A proposed "Affordability Index" for common cooking fuels

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Affordability is one of the most significantly reported barriers to the adoption and consistent use of clean cookstoves and fuels[1]. The intuitive definition for affordability is "*the capacity to pay for a minimum level of service*" [2] (pg. 228). Affordability for clean cooking can be divided into two components: the upfront cost of the stove; and the recurring cost of the fuel. In our recent comprehensive review of affordability of clean cooking solutions, we found diverse frameworks, definitions and metrics in use, with frequent discussions on stove price, fuel costs, microfinance, and the smaller procurement quantities charasterics of most household consumers[3].

The clean cooking literature offers multiple metrics in the form of capital costs, affordability indices, capital versus 'O&M' ratios, thresholds, per unit metrics, proxy indicators, and social costs to quantify affordability. The literature then often compares different fuels based on these metrics and simplifies affordability to a cost comparison of alternative fuels.

In practice, national governments, non-governmental organizations, and the voluntary carbon market must weigh the pros and cons of different fuels to pursue for programming. In a new article, we argue the cooking sector would best serve both energy access and justice, and climate goals by focusing attention and support on 'pro-health' fuels and stoves. We define this to mean stoves that meet the World Health Organization's health standard that deliver significant health benefits to cooks and other household members and that are affordable for households to realistically adopt and continually use. Thus, in our recent comment, we evaluated stoves based on up-front and recurring, size of purchasable quantities, availability, and accessibility. We also considered stove, fuel, and infrastructure estimates for various stoves from the first author's other research into the costs and benefits of different cooking transitions[4].

Our review indicated that affordability metrics for clean cooking should be constructed to reflect the uncertain and irregular nature of low-income households' income streams, the persistence of fuel stacking, and non-discretionary expenses such as food and water. In the meantime, we draw on the existing literature to rank these fuels[3].

To construct the affordability index, we integrated the costs for both the household and the government and/or private sector. For example, a government subsidy in China covers a third of the upfront cost of a biogas plant, yet the remaining upfront cost is still a financial barrier for households [5]. Thus, even if the recurring cost of biogas is lower than other fuels, the upfront cost affects its overall affordability ranking. Similarly, LPG use is still burdensome even in Peru's and Côte d'Ivoire where the government provides subsidies for LPG stoves [6,7]. India's PMUY policy offers the initial LPG connection (hose & regulator) for free to BPL households. However, the households remain responsible for purchasing the stove and initial cylinder, with a loan if needed [8]. Therefore, even if the stove cost for the household is lower under some policies, we base our ranking on affordability of LPG overall.

Additionally, we considered liquidity constraints, as household struggle to afford the upfront cost of the stove. Liquidity constraints were routinely mentioned for LPG, biogas, and improved biomass stoves [9–13]. Thus, we considered within the index the cost of the stove, but also how the household must purchase it. Microfinance models and pay-as-you-go cooking devices are expanding; however, standard purchasing models remain the most widely available financial option.

To build the index, we also include the supply chains of the different fuels[14]. For example, electricity per unit energy was often less expensive; however, although expanding, the scale and reliability of national grids and availability of mini grids remain limited[1]. Households often face extremely high upfront costs to extend poles to their homes even if the grid is close. We are optimistic regarding the expansion of solar panels and hot plates as part of a suite of affordable clean options, but these options are not yet widely available and thus unaffordable to the global community[15,16]. Similarly to obtaining grid access, households struggle to obtain and afford piped natural gas, which although cost competitive in some settings[17], is also limited to specific, typically urban areas[18]. We incorporated the infrastructure costs associated with each fuel beyond the upfront cost of the stove or recurring fuel cost and adjusted each fuel's placement accordingly.

We triangulated between these sources to admittedly oversimplify an incredibly nuanced concept of affordability (see Supplemental Table 1). We attempted to draw from a range of locations and policy circumstances; however, affordability does differ between country, context, and time.

This work resulted in the following index:

Table 1. Affordability Index

Fuel	**Affordability Index (0 – 9 least to most affordable)**
Three Stone Fire or Improved Firewood	9
Charcoal (Traditional and Improved)	8
WHO Tier 4 Biomass Pellet Gasifier	7
Coal Briquettes/HoneyComb/Powder/Hard	6
Kerosene	5
Ethanol from Wood/Sugar Cane	4
LPG	3
Electricity	2
Natural Gas	1
Biogas	0

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data/RESOURCE/file/000/000/170-1.pdf.
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Supplemental Information:

I. Annotated Bibliography

Table S1. Sources and ranking descriptions from Gill-Wiehl et al. 2021[3]

Source	Ranking Description
Abdulai, Martha Ali, Samuel Afari-Asiedu, Daniel Carrion, Kenneth Ayuurebobi Ae-Ngibise, Stephaney Gyaase, Mujtaba Mohammed, Oscar Agyei, et al. 2018. "Experiences with the Mass Distribution of LPG Stoves in Rural Communities of Ghana." *EcoHealth* **15 (4)**: 757–67. https://doi.org/10.1007/s10393-018-1369-7.	Refilling LPG was more expensive than traditional firewood, including the transport costs to obtain the LPG refill.
Benka-Coker, Megan L, Wubshet Tadele, Alex Milano, Desalegn Getaneh, and Harry Stokes. 2018. "A Case Study of the Ethanol CleanCook Stove Intervention and Potential Scale-up in Ethiopia." *Energy for Sustainable Development* **46**: 53–64. https://doi.org/10.1016/j.esd.2018.06.009.	Daily cost of cooking comparing ethanol fuels to alternatives (least to most expensive): electricity, fuelwood, charcoal, ethanol, kerosene, and LPG
Beyene, Getachew E, Abera Kumie, Rufus Edwards, and Karin Troncoso. n.d. "Opportunities for Transition to Clean Household Energy in Ethiopia Application of the WHO Household Energy Assessment Rapid Tool (HEART)."	Ranked (least to most affordable): electric, firewood, ethanol, kerosene, LPG, and charcoal
Bounds, Martin. 2012. "Ethanol as a Household Fuel in Madagascar." Warwickshire.	Ranked least to most expensive for annual cost of the stove: charcoal stove, woodstove equal to ethanol stove, LPG stove
"Clean and Improved Cooking In Sub-Saharan Africa: A Landscape Report Africa Renewable Energy Access Program (AFREA)." 2014. Washington D.C.	Ranks annual cost (least to most expensive): biogas, biomass gasifier, improved firewood, improved charcoal, ethanol, LPG, traditional charcoal, electric. Ranks upfront cost (from least to most expensive): traditional biomass stove, improved firewood stove, improved charcoal stove, electric stove, ethanol stove, gasifier, biogas digester.

Dagnachew, Anteneh, Paul Lucas, Detlef van Vuuren, and Andries Hof. 2018. “Towards Universal Access to Clean Cooking Solutions in Sub-Saharan Africa.” www.pbl.nl/en.	“For all cooking solutions except biogas, annual operating costs are higher than the initial capital costs of purchasing the cookstove. Kerosene and electricity, especially, involve high operating costs, followed by LPG. The annual operating costs related to biogas are close to zero, but the initial capital costs are high, especially those related to the digester. Traditional cookstoves, kerosene and coal are considered mature technologies and, therefore, are assumed not to decrease any further in price. LPG and natural gas cookstoves are also relatively mature technologies and, therefore, are assumed to have only a relatively modest annual cost decline of 1%, up to 2050. For the other cooking technologies – electricity, improved and advanced cookstoves and biogas – an average annual capital cost decline of 2% is assumed" (pg. 20). See Figure 4 for the comparison ranking of annual operating expenditure and assumed capital expenditure.
Dalberg. Scaling up clean cooking in urban Kenya with LPG & Bio-ethanol: A market and policy analysis. 2018. https://southsouthnorth.org/wp-content/uploads/2018/11/Scaling-up-clean-cooking-in-urban-Kenya-with-LPG-and-Bio-ethanol.pdf	Rank annual cost of cooking for average Nairobi HH (least to most expensive): charcoal, bioethanol v2, kerosene, bioethanol v1, LPG. Ranked stove retail price: charcoal, kerosene, more efficient charcoal (i.e., Burn/Envirofit), bioethanol, LPG. Infrastructure: bioethanol is much cheaper than LPG to supply 2 million additional households in urban Kenya (16 million USD compared to 290 million USD).

Dave, Rutu, Sandra Keller, Bryan Bonsuk Koo, Gina Fleurantin, Elisa Portale, and Dana Rysankova. 2018. "Beyond Connections Cambodia Energy Access Diagnostic Report Based on the Multi-Tier Framework." Washington D.C. www.worldbank.org.	In order of increasing proportion expenditure on cooking fuel of household budget: three-stone fire, improved cookstove, traditional stove, clean fuel stove.
Demierre, Jonathan, Morgan Bazilian, Jonathan Carbajal, Shaky Sherpa, and Vijay Modi. 2015. "Potential for Regional Use of East Africa's Natural Gas." *Applied Energy* 143 (April): 414–36. https://doi.org/10.1016/J.APENERGY.2015.01.012.	Ranked least to most expensive: wood, charcoal, electric, kerosene, LPG
Dhingra, Chhavi, Shikha Gandhi, Akanksha Chaurey, and P K Agarwal. 2008. "Access to Clean Energy Services for the Urban and Peri-Urban Poor: A Case-Study of Delhi, India." *Energy for Sustainable Development* **12 (4)**: 49–55. https://doi.org/10.1016/S0973-0826(09)60007-7.	Ranked least to most expensive per month: kerosene, LPG, and then biomass
Hakizimana, Jean de Dieu K, and Hyung-Taek Kim. 2016. "Peat Briquette as an Alternative to Cooking Fuel: A Techno-Economic Viability Assessment in Rwanda." *Energy* **102**: 453–64. https://doi.org/https://doi.org/10.1016/j.energy.2016.02.073.	Peat briquettes found to be 30% cheaper per day than charcoal
Hamid, R G, and R E Blanchard. 2018. "An Assessment of Biogas as a Domestic Energy Source in Rural Kenya: Developing a Sustainable Business Model." *Renewable Energy* **121**: 368–76. https://doi.org/10.1016/j.renene.2018.01.032.	Ranking per unit delivered energy (from least to most expensive): charcoal, kerosene, biogas, firewood, LPG
Jagger & Das. Implementation and scale up of a biomass pellet and improved cookstove enterprise in Rwanda. Energy for Sustainable Development. 2018	"The other main clean cooking competitor in Rwanda, liquefied petroleum gas (LPG), is currently much more expensive than the Inyenyeri system. A two-burner Jiko LPG stove and cylinder (12 kg) costs 125,000 RWF ($US149), and a three-burner Jiko LPG stove and cylinder costs 130,000 RWF ($US155). After the initial capital investment in the stove and cylinder, each additional

	cylinder used is 12,500 RWF ($US15)”
Jain, Abhishek, Poulami Choudhury, and Karthik Ganesan. 2015. “Clean, Affordable and Sustainable Cooking Energy for India Possibilities and Realities beyond LPG: CEEW Report.” New Delhi.	Comparing the LCOE of various cooking options (Figure 1) (increasing in cost): biogas (community), biogas (household), PNG, electric stove, induction stove, forced draft improved firewood stove, LPG, forced draft pellets
Kebede, Bereket, Almaz Bekele, and Elias Kedir. 2002. “Can the Urban Poor Afford Modern Energy? The Case of Ethiopia.” *Energy Policy*. **30**. DOI?	Ranked least to most expensive: kerosene, butane, and electricity
Kohler, Marcel, Bruce Rhodes, and Claire Vermaak. n.d. “Developing an Energy-Based Poverty Line for South Africa.”	Per unit energy ranked least to most expensive: Bagasse, coal, wood, electric, diesel, kerosene, gas, solid biomass, solar
Lucon, Oswaldo, Suani Teixeira Coelho, and José Goldemberg. 2004. “LPG in Brazil: Lessons and Challenges.” *Energy for Sustainable Development* **8 (3**): 82–90. https://doi.org/https://doi.org/10.1016/S0973-0826(08)60470-6.	Ranked least to most expensive: fuelwood (native), fuelwood (reforested), charcoal, natural gas, LPG, diesel oil, electricity (residential)
Maliti, Emmanuel., and Raymond. Mnenwa. n.d. *Affordability and Expenditure Patterns for Electricity and Kerosene in Urban Households in Tanzania*.	Ranked upfront cost (increasing): kerosene, LPG, electricity. Ranked annualized costs (increasing): kerosene, electricity, LPG
Masera, Omar R, Barbara D Saatkamp, and Daniel M Kammen. *From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model*. *World Development*. **28**. Pergamon. https://doi.org/10.1016/S0305-750X(00)00076-0.	Ranked stove capital costs: dung, agricultural waste, wood, charcoal, improved wood stove, improved charcoal, kerosene, LPG, electric
Mottaleb, Khondoker Abdul, and Dil Bahadur Rahut. 2019. “Biogas Adoption and Elucidating Its Impacts in India: Implications for Policy.” *Biomass and Bioenergy* **123** (April): 166–74. http://www.sciencedirect.com/science/article/pii/S0961953419300583.	Ranked monthly expenditure (increasing): (1) kerosene, coal, and charcoal, (2) expenditure on biomass and firewood, (3) electricity and LPG. On average, a sampled household spent Rs.1,414 per month for a member; however,

	it was Rs.1,403 for a household that did not use biogas and Rs.1,472 for the households that used biogas.
Mudombi, Shakespear, Anne Nyambane, Graham P von Maltitz, Alexandros Gasparatos, Francis X Johnson, and Boris Chenene Manuel L.and Attanassov. 2018. "User Perceptions about the Adoption and Use of Ethanol Fuel andcookstoves in Maputo, Mozambique." *Energy for Sustainable Development,* **44** (June): 97–108. https://doi.org/10.1016/j.esd.2018.03.004.	Ranked least to most expensive: firewood, electric, charcoal, LPG, kerosene, ethanol This source also acknowledges that the cost does depend on purchased quantity.
Nerini, Ray and Boulkaid. The cost of cooking a meal. The case of Nyeri County, Kenya. *Environmental Research Letters*, **X** https://doi.org/10.1088/1748-9326/aa6fd0	Ranked LCOMs from least to most expensive: improved firewood (gathered), three stone fire (gathered wood), improved firewood stove (purchased), improved charcoal, traditional charcoal, three stone fire (purchased wood), kerosene, LPG, and electric (roughly equal to LPG)
Nexant, Inc. 2005. "LPG Market Assessment Study for Mozambique."	"The average monthly expenditure on fuels is as follows: Electricity (battery) - $45.4; Electricity (line) - $43.4; LPG - $15.6; Charcoal - $6.9; Firewood - $2.5; and Paraffin - $2.3. While expenditure on electricity is higher than on other fuels, electricity is also used for a variety of end uses other than cooking. Average expenditure on charcoal is about half that on LPG."
Osano, A., J. Maghanga, C. F. Munyeza, B. Chaka, W. Olal, and P. B.C. C Forbes. 2020. "Insights into Household Fuel Use in Kenyan Communities." *Sustainable Cities and Society* **55** (April): 102039. http://www.sciencedirect.com/science/article/pii/S2210670720300263.	Ranked fuel costs from least to most expensive in each area: Bomet Urban: sawdust, firewood, kerosene, LPG, charcoal. Bomet Rural: sawdust, kerosene, LPG, Charcoal, firewood.

	Voi Urban: sawdust & firewood, kerosene, LPG, charcoal. Voi Rural: LPG, sawdust, kerosene, charcoal, firewood. Mombasa Urban: sawdust & firewood, kerosene, LPG, charcoal. Mombasa Rural: sawdust & firewood, LPG, kerosene, charcoal. Narok Urban: firewood & sawdust, kerosene, charcoal, LPG. Narok Rural: sawdust and firewood, kerosene, charcoal, and LPG
Scott, Nigel, Herbert Candia, Innocent Agbelie, and Bryce McCall. n.d. "Transitioning to Modern Energy for Cooking."	Ranked cost of fuels from least to most expensive: Ghana: firewood, charcoal, LPG on par with electric Uganda: firewood, charcoal, electric, LPG
Toman, Michael, and Randall Bluffstone. 2017. "Challenges in Assessing the Costs of Household Cooking Energy in Lower-Income Countries." http://econ.worldbank.org.	Ranking stove and fuel cost ($/year) from least to most expensive: kerosene, traditional wood, improved charcoal, traditional charcoal, improved wood, propane, electricity. Ranking total direct cost (including cooking time) ($/year) from least to most expensive: kerosene, improved charcoal, traditional charcoal, propane, traditional wood, improved wood, electricity. See Table 3

Yasar, Abdullah, Saba Nazir, Rizwan Rasheed, Amtul Bari Tabinda, and Masooma Nazar. 2017. "Economic Review of Different Designs of Biogas Plants at Household Level in Pakistan." *Renewable and Sustainable Energy Reviews* **74**: 221–29. https://doi.org/https://doi.org/10.1016/j.rser.2017.01.128.	Ranked savings from a switch to biogas (increasing in savings): electricity, wood, kerosene. However, biogas plants have upfront costs of 307-422 USD. See Figure 6.
ESMAP. Kenya. Beyond Connections. Energy Access Diagnostic Report Based on the Multi-Tier Framework. 2019	Ranked by the increasing percentage spending more than 5% of household expenditure: traditional charcoal stove, improved charcoal stove, improved wood stove, clean stove, kerosene stove, three stone fire
ESMAP. Cooking with Electricity.	Case study in Kenya 1: charcoal is more expensive ($/month) than fuel stacking Grid eCook and LPG. Case study in Zambia 2: charcoal is more expensive ($/month) than fuel stacking Grid-battery eCook. Case study in Myanmar 3: Error bars cannot distinguish between firewood and the mini-grid battery-eCook (firewood has a larger confidence interval). Case study in Tanzania 4: Stacking mini grid eCook and LPG is more expensive than charcoal. Case study in Kenya 5: Charcoal is more expensive than solar battery-eCook and LPG.

II. Comparison with the estimates in Gill-Wiehl et al. 2022'[4]

A. Fuel Costs

Fuel Costs

Kenya			
Charcoal	0.46	USD/kg	[19–22]
Wood	0.1	USD/kg	[19–22]
LPG	1.6	USD/kg	[19–22]
Pellets	0.45	USD/kg	[19–22]
Ethanol	0.81	USD/l	[22]
Electricity	0.23	USD/kWh	[23]
Kerosene	0.89	USD/l	[24]
Rwanda			
Charcoal	0.29	USD/kg	[25–28]
Wood	0.17	USD/kg	[25–28]
LPG	1.21	USD/kg	[25–28]
Pellets	0.25	USD/kg	[25–28]
Electricity	0.21	USD/kWh	MECS reports a demand of 2.78 kWh/day for cooking needs, [15] and then we assume the 0.21 USD per kWh, which is the middle tier of Rwanda's electricity pricing.[27]
Kerosene	1.00	USD/l	[29]

Haiti			
Charcoal	0.2	USD/kg	[30]
Wood	0.0	USD/kg	[30]
LPG	1.0	USD/kg	[31]
Electric	0.3	USD/kWh	[32]
Nigeria			
Charcoal	0.36	USD/kg	[33]
Wood*	0.13	USD/kg	[34]
LPG	1.28	USD/kg	[35]
Electricity	0.11	USD/kWh	[36]
Kerosene	0.67	USD/l	[34]

B. Stove Costs

Stove Costs			
Kenya			
Firewood	0.00	USD/stove	[22]
Charcoal	7.00	USD/stove	[22]

Improved Charcoal	26.00	USD/stove	[22]
LPG	81.73	USD/2-burner stove	[21,22]
Pellets	150.00	USD/2-stoves (2 burners)	[19]
Electric: Average from electric induction stove/hot plate	67.25	USD/stove	[23]
Ethanol	55.00	USD/two burner	[22]
Kerosene	16.50	USD/stove	[37]
Rwanda			
Firewood	0	USD/stove	[26]
Charcoal	6.5	USD/stove	[38]
LPG	149	USD/2-burner stove	[28]
Pellets	150	USD/2-stoves (2 burners)	[39]
Electric: Average from electric induction stove/hot plate	57.5	USD/stove	[27]

Haiti			
Trad Charcoal	2.37	USD	30
Improved Charcoal	41.00	USD/stove	40
Wood	0.00	USD/stove	30
LPG	51.00	USD/2-burner stove	31
Electric	174.00	USD/stove	41
Kerosene	36.00	USD/stove	42
Nigeria			
Charcoal	3	USD/stove	34
Wood	0	USD/stove	34
LPG	100	USD/2-burner stove	35
Electricity	41	USD/stove	43
Kerosene	10	USD/stove	34

C. Cooking Fuel Infrastructure/Capital Expenditure Costs

Rwanda					
Fuel/Stove	CAPEX per HH/stove	Stove Lifetime (yr)	Technology Lifetime (yr)	Stove Subsidy (household/technology lifetime)	Source

LPG	142.80	5	20	36	[44]
Pellet	171.40	5	20	43	[39]
Electric	157.50	3	20	24	[45]
Kenya					
Fuel/Stove	CAPEX per HH/stove	Stove Lifetime	Technology Lifetime (yr)	Stove Subsidy (household/technology lifetime)	Source
Ethanol	8.00	7.8	10	6	[22]
LPG	100.60	6.7	20	34	[46]
Pellet	171.40	4	20	34	[39]
Electric	669.00	3	20	100	[47]
Haiti					
Fuel/Stove	CAPEX per HH/stove	Stove Lifetime	Technology Lifetime (yr)	Stove Subsidy (household/technology lifetime)	Source
Electric	164.45	3	20	25	[48]
LPG	76.30	5	20	19	[49]
Nigeria					
Fuel/Stove	CAPEX per HH/stove	Stove Lifetime	Technology Lifetime (yr)	Stove Subsidy (household/technology lifetime)	Source
LPG	124.95	5	20	31	[50]