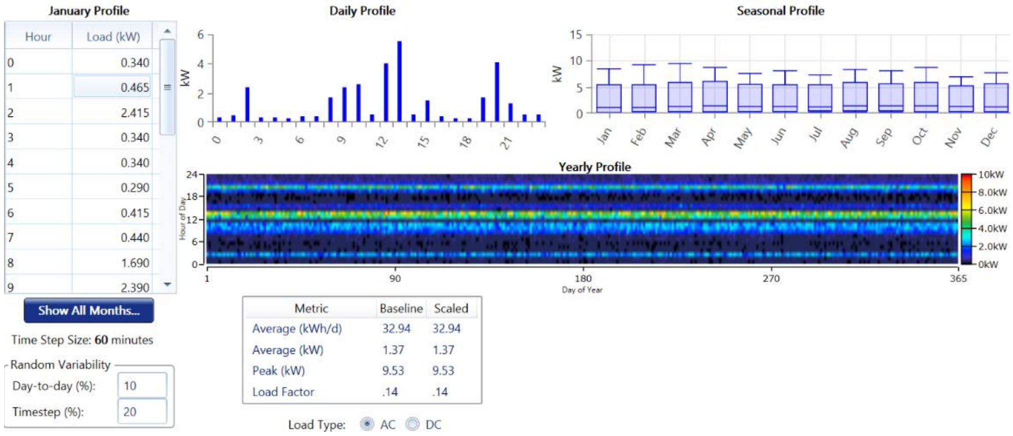


Figure 2: Household energy consumption by end-uses

Model Development

The objective function based on the data in Table 1 and different household end-uses Eqn (1) becomes as shown in Eqn 15:

Minimize: $Z_1 = 182.93X_{11} + 350\,X_{21} + 350X_{22} + 350\,X_{23} + 350X_{24} + 299.48\,X_{31} + 299.48X_{32} + 90X_{41} + 90X_{42}$ Eqn (15)

Where Z_1 is objective function for the total cost of energy used across different end-uses.

Considering the technologies and energy efficiency of the appliances, devices, or machines, Eqn (2) for different end-uses results in constraints defined in Eqn (16) through Eqn (19).

End-Uses Constraints

- Cooking constraints:

$$0.5X_{11} + 0.74X_{21} + 0.64X_{31} + 0.66X_{41} \geq 1214.72 \qquad \text{(Eqn 16)}$$

- Lighting constraints:

$$0.85X_{22} + 0.85X_{32} + 0.85X_{42} \geq 185.3 \qquad \text{(Eqn 17)}$$

- Appliances constraints:

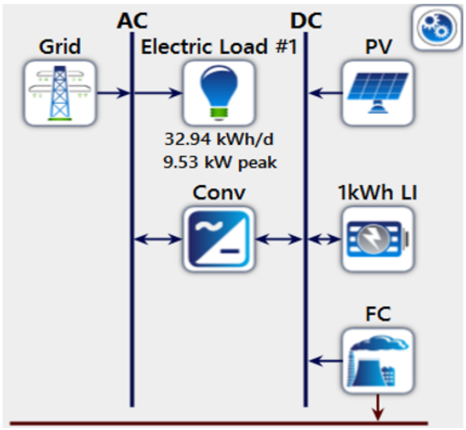
$$0.75X_{23} \geq 7376.19 \qquad \text{(Eqn 18)}$$

- Entertainment & communication constraint:

$$0.9X_{24} \geq 637.29 \qquad \text{(Eqn 19)}$$

Energy System Layout, Simulation and Optimization

The model integrates PV solar, grid electricity and natural gas fuel cell to provide reliable, low emission electricity in Dar es Salaam. A load-following strategy ensures continuous supply despite solar variability and grid fluctuations. Simulation optimized technical performance and feasibility, while sensitivity analysis addressed renewable intermittency and demand variations. Figure 3 illustrates the system design.



Legend

AC	Alternating Current
DC	Direct Current
Conv	Converter that converts electricity from AC to DC or vice versa
FC	Fuel Cell using natural gas
Grid	Electricity from the national grid
PV	Photovoltaic solar panels
Electric Load #1	Household electricity needs
1 kWh Li	Lithium battery with 1 kWh capacity

Figure 3: System component design and configuration

Optimized Energy Sources Results

The optimal energy sources determined using LINGO 17.0 software based on the least cost approach (Marnewick et al. 2019), by minimizing the objective function (Eqn 15) subject to the requirement constraints (Eqn (16) to Eqn (19)) are shown in Table 4.

Table 4: Optimized amount (kWh per year) required to meet household demands from preferred energy carriers.

Energy Carrier	**Energy end-uses**			
	Cooking (kWh)	**Lighting (kWh)**	**Appliances (kWh)**	**Entertainment & Communication (kWh)**
Charcoal	0	0	0	0
Electricity	0	0	3993.80	730
LPG	0	0	0	0
Natural gas	1840.4	211.7	0	0

The modelling of the household energy service demands indicates that natural gas and electricity are the preferred energy sources. Notably, charcoal and LPG are absent, suggesting that alternative solutions have been identified as more efficient and cost-effective for meeting energy needs as shown in the optimized model in Eqn (20). Table 5 shows the input quantities required to fulfil household demands.

$$Z_1 = 350\, X_{23} + 350 X_{24} + 90\, X_{41} + 90 X_{42} \quad \text{Eqn (20)}$$

Table 5: The input amount (kWh per year) to meet demands of the energy end-uses

Energy Carrier	**Energy end-uses**			
	Cooking (kWh)	Lighting (kWh)	Appliances (kWh)	Entertainment & Communication (kWh)
Charcoal	5986	-	-	-
Electricity	1642.5	547.5	9834.93	708.1

LPG	1898	219	-	-
Natural gas	1861.5	218	-	-

Charcoal is primarily used for cooking, with the highest consumption among energy sources, while electricity is versatile and can be used for all household energy needs. Natural gas, however, requires less energy compared to other sources for cooking, as depicted in Table 5.

Costs Trade-Offs in Cooking Energy Choices

Optimizing household energy system requires balancing initial investment costs with long-term savings. Low-cost, inefficient energy sources like charcoal lead to frequent fuel expenses and higher long-term costs. Natural gas and LPG installations demand a considerable initial investment but result in lower annual energy costs. In contrast, natural gas and LPG require a higher initial investment but reduce annual energy costs. Figure 4 illustrates the comparative cost trajectory of different cooking energy sources over 25 years, visualizing how initial investment, maintenance cost, operational costs, and replacement cost impact total expenditure. The figure provides a clear representation of short-term affordability versus long-term savings, reinforcing the cost trade-offs analysis. Charcoal has low upfront costs but high long-term expenses due to inefficiencies and price fluctuations. In contrast, LPG and natural gas require higher initial investments but offer lower long-term costs. This highlights the financial advantages of efficient energy sources and the need for structured financing like subsidies and incentives (Patel et al. 2016).

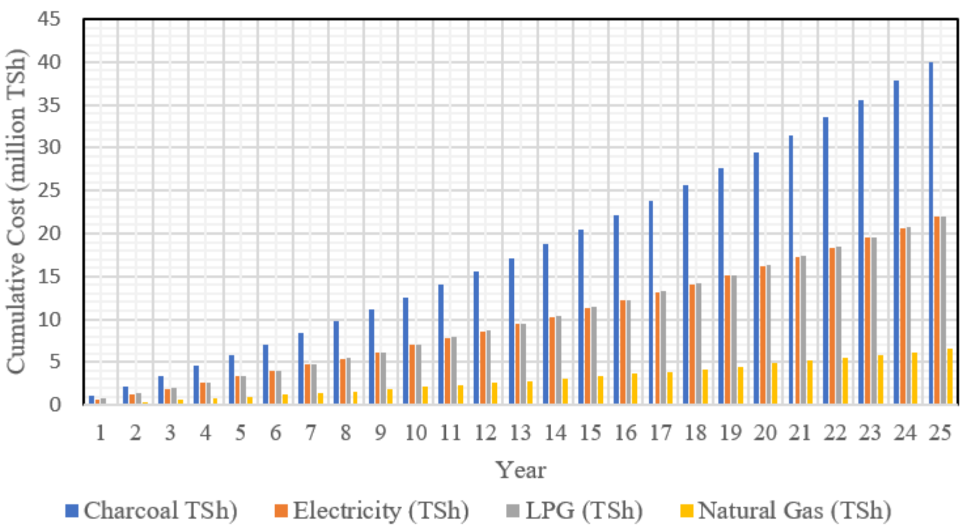


Figure 4: Trade-offs between initial investment and long-term savings in cooking.

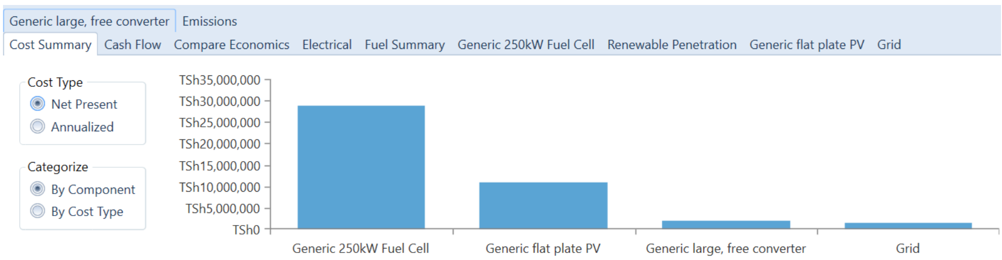
Electricity Modelling Results

The household electricity demands were modelled using solar PV, grid electricity, and a natural gas fuel cell, supported by an inverter and lithium battery bank for stability and reliability as shown in Figure Based on the simulation and optimization models, the best solution with lowest cost includes an optimal combination of a 9.82 kW solar PV system, a 250-kW natural gas fuel cell, grid-electricity and a converter operating at 5.06 kW, as shown in Figure. This figure presents an optimized household energy system configuration, balancing affordability and efficiency. The net present cost (NPC), which reflects the total system cost over the project's lifetime minus revenue from any sale of electricity or other by-products is TSh 43.2 million, while the initial investment cost required is TSh 8.4 million.

					PV (kW)	FC (kW)	1kWh LI	Grid (kW)	Conv (kW)	Dispatch	COE (TSh)	NPC (TSh)
					9.82	250		999,999	5.06	CC	TSh111.14	TSh43.2M
					11.1			999,999	5.06	CC	TSh124.79	TSh50.3M
					9.83	250	4	999,999	5.11	CC	TSh138.39	TSh54.0M
					10.9		4	999,999	5.03	CC	TSh152.37	TSh61.1M

Figure 5: Optimal energy system configuration based on the net present cost (NPC) and least cost of energy (COE).

The chosen system integrates solar PV, grid electricity, and a natural gas fuel cell, demonstrating how a well-structured energy mix minimizes long-term costs while ensuring a stable power supply. Figure 6 to Figure 8 show further details of the best model based on the least cost approach. Figure 6 gives the Project lifetime cost breakdown for selected energy system configuration.



ıponent	Capital (TSh)	Replacement (TSh)	O&M (TSh)	Fuel (TSh)	Salvage (TSh)	Total (TSh)
Generic 250kW Fuel Cell	TSh750,000.00	TSh1,035,497.50	TSh558,079.80	TSh26,588,986.15	(TSh158,400.91)	TSh28,774,162.55
Generic flat plate PV	TSh6,429,545.45	TSh0.00	TSh4,521,135.79	TSh0.00	TSh0.00	TSh10,950,681.24
Generic large, free converter	TSh1,265,625.00	TSh1,034,813.03	TSh0.00	TSh0.00	(TSh301,609.63)	TSh1,998,828.41
Grid	TSh0.00	TSh0.00	TSh1,512,399.85	TSh0.00	TSh0.00	TSh1,512,399.85
System	TSh8,445,170.45	TSh2,070,310.54	TSh6,591,615.44	TSh26,588,986.15	(TSh460,010.53)	TSh43,236,072.05

Figure 6: Project lifetime cost breakdown for selected energy system configuration

This figure provides not only a cost breakdown of selected system configuration but also interprets the financial implications of components, namely fuel cell system, PV system, converter, and grid integration. Each of these is analysed in terms of key cost components, namely initial investment (capital), replacement, operation and maintenance (fuel), and salvage value, to provide a comprehensive view of the total cost of ownership over the system's lifetime.

The analysis reveals the impact on the overall economic viability, emphasizing the importance of balancing upfront costs with on-going operational expenses. Figure 7 gives detailed cash flows of the selected system configuration over the project's lifetime, covering initial investment costs, operating expenses, natural gas fuel cost, replacement and salvage values.

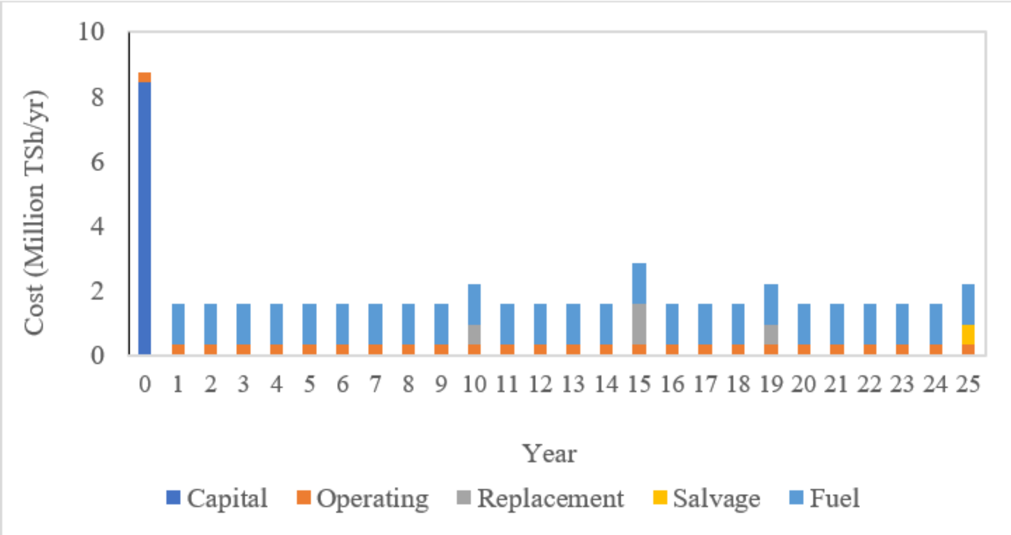


Figure 7: Cash flow analysis over 25 years of selected energy system configuration

The initial investment costs reflecting initial investment in infrastructure and technology, while operating cost cover on-going expenses related to maintenance and usage. Fuel costs fluctuate based on energy source prices and replacement cost account for periodic upgrades or replace components throughout the system's lifespan. Finally, the salvage value at the end of the project provides a return on investment in mitigating overall costs. The analysis emphasizes the long-term financial benefits of adopting a diversified energy mix.

The dynamic nature of Figure 8 explains fluctuations in power generation and consumption across different energy sources, including solar PV, grid electricity, and natural gas. The integration of multiple energy sources ensures reliability throughout the year by compensating for variations in solar energy production.

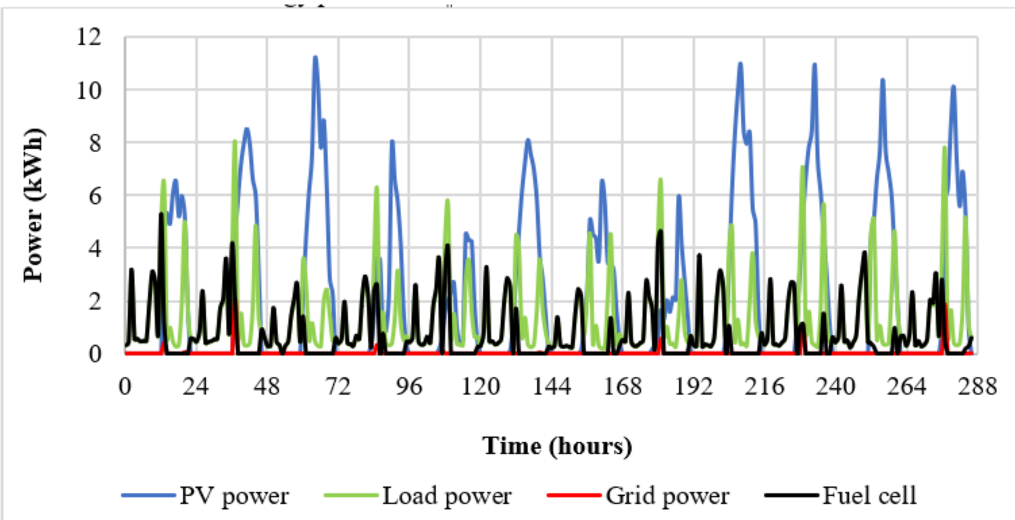


Figure 8: Hourly primary power load and energy sources utilization throughout the year.

In summary, the findings indicate that natural gas is the preferred energy for cooking while household's other energy needs are met through a combination of electricity from a 10.5kW PV solar system, grid-electricity and a 250-kW natural gas fuel cell. This configuration was optimized to align with household's electricity demand. However, the results also show that the levelized cost of electricity (LCOE) from PV system is 28.5 TSh/kWh, while the marginal generation cost from the natural gas fuel cell is 210 TSh/kWh. These figures reflect the electricity production costs annualized over the project's lifetime to determine the yearly cost of production. This supports the energy mix modelling outlined in Eqn (21) through Eqn (23).

$$E_{total} = E_{PV-solar} + E_{grid-electricity} + E_{natural\ gas\ fuel\ cell} + E_{natural\ gas} \quad \text{Eqn (21)}$$

Where E is energy and the subscripts shows the total energy and corresponding energy source

$$C_{total} = C_{PV-solar} + C_{grid-electricity} + C_{natural\ gas\ fuel\ cell} + C_{natural\ gas} \quad \text{Eqn (22)}$$

$$Z = C_{total} = f(E_{PV-solar}, E_{grid-electricity}, E_{natural\ gas\ fuel\ cell}, E_{natural\ gas}) \quad \text{Eqn (23)}$$

Where C is cost and the subscripts denote total cost and costs from different energy sources and their associated specific costs (initial investment, operation and maintenance (O&M)

Household Energy Mix Model

Using the least-cost and energy-efficiency concept, the model that meets household energy demand is developed as shown in Eqn (24)

$$Z = 28.5E_{PV-solar} + 350E_{grid-electricity} + 201E_{natural\ gas\ fuel\ cell} + 90E_{natural\ gas}. \quad \text{Eqn (24)}$$

The model assumes that the cost associated with energy production for each energy component remains constant over the lifetime of the appliance. However, levelized cost of 28.5 TSh/kWh for the PV system and the marginal generation cost of 201 TSh/kWh for the fuel cell system remain constant only up to a certain energy threshold set in the energy demand model; beyond this, costs may vary depending on the energy required to meet household demand.

Impact of Price Fluctuations on Energy Expenditure

The sensitivity analysis revealed that energy costs are highly sensitive to fluctuations in power prices. As grid electricity prices increase, the model reduces its dependence on grid energy and seeks more cost-effective alternatives. This behaviour is evident in Figure 9, where grid energy purchased (kWh) decreases as the power price (TSh/kWh) rises from 300 to 400 TSh/kWh. This trend suggests that when electricity becomes more expensive, model explores alternative energy sources, such as fuel-based systems and solar PV.

Figure 9 highlights the impact of power price on energy expenditure and significant role of energy affordability in shaping energy preferences. To minimize costs, the model increases reliance on fuel-based energy and solar PV, emphasizing the importance of economic adaptability in managing energy consumption amid fluctuating prices.

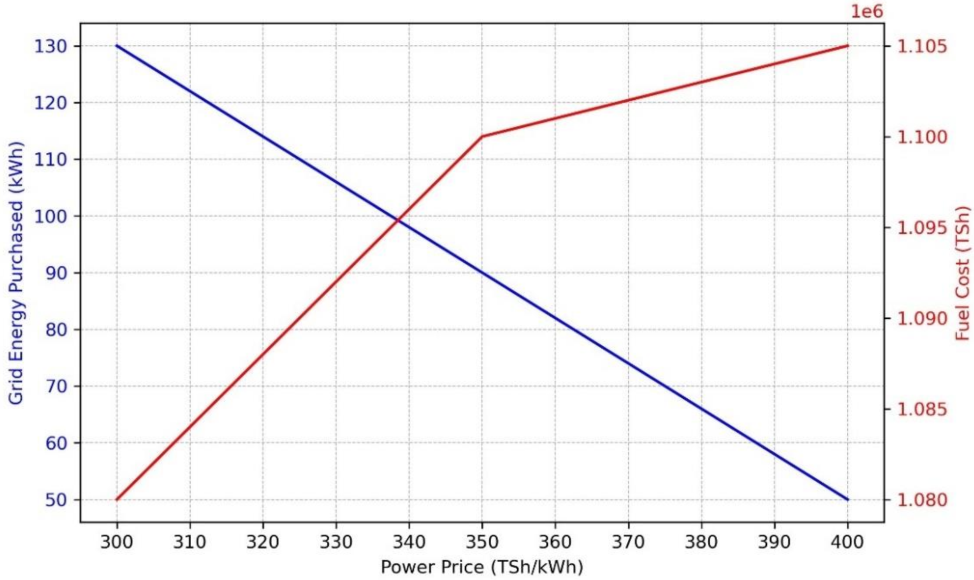


Figure 9: Impact of power price on energy expenditure

Seasonal Variability in Energy Demand

The seasonal analysis showed that electricity demand fluctuates significantly throughout the year, with peak production observed during relatively hot months (September to March) when air conditioning usage increases. Conversely, during the relatively cold months (April to August), energy demand for cooling systems decreases leading to decreased electricity production as depicted in Figure 10. Solar PV output is also affected by seasonal variations, day, and night with lower energy production during rainy season and night periods due to limited sunlight exposure. However, this reduction is offset by the availability of grid electricity and natural gas fuel cells, ensuring a stable energy supply. The integration of these sources in the optimized energy mix model improved energy security and reliability, reducing the risk of shortages during seasonal fluctuations.

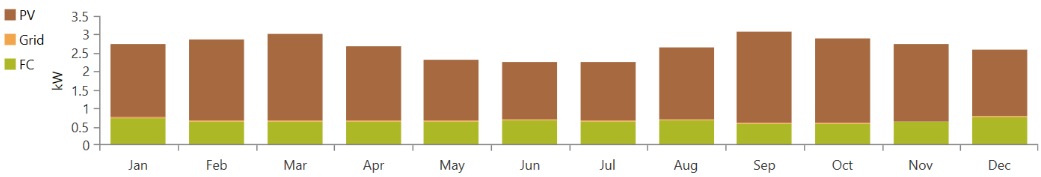


Figure 10: Monthly average electric production

Reliability of the Energy Mix Model

The findings confirm that a diversified energy mix of natural gas, solar PV, and grid electricity provides a stable and cost-effective household energy solution. The sensitivity analysis validated the model's ability to adapt to price changes, while seasonal variability assessments confirmed its efficiency despite fluctuating energy demands. Overall, these results highlight the importance of energy diversification in mitigating economic and seasonal uncertainties. By leveraging a combination of energy sources, households can enhance energy security, minimize costs, and reduce reliance on biomass fuels, supporting sustainable energy transition goals in urban Tanzania.

Validation Analysis of Household Energy Mix Model

The validation analysis using the cost reduction percentage, demonstrated the model's capacity to accurately predict energy cost reductions when the proposed household energy mix model was implemented to households. The predicted energy costs, derived from energy mix model Eqn (24), were compared with the actual household energy costs based on their current energy mix, resulting in a significant cost reduction, as shown in Table 6

Table 6: Comparison of cost reduction between actual energy cost and predicted cost

Energy mix scenario	Actual cost (TSh/year)	Predicted cost (TSh/year)	Cost reduction (%)
W_1	4,527,663.23	1,814,083.50	59.93
W_2	4,001,057.29	1,814,083.50	54.66
W_3	3,600,179.25	1,814,083.50	49.61
W_4	4,007,519,25	1,814,083.50	54.73

The analysis revealed that households following this optimized household energy mix model achieved 50–60% average annual cost savings compared to their actual expenditures. This confirms that the model effectively reduces household energy costs while ensuring sustainable and efficient energy use.

Household Energy Mix Model Implementation Challenges

Despite its economic and environmental benefits, implementing the proposed energy mix model faces significant challenges, including infrastructure limitations, policy barriers, and consumer resistance. Limited access to natural gas and unstable electricity grids hinder adoption, requiring heavy investment in energy infrastructure. High import tariffs and inconsistent subsidies increase household energy costs. Lessons from India and South Africa show that targeted subsidies and financial programs accelerate adoption, while regions like Sub-Saharan Africa without such support face slower transitions (Bouckaert et al. 2021, Geels et al. 2017, Sovacool 2016, Smil 2010). Studies highlight that, cities with well-integrated networks experience smoother energy transitions (Tardioli et al. 2019, Keirstead et al. 2012).

Consumer resistance, driven by short-term cost concerns, also slows adoption. Research suggests combining economic incentives with education can drive adoption (Geels et al. 2017, Ratti et al. 2005). A holistic approach, integrating infrastructure development, financial support, and consumer engagement, is essential for a sustainable transition, while reliance on traditional fuels persists due to familiarity and cost concerns.

Conclusion

The study demonstrates that a household energy-mix model is a sustainable and cost-effective solution to meeting energy demands. By using natural gas for cooking and a combined heat and power (CHP) fuel cell for electricity and heat recovery, households can optimize efficiency, affordability, and sustainability. This model reduces reliance on traditional biomass and grid electricity, improving energy security and long-term cost savings, while contributing to environmental sustainability. However, challenges such as infrastructure limitations, regulatory barriers, and consumer adoption must be addressed. Successful implementation requires strengthening infrastructure, including expanding natural gas networks and stabilizing electricity grids. Financial incentives like subsidies, tax reductions, and low-interest loans can encourage renewable energy adoption. Clear policies and reviews (Mandelli et al. 2014), streamlined approvals, and public awareness campaigns are essential to facilitate the transition. Public-private partnerships should support energy programs, while stakeholders should promote local manufacturing and better after-sales support. Future research should explore energy access disparities, efficiency innovations, and long-term impacts.

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