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Cost-Effectiveness of Rural Energy Access Strategies

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Abstract

Quantitative benchmarks for cost-effective provision of rural energy access are difficult to obtain because deployment costs vary across technologies, contexts, and technical assistance approaches – but crucially also across sustainability assumptions. As an alternative, this policy perspective provides a qualitative cost-effectiveness assessment of different energy access strategies. We discuss the different cost factors, accounting for differences in impact potentials across rural energy access options. We include on-grid and off-grid electrification and improved cooking technologies. The focus is on rural sub-Saharan Africa (SSA), where energy access rates are low. We document largely disappointing impacts of high-power electrification technologies, turning stand-alone solar into the more cost-effective electrification strategy in that setting. We conclude by emphasizing the high impact-cost ratio for energy-efficient biomass cookstoves.

JEL-Codes: H54, O21, O33

Keywords: Energy access; rural electrification; modern cooking energy; sub-Sahara Africa

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1. Introduction

Investment requirements to reach Sustainable Development Goal 7 – universal access to electricity and modern cooking energy – are high. The level of investment needs to grow by at least 35 percent to reach the goal by 2030 or even more than 100 percent if climate goals are also to be met (IEA & IFC 2023). While public investment flows are scarcer due to the multiple crises around the world, more public funds are pledged to climate mitigation and adaptation agreements, such as the Loss and Damage Fund established at the UN Climate Change Conference in 2022, COP27.

This paper reviews costs and benefits of rural energy-access options to improve the effectiveness of public resources in achieving the universal energy access goal and subsequent poverty impacts. We consider on- and off-grid electrification and improved cooking technologies. The regional focus of our analysis is on Sub-Saharan Africa (SSA). Quantitative benchmarking is difficult and hence we provide a qualitative cost-effectiveness assessment, taking into account capital costs and technical assistance costs as well as impact potentials. This assessment, therefore, borrows from cost-benefit analysis. The discussion is informed by our experience working in various SSA energy sectors and several impact evaluations we have conducted. It is hence a perspective paper, supported by substantive evidence.

The different technologies under scrutiny serve different purposes. Most notably, electricity is rarely used for cooking in SSA, even in areas where the grid is available. Households traditionally use firewood and charcoal as cooking fuels and improved or clean cooking solutions are based on more efficient biomass combustion technologies or Liquefied Petroleum Gas (LPG). Project assessments therefore rarely compare the cost-effectiveness of electrification and improved cooking to justify the investment. This comparison is nevertheless important since donor investments into these two policies often come from the same portfolios.

2. Qualitative cost-effectiveness assessment

In Table 1 we provide an overview of costs and benefit potentials for the different energy access technologies. First, we compile indicative figures for capital costs of different energy access technologies (see column 1). Note that while these numbers cannot be taken at face value in any specific context, they broadly reflect the incurred acquisition costs regardless of who pays. Depending on the cost-sharing model, the national government, donor agencies and end-users may contribute in varying proportions. For example, the lion's share of grid connection costs is typically borne by the government and its utility, often supported by an international donor, while the end users contribute a smaller share through the connection fee. In many improved stove and off-grid solar programs, in contrast, it is the end user who bears the entire capital costs by purchasing the appliance at a costcovering price. Here, a donor agency's contribution typically is to provide technical assistance, for example to support institutionalizing market structures. Such technical assistance costs come on top of the numbers in column (1). This is an important caveat for the interpretation of Table 1 because technical assistance requirements vary considerably between the different technologies as indicated in column (2), from fairly low for grid extension to very high for the mostly nascent mini-grid sector.

Table 1 also features the technologies' energy service potential (column 3) and a qualitative assessment of impacts effectively observed in programs across SSA (column 4). Broadly speaking, energy-efficient biomass cookstoves have proven to deliver in terms of their expected impacts, that is, a reduction of fuelwood consumption and hence, of monetary expenditures or firewood collection time, depending on whether the woodfuel is purchased or collected (Jeuland et al. 2020). These are noteworthy impacts in most settings in rural SSA, especially since the reduced workload for firewood collection mainly accrues to women (Bensch and Peters 2020; Berkouwer and Dean 2022; Das et al. 2023; Jeuland et al. 2021). The evidence on reducing household air pollution induced by woodfuel usage, however, is more pessimistic, not only for efficient biomass cookstoves but also for LPG and clean gasifier stoves. While it remains true that only exclusive use of clean stoves has the potential to fully eliminate household air pollution, clean stoves today usually fail to fully displace all dirty stoves in a household (Pope et al. 2021). Nevertheless, the impact potentials of improved cooking are impressive relative to the low costs, in particular for efficient biomass cookstoves. Among energy access technologies, improved cooking therefore clearly has the best cost-benefit ratio, even under very conservative assumptions.

For electrification, the case is much more complex. Different technologies have, *in theory*, different impact potentials, but *empirically* impacts do not differ in most cases. For higher-power technologies, technically possible demand potentials are not exploited, and consumption remains on a very low level. In other words, impacts of on-grid electrification and mini-grids on the household level in most of rural SSA are not very different from most solar home systems. Some small enterprises in newly grid-connected areas do use electric machinery (typically shops, tailors, hairdressers, welders and carpenters), but the restricting factor for economic development is market access – which is very limited in most villages in SSA. New and larger enterprises rarely emerge as a result of the village's connection to the grid. The major difference between the technologies is that grid access would allow demand growth to give way to endogenous local growth.

Table 1. Cost-effectiveness appraisal for rural energy access technologies

	Cost per connection, in US$ (1)	**Technical assistance requirement** (2)	**Energy service potential, by MTF Tier*** (3)	**Impact evidence** (4)	**Technical life-time; operation & maintenance (O&M) intensity** (5)
Electricity					
Pico PV	20-50	Medium mainly to establish market structures	Tier 1 one spotlight and one charging slot	convenience and improving daily routines, minor monetary or time savings impact potential constrained by baseline technology, typically dry-cell battery driven LED	2-5 years low O&M intensity
Stand-alone Solar Home System (SHS)	100-700 e.g. depending on capacity	Medium mainly to establish market structures	TIER 1-2 multiple light points, phone charging, radio and potentially TV or fan	convenience and improving daily routines, minor time saving impacts productive use impacts restricted to small shops and extended working hours, mainly by limited power	5+ years medium O&M intensity
Mini-Grid	750-2000 e.g. depending on connec-tion rates and anchor customers	High because most countries lack enabling regulatory framework	TIER 3-5 Tier 2 + any medium-power appliances such as refrigerators; partly also high-power appliances, such as mills	few impacts beyond conve-nience and time saving impacts impacts constrained by low electricity consumption due to limited affordability (to buy electric devices), lacking market access for enterprises, and if mini-grids do not operate all day	10-20 years high O&M intensity
On-Grid	500-1500	rather low due to long-standing local know-how	TIER 4-5 Tier 3 and high-power appliances, such as mills	few impacts beyond conve-nience and time saving impacts impacts constrained mainly by low electricity consumption due to limited affordability (to buy electric devices) and lacking market access for enterprises	20+ years low to medium O&M intensity
Cooking					
Energy-efficient biomass cookstoves	5-30	medium to high (low in urban areas) to establish market structures low to medium if provided for free	TIER 0-2 higher energy effici-ency; no reduction in air pollution	reduced woodfuel consumption and subsequent impact on monetary and time savings	2-5 years low to medium O&M intensity
Advanced biomass cookstove	75-100	very high to establish market structures medium if provided for free (to train users)	TIER 2-3 higher fuel efficiency and lower emissions	even stronger reduced fuel consumption and thus on time savings but mixed results regarding air pollution impacts constrained mainly by continued use of traditional stoves ('stove stacking'), inappropriate use, and limited availability/high cost of processed woodfuels (pellets)	2-5 years medium O&M intensity
Liquefied Petroleum Gas (LPG)	20-100	very high to establish market structures, particularly LPG supply chain in rural areas	TIER 4-5	strong reduction of traditional fuel use and thus on time savings, but so far no evidence for reducing health risks (mainly due to continued use of solid fuels and ambient air pollution)	5+ years

	Cost per connection, in US$ (1)	Technical assistance requirement (2)	Energy service potential, by MTF Tier* (3)	Impact evidence (4)	Technical life-time; operation & maintenance (O&M) intensity (5)
	plus fuel costs	high if provided for free	high fuel efficiency and low to zero emissions	adoption typically constrained due to high costs of fuel supply (e.g. to rural areas) and need of bulk cylinder purchase	low O&M intensity
Biogas digester	500-1500	very high	TIER 4-5	similar to LPG, in addition co-benefits for agricultural households (fertilizer) and zero monetary fuel costs	10-20 years
	e.g. depending on capacity	due to need to change behaviour, including keeping cattle in stable	high fuel efficiency and low emissions, lighting as co-benefit	virtually all programs in Africa have low adoption rates or have failed due to high up-front and maintenance costs, and not enough cow dung and water	high O&M intensity

Sources on costs: Lighting Global et al. 2022 *(SHS)*; AMDA 2022, BloombergNEF 2020, ESMAP 2022 *(Mini-grids);* Lee et al. 2020b, BloombergNEF 2020 *(on-grid)*, ESMAP 2020, Jeuland et al. 2018 *(cooking)*. *The Tiers of energy access are described in the Multi-Tier Framework (MTF), developed by ESMAP. Energy access is measured on a tiered spectrum, from Tier 0 (no access) to Tier 5 (the highest level of access), differentiated by household electricity and domestic cooking energy.

In contrast, solar home systems lack this possibility due to the absence of high-power electricity. It is also important to note that if there is productive use potential in a not-yet-connected village, electricity is already there, by means of diesel generators in most cases. It is rare that demand potentials are not exploited and only emerge once the grid is available. These patterns have been observed in well-crafted impact evaluations in several SSA countries (Bensch et al. 2019, 2022; Chaplin et al. 2017; Lee et al. 2020b; Masselus et al. 2024; Lenz et al. 2017; Pelz et al. 2023; Peters et al. 2011; Schmidt and Moradi 2023; Taneja 2018). The absence of considerable economic impacts in electrification programs is also documented in literature reviews (Bos et al. 2018; Lee et al. 2020a; Peters and Sievert 2016).

Effects of small-scale solar are mostly on the level of convenience and improving daily routines like studying at home and housework (Grimm et al. 2017, 2020; Stojanowski et al. 2021). There are only minor impacts on time savings and monetary expenses (while amortization is not always a given), and no discernable positive effects on productive and commercial uses. Women certainly also benefit from the convenience and housework chore effects of small-scale solar, but this is hardly transformative and certainly much less pronounced than the considerable time savings and workload reductions that have been diagnosed for energy-efficient biomass cookstoves. It is also worth emphasizing that some of the positive evidence on small-scale solar stems from a baseline situation in which costly and dirty kerosene lamps have been replaced. This, however, is no longer the baseline situation in most settings in SSA because LED torches and non-branded solar has replaced kerosene virtually everywhere (Bensch et al. 2017), reducing impact potentials for small-scale solar considerably. When scaled from small-scale solar to larger solar home systems, effects change with regards to a few appliance types that are additionally used, mostly TV sets and fans. Productive and commercial use is still very limited (Aklin et al. 2017; Bensch et al. 2018; Kizilcec and Parikh 2020; Lee et al. 2016; Radley and Lehmann-Grube 2022), for the same reasons as outlined for grid electrification above.

Beyond the classical impact categories typically scrutinized in impact evaluations, we stress that large infrastructure like the power grid also has more subtle but potentially important effects, which are under the radar of such impact evaluations. For example, the availability of the grid might provide a sense of social inclusion. It might affect participation in elections, and via television also lead to modernization, not least with respect to gender norms (Tanner and Johnston 2017). Such effects are much likelier (although largely unknown) for on-grid electrification and perhaps functioning mini-grids than for stand-alone solar and improved cookstoves. Yet, while these are noteworthy effects, and perhaps detectable on the country level, they are probably too subtle to decisively affect the cost-benefit analysis on the project level, given the high investment costs of grid extension.

Two important additional considerations need to be taken into account when interpreting the indicative cost numbers in Table 1: sustainability and low connection rates. Sustainability of on-grid electrification could indeed alter the cost-benefit analysis. When looking at a very long-term perspective, say, 15 or 20 years, the power grid is much more likely to provide sustainable electricity access than decentralized electricity sources, which need to be maintained and replaced. The maintenance of the grid is a decades-old fair for utilities, and they make sure the grid operates, in the long run – on behalf of and financially supported by the government. Organizing maintenance for mini-grids and, even more so, for stand-alone solar, is a much more difficult task (Duthie et al. 2023; Peters et al. 2019; Tenenbaum et al. 2014; Zigah et al. 2023). In other words, the costs of *sustainable* provision to the services in Table 1 might well alter the relationship between the different technologies, in favor of grid extension. Nonetheless, this will probably not change the qualitative verdict that grid extension into rural areas is very expensive given the low demand and impact expectations. This verdict is further substantiated by the importance of connection rates for costs per connection: Costs per connection easily run into thousands of EUR if only a fraction of households in a village in fact connect, as it was observed, for example, in recent impact evaluations with connection rates below 30% in Tanzania (Chaplin et al. 2017) and below 10% in Kenya (Lee et al. 2020b) and Burkina Faso (Schmidt and Moradi 2023).

3. Conclusion and Policy Implications

All things considered, from a cost-effectiveness perspective, it is hard to make a case for grid extension. The same arguments, though, also apply for mini-grids, especially when sustainability considerations are taken into account (unless mini-grids are targeted to areas far away from the grid with a high-demand anchor customer). It is hence likely that the most cost-effective electricity access solution in most rural areas will be stand-alone solar. However, broadening the scope beyond electrification, energy-efficient biomass cookstoves stand out in terms of cost-effectiveness, since they clearly deliver important impacts – especially for women – at very low costs. Also from a sustainability standpoint, low-maintenance models of energy-efficient biomass cookstoves exist that do not require major investments until replacement is due.

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